Crop specific drought monitoring and yield loss assessment by integrating geospatial, climate and crop modelling.

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CERTIFICATE

This is to certify that Mr. T.Rajasivaranjan has carried out the thesis entitled "**Crop specific drought monitoring and yield loss assessment by integrating geospatial, climate and crop modelling**" in partial fulfillment for the award of degree of Master of Technology (M. Tech.) in Remote Sensing and GIS. The thesis has been carried out in Agriculture and Soils Department and is the original work of the candidate under the guidance of **Dr N.R.Patel**, Scientist/Engineer-F, Agriculture and Soils Department, Indian Institute of Remote Sensing, Dehradun, India.

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Abstract

Understanding the behavior of crop yields becomes increasingly important for modeling production functions, forecasting price movements, and understanding farmers' responses to government programs. Variability in crop yields is a principal source of instability in production levels *(Hazell 1985)* and it is utmost important to predict the future prospect for policy makers in the government for further course of action planning. The tools like DSSAT has capability for spatial analysis and it not only assess the impact and also likely to help in mitigating the expected climate.

The present study on Crop Specific Drought Monitoring and yield loss assessment by integrating the climate - crop modeling approach demonstrated the capability of WRF climate driven DSSAT crop models coupled with GIS in presenting the spatial patterns of drought related constrains during 2009 and 2014. In this study the performance of WRF model with improved land surface condition derived from satellite data were evaluated for rainfall, minimum, maximum and average temperature. The results are showing a reasonable accuracy with an index of agreement around 65 and 62 percent for daily rainfall during 2014 in Haryana and Punjab respectively. The minimum, maximum and average temperature were validated with the ISRO AWS stations and it showed RMSE of 2.94, 3.8 and 6.4 degree Celsius variation in daily average, maximum and minimum temperature for the year 2014. The downscaled high resolution data obtained from WRF served as input to crop model in order to study the drought related constraint in rice crop production.

The crop simulation were conducted using DSSAT- CERES Rice model for two different years 2009 and 2014. Then, the results of simulated rice productivity was validated with district level yield data. The yield predicted by the model shows an R^2 value of 0.62 and 0.74 for Punjab and Haryana respectively. The water balance components of DSSAT model is validated with detrended yield anomaly of historical district level yield data. Relationship between water stress factor and yield anomaly at vegetative and reproductive stages of crop had R2 value of 0.64 and 0.52 respectively for Haryana and 0.73 and 0.68 respectively for Punjab. A poor association was found between crop water stress at maturity stage and rice yield anomaly of both Punjab and Haryana. This implies the initial and middle stages drought contribute more yield losses in rice crop than the later ones.

Key words: Crop yield Prediction, DSSAT, WRF, Regional Climate modelling, Yield anomaly, Detrending.

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1. Introduction

1.1 Background:

Drought is one of the major obstacles to food security in India. Development of strategies to effectively cope with drought and increase crop success is fundamental to ensure food security and improve the livelihood of the people of this country (Pandey, Sushil, et al). The Indian economy highly depends on agriculture. Agriculture in India consists primarily of small and marginal farmers using low level technology in a mixed crop-livestock farming system, and is highly dependent on monsoon rainfall. Delayed onset of the monsoon, prolonged breaks during the normally most active months of July and August, early withdrawal, and erratic distribution of rainfall during monsoon season make the country, especially the low rainfall belts, vulnerable to droughts.

Agriculture is the first sector to be affected by drought. Within the agricultural sector, marginal and small farmers are more vulnerable to drought because of their dependence on rain fed agriculture and related activities. As a consequence, they face much greater relative loss of assets, thus widening disparities between small and large farmers. Also, as unemployment increases purchasing power decreases- credits shrink and the cost of credit increases. Consequently, the vulnerable segments are either forced to migrate, work at lower wages or live in near hunger conditions. Pressure and fear of losing social status due to drought induced poverty forces farmers to take drastic steps like suicides (Drought guidelines India).

India has experienced many such crisis situations with varying magnitude, duration and extent. For example, abnormally low rainfall in 1979 in India reported reduction in overall food grain by 20%. The 1987 drought in India damaged 58.6 million hectares of cropped area affecting over 285 million people. Drought in 2002 has recorded reduction in food grain production to 174 million tons from 212 in 2001, resulting into a decline of 3.2% in agricultural GDP (Ministry of agriculture).

As drought is intimately related with food and nutrient security; its diagnosis and monitoring are essential. Agriculture-based livelihood systems that are already vulnerable to food insecurity face immediate risk of increased crop failure, new patterns of pests and diseases, lack of appropriate seeds and planting material, and loss of livestock (FAO, 2008).Therefore, there is a need for effective monitoring and early prediction of drought, its onset, progression and impact on crops to minimize the damages.

1.2 Need for the Research:

Drought is a recurring phenomenon causing severe damage to food and agricultural production.
In India, droughts during 1967, 1968, 1969, 1972, 1974, 1979, 1982, 1987, 2002, 2009 (Ministry of Agriculture, 1988) had considerable impact on food grains production .For example, the drought of 1966–67 reduced overall food grains production by 19%, and the loss in production of rice and other pulses was 30% in 1965–66, 66% in 1966–67, and 86% in 1967–68. The droughts of 1972–73 reduced the food grains production from 108 to 95 million tons, causing a loss of about $400 million. The 1987 drought in India damaged 58.6 million hectares of cropped area affecting over 285 million people(Ray et al., 2015). Drought in 2002 has recorded reduction in food grain production to 174 million tons from 212 in 2001, resulting into a decline of 3.2% in agricultural GDP (Ray et al., 2015),(Rathore et al., 2009). Although number of studies have been conducted to quantify the drought, the evaluation of agricultural drought in terms of production loss is very limited. Therefore there is a need for efficient method to monitor agro-drought in

terms of production loss. Thus, this study focuses on impact of drought in crop yield using an integrated approach of various techniques.

1.3 Climate and Crop Modelling for drought prediction:

As drought is a slowly developing phenomenon, starting with precipitation deficit, affecting the entire water cycle (e.g., soil moisture, stream flow, lake and reservoir levels, and groundwater) and bearing direct impacts on agricultural production, all these components need to be considered for effective drought management. Among different types of droughts, agricultural drought seems to be the most complex, as it is driven by both surface (i.e., evapotranspiration) and subsurface hydro climatic fluxes (i.e., soil moisture) at a local scale and also it differs from one crop to another. Understanding the anatomy of an agricultural drought will remain a challenge due to our limited understanding of moisture demand and supply for crop growth (Chaves). In this perspective, crop models are considered to be valuable tools for improving agricultural drought management by simulating physiological processes of soil-plant atmosphere interaction.

The discipline of crop simulation modeling has advanced rapidly in the last decades or so. The complexity of the modeling approach varies from empirical relationships that describe how a few variables affect crop yield, to more process-based equations of some of the underlying chemical and physical processes. Crop simulation models attempt to provide the equations which describe plant physiology and how these processes are affected by genotype, environment and farm management practices. They can be used to quantify the yield gap between the maximum potential and actual yields, to evaluate the management option and determine likely environmental impacts. They can also be used to forecast yields prior to harvest and extrapolate the results for decision making. The key strength of crop model is their ability to quantify variability of crop performance due to variability in seasonal weather condition and to predict the long-term impacts of climate change and land use options. Thus crop models can potentially provide a unique means of quantifying the potential impacts of drought on crop performance. A number of broad types of simulation models have developed. For example, SUCROS and related models (Bouman et al. 1996), the IBSNAT models (Uehara and Tsuji 1993), and the APSIM model (McCown et al. 1996). All these crop simulation models have one thing in common; they require climate information as an input.

In recent times, advancement in Numerical weather prediction have shown that the variability in tropics can reasonably be resolved, thereby creating a great scope for improving the monsoon prediction. Prediction of intra-seasonal variations is very crucial for agricultural planning important. Advancement in Numerical Weather prediction and climate forecast at different lead-times ranging from few days to whole season have stimulated substantial interest in predicting the impact of drought on crop growth and its relative yield reduction as a means of improving drought management and policy-level interventions. Hence, there is a need for integrated, interdisciplinary climate-crop performance forecasting system to improve the operational decision making in drought management.

In this study, I seek to put such work in context by integrating Weather Research and Forecasting (WRF) regional model output with crop model in order to address the drought related constraints in agricultural development.

1.4 Regional climate Modeling:

Regional climate models are important for the simulation and prediction of high impact severe weather systems. Such models remain important for an operational numerical weather prediction center, because they can be run at very high resolution on a nested grid with a wide variety of options for the parameterization of physical processes. During the last decade, research has demonstrated that an RCM is a useful downscaling tool for providing climate information at the scale appropriate for societal use (Leung et al. 2003). The ability of RCMs to downscale depends on large-scale boundary conditions and regional-scale forcing, such as orography, land cover and land use, and lake and urban effects, which influence not only local climate but also may have far reaching effects. The global models do not have such privileges and, they are very expensive to run at high resolutions.

Thus the main aim of this research is evaluating the performance of Weather Research and Forecasting (WRF) regional model simulation during Indian Summer Monsoon with ingestion of regional land-surface condition derived from Indian Satellites such as INSAT fractional vegetation cover, AWiFS land use land cover and integrate the improved Weather outputs from WRF model with crop model to study the spatio-temporal impacts of agricultural drought and its associated yield losses.

1.6 Research Objectives:

The general objective of this study is '*To develop an regional agricultural Drought prediction methodology based on soil water balance component and actual crop growth simulation using Comprehensive climate drive crop models, in combination with remote sensing and geographical information system*'.

- To study the performance of climate simulation by providing realistic land-surface initial conditions from satellite observation.
- To predict the crop water stress for Rice crops in North-west India using a comprehensive climate driven crop models (DSSAT).
- To improve crop forecast and associated reduction in crop yields due to drought stress.

1.7 Research Questions:

- What will be the accuracy of forecast with advanced parameterization schemes and realistic land-surface initial conditions from satellite observation?
- How best can forecasted weather data be utilized by the crop model to understand the drought evolution during the crop period?
- What will be impact of drought and it its associated yield losses using comprehensive climate driven crop models?

2. Review of Literature

2.1 Drought Concepts, Definition and Types:

Drought is a natural phenomenon that has significant impact on socio-economic, agricultural, and environmental spheres (Bhuiyan, 2004). It differs from other natural hazards by its slow accumulating process and its indefinite commencement and termination. Being a slow process although drought often fails to draw the attention of the world community, its impact persists even after ending of the event (Bhuiyan, 2004). A single definition of drought applicable to all spheres is difficult to formulate since concept, observational parameters and measurement procedures are different for experts of different fields. Besides, the concept of drought varies among regions of differing climates (Bhuiyan, 2004).In general, drought gives an impression of water scarcity resulted due to insufficient precipitation, high evapotranspiration, and over-exploitation of water resources or combination of these parameters (Bhuiyan, 2004).

2.1.1 Drought Definition

"Drought is a protracted period of deficient precipitation resulting in extensive damage to crops, resulting in loss of yield." (NDMC's Drought Impact Reporter).

Although deviation of rainfall from normal over an extended period of time is broadly accepted as the cause for drought, there is no one, universally accepted definition for drought. Often, the difference between an estimated water demand and an expected water supply in a region becomes the basis to define a drought for that region.

2.1.2 Types of Drought:

Wilhite and Glantz (1985) analyzed more than 150 definitions of drought and then broadly grouped those definitions under four categories: meteorological, agricultural, hydrological and socio-economic drought.

1. Meteorological drought: A period of prolonged dry weather condition due to precipitation departure.
2. Agricultural drought: Agricultural impacts caused due to short-term precipitation shortages, temperature anomaly that causes increased evapotranspiration and soil water deficits that could adversely affect crop production.
3. Hydrological drought: Effect of precipitation shortfall on surface or subsurface water sources like rivers, reservoirs and groundwater.
4. Socioeconomic drought: The socio economic effect of meteorological, agricultural and hydrologic drought associated with supply and demand of the society.

2.1.3 Drought Indices:

Several drought indices have been used to quantify the drought events, each having its own strengths and weaknees. Generally most of this indices are based on the meteorological and hydrological parameters such as rainfall, temperature Evapo-Transpiration, Potential Evapo-Transpiration, soil moisture etc. Most commonly used indices are Percent Normal, Palmer Drought Severity Index, Soil Water Supply Index, Standardized Precipitation Index, Crop Moisture Index, and Standardized Precipitation Evapo-Transpiration Index

2.2 Drought in India:

The inter-annual variability of monsoon rainfall during the month between June and September is the major cause of drought in India. Delayed onset of the monsoon, prolonged breaks in the monsoon during the normally most active months of July and August, early withdrawal of the monsoon, and erratic distribution of rainfall during monsoon season make our country, especially the low rainfall belts, vulnerable to droughts. India has experienced 24 major droughts listed in table below. During 1900-2012, 14 droughts have occurred with 1061 million people affected and 2441 million dollar economic loss (Ray et al., 2015).

2.2.1 Drought history in India:

Droughts that occurred in India in the past 1967, 1968, 1969, 1972, 1974, 1979, 1982, 1987, 2002, 2009 (Ministry of Agriculture, 1988) had considerable impact on food grains production .For example, the drought of 1966– 67 reduced overall food grains production by 19%, and the loss in production of rice and other pulses was 30% in 1965–66, 66% in 1966–67, and 86% in 1967–68. The droughts of 1972–73 reduced the food grains production from 108 to 95 million tons, causing a loss of about $400 million. The 1987 drought in India damaged 58.6 million hectares of cropped area affecting over 285 million people(Ray et al., 2015). Drought in 2002 has recorded reduction in food grain production to 174 million tons from 212 in 2001, resulting into a decline of 3.2% in agricultural GDP (Ray et al., 2015),(Rathore et al., 2009).

Periods	Drought years	No.of Years
1801-1825	1801,04,06,12,19,25	6
1826-1850	1832,33,37	3
1851-1875	1853,60,62,66,68,73	6
1876-1900	1877*+,91,99*+	3
1901-1925	1901*,04,05*,07,11, 13,15,18*+,20,25	10
1926-1950	1939, 41*	2
1951-1975	1951,65*,66,68, 72*+,74	6
1976-2009	1979*,82,85,87+, 2002*, 2009*	6

Table 1 Drought History

* Severe drought years
\+ Phenomenal drought years

Source: Drought Research Unit (DRU), India Meteorological Department (IMD), Pune

2.2.2 Drought classification in India:

In India, according to Indian Meteorological Department, drought is defined as “a situation when the seasonal rainfall received over the area is less than 75% of its long term average value. It is further classified as "moderate drought" if the rainfall deficit is between 26-50% and "severe drought" when the deficit exceeds 50% of the normal”.

The IMD recognizes:

- A drought week; when rainfall in a week is less than half of its normal amount,
- An agricultural drought; when four drought weeks occur consecutively during mid-June to September,
- A seasonal drought; when seasonal rainfall is deficient by more than the standard deviations from the normal,
- A drought year; when annual rainfall is deficient by 20 % of normal or more, and
- Severe drought year; when annual rainfall is deficient by 25-40% of normal or more.

Drought is also classified according to the timing of rainfall deficiency during a monsoon season. Rainfall deficiency during July month is termed as early season droughts and provide sufficient lead-time to mitigate its impact. Mid-season droughts occur in connection with the breaks in the southwest monsoon. Rainfall deficiency during September is termed as late season drought.

2.2.3 Probability of Drought occurrence in India

1. In North West India, Probability of moderate drought varies from 12-30% and that of severe drought varies from 1-20% in most of the parts and about 20-30% in extreme north-western parts (Ray et al., 2015).
2. In West Central India, the probability of moderate drought varies from 5-26% and that of severe drought varies from 1-8% (Ray et al., 2015).
3. In peninsular region probability of moderate drought varies from 3-27% and that of severe drought varies from 1-9% in major parts (Ray et al., 2015).
4. In the Central Northeast region , the probability of moderate drought varies from 6-37% and that of severe drought varies from 1-10% (Ray et al., 2015).

Regions	Frequency of deficient rainfall (75 % of normal or less)
Assam	Very rare, once in 15 years
West Bengal, Madhya Pradesh, Konkan, Bihar and Orissa	Once in 5 years
South interior, Karnataka, Eastern Uttar Pradesh and Vidarbha	Once in 4 years
Gujarat, East Rajasthan, Western Uttar Pradesh	Once in 3 years
Tamil Nadu, Jammu & Kashmir and Telangana	Once in 2.5 years
West Rajasthan	Once in 2 years

Table 2 Probability of Drought Occurrence in various region in India

5. In the Northeast region, the probability of moderate drought varies from 1-26% and that of severe drought varies from 1-3% (Ray et al., 2015).

6. In the hilly region, the probability of moderate drought varies from 9-31% and that of severe drought varies from 1-12% except in Leh and Lahul & Spiti (Ray et al., 2015).

2.3 Drought Monitoring in India:

"In India, Rainfall situation over different spatial and temporal scales in the country were monitored using network of meteorological observatories by Indian Meteorological Department (Rathore et al., 2009).The rainfall reports were generated based on this data are given to the various stakeholder in the country. Until 2012, IMD was monitoring drought using two drought indices namely percent normal deviation and Aridity Anomaly Index. Percent normal deviation covers meteorological drought while Aridity Anomaly Index (AAI) is tell agricultural drought (Rathore et al., 2009). From 2013 onwards, it started monitoring drought using Standardized Precipitation Index at districts level on monthly scale. This is in accordance with the guidelines issued by the WMO which recommends SPI as the most versatile tool which covers all three forms of drought namely meteorological, agricultural and hydrological (Rathore et al., 2009). To monitor agricultural drought and its onset, progress and recession, four weekly district SPI are computed and prepared every week. In addition to the percent normal, AAI, and SPI indices, the Normalized Difference Vegetation Index (NDVI) is also used (Rathore et al., 2009). Apart from IMD, the other nodal agencies which provides drought early warning are the National Centre for Medium Range Weather Forecasting, National Remote Sensing Centre, Central Water Commission, and National Rainfed Area Authority (Rathore et al., 2009).

To conduct studies on various aspects of droughts in India the Drought Research Unit was established by the Indian meteorological Department in 1967 (Rathore et al., 2009). At district level the ICAR in collaboration with IMD has set up 130 Agro Meteorological Field Units (AMFUs) to provide medium range weather forecast based agro-advisories (Rathore et al., 2009). At the Central level the Crop Weather Watch Group, collects data from monitoring mechanisms of water resources, rainfall, crop growth etc. and on a weekly basis assesses the status of these parameters (Rathore et al., 2009).

In order to overcome the limitations of drought monitoring, the National Agricultural Drought Assessment and Monitoring System (NADAMS) project provides near real-time information on prevalence, severity level and persistence of agricultural drought at state/district/sub-district level(Rathore et al., 2009). Currently, the project covers 13 states of India which are predominantly agriculture based and prone to drought situation (Rathore et al., 2009). National Atlas and Thematic Mapping Organisation (NATMO) develops the drought atlas for India which help to identify and prioritize specific areas in risk management" (Rathore et al., 2009).

2.3.1 Limitations of using rainfall as agricultural drought indicator

Number of studies have showed that spatial and temporal distribution of rainfall is crucial than the total rainfall in a month or season. A review of past agricultural droughts in the country reveal the lack of unique relationship between incident ground measured rainfall (only a part of which replenishes soil moisture and thus available to vegetation) and the resulting vegetation development within and between seasons as well as across space (Murthy and Sesha Sai, 2010). The "rainfall use – efficiency" varying over both time and space and the vegetation species dependence limits the use of rainfall as a sole or major agricultural drought indicator. Rainfall as an agricultural drought indicator is limited by the sparse ground observations (especially in view of high spatial variability of tropical rainfall) as well as the lack of spatially and temporally unique relationship between incident rainfall and vegetation development (Murthy and Sesha Sai, 2010). Though the daily reporting network of IMD is supplemented by the State Government raingauge network in each state, real-time information from the latter is normally limited to rain-gauges located at Tahsil Headquarters (Murthy and Sesha Sai, 2010). The possibility of observational errors also makes it necessary to process this data prior to its use leading to time delays. Aridity anomaly data currently available is only representative of large areas such as meteorological sub-divisions (Murthy and Sesha Sai, 2010).The aridity anomaly also suffers from the same limitations as that of rainfall.

2.3.2 Water Balance Approach

Using the soil characteristics and initial soil moisture values, weekly/monthly water balance computations can be carried out. If monthly water balances are to be calculated input data required by the model consists of monthly values of precipitation, Pm , and potential evapo-transpiration, PET m (calculated by any method appropriate to the region and available data). These values can be climatic-average values of a time period or actual monthly averages of a series of annual registers. Also the model requires the soil-water storage maximum capacity, Smax and the initial soil moisture content, S0. The water balance model will then calculate soil moisture content, actual evapotranspiration and runoff (here water surplus).

i. Soil moisture content

If for a given month Pm > PETm, the soil moisture at the end of that month is then obtained as:

$$Sm = \min \{(Pm- PETm) + Sm-1, Smax \} .$$

Otherwise, if Pm < PETm, the soil moisture is given as:

$$Sm = Sm-1 * \exp (Pm - PETm / Smax)$$

ii. Actual evapotranspiration (ETm)

For the first of the cases, Pm > PETm,

$$ETm = PETm \text{ , otherwise}$$

$$ETm = Pm+ Sm-1 - Sm$$

Water surplus

It is assumed that soils will only produce water surplus whenever the soil moisture content at the end of a month will equal its maximum water storage capacity. In that case water surplus, **Tm**, will be calculated as

$$Tm = Pm - PETm + Sm-1 - Sm$$

Rainfall departures and Soil Moisture Index (SMI) values are useful for contingency crop planning based on the climatic conditions. Spatial distribution of weekly SMI (actual / available moisture) maps reveals moisture status spatially and temporally in a given area. Time to time contingencies can be suggested to the farmers, by closely monitoring the weather conditions during the season. The crop production strategies situation-wise alternate crops / cropping systems could be suggested.

2.3.3 WRSI – Indicator of drought:

The Water requirement satisfaction index (WRSI) is an operational monitoring index, which indicates the performance of a crop based on the availability of water during growing season (Allen et al., 1998). It is determined as the ratio of seasonal actual crop Evapotranspiration (AET) to the crop water requirement (WR), which is the product of reference crop evapotranspiration (ET0) and crop coefficient (Kc) value of the specific crop *(Senay et al., 2011)*. AET represents the actual amount of water withdrawn from the soil water reservoir and can be estimated by energy balance and water balance methods. WRSI acts as a tool to evaluate the crop water status in the next decade based on the availability of moisture in the soil.

Quantitatively it can be represented as percentage and it has four broad categories.

i. An index between 80-100% indicates sufficient water in the root zone to support the crop without water stress for the next decade.
ii. 70 – 79% indicates there is satisfactory water in the root zone and this shows conditions ranging from smaller degree of water stress to sufficient soil moisture.
iii. 50 – 69%, is an indication that the crop is likely to experience from severe to moderate water stress
iv. Finally is the index value of 0 – 50% and this indicates the soil is already at very low moisture level which can cause permanent wilting point and crop failure *(Senay, 2008)*.

WRSI model requires a start-of-season (SOS) and end-of-season (EOS) time. The threshold used to determine SOS is based on the amount and distribution of rainfall received in three consecutive decades. On the other hand, the end of seasons (EOS) is estimated by adding Length of Growing period (LGP) and SOS. The determined WRSI value of a given pixel represents the seasonal integrated conditions from the start of the growing season until the time of modelling *(Brown, 2008)*.

2.4 Agricultural observations

Agriculture departments of different states collects information on crop sown areas, crop development, pests and diseases, etc., to assess the drought situation. A special task force known as Crop Weather Watch Group is constituted in India by Ministry of Agriculture. This group reviews the progress of monsoons, crop situations, water levels in reservoirs/dams, availability of fertilizers etc. Though the ground observations of agricultural conditions by the State Departments of Agriculture and Revenue are exhaustive such a system involves a significant amount of subjective judgment at various stages. The periodicity and extent of ground observations also vary significantly between different states. The nature of sparse ground observations also make it difficult to assess, in near real-time, average drought conditions over the district. Thus ground monitoring of both causative factors as well as impact of drought assessment suffer from various limitations such as sparse observations, subjective data etc.

2.5 Crop Simulation for Drought prediction

Crop growth models are computer programs that mimic the growth and development of crops. Data on weather, soil, and crop management are processed to predict crop yield, maturity date, and efficiency of fertilizers and other elements of crop production. The calculations in the crop models are based on the existing knowledge of the physics, physiology and ecology of crop responses to the environment (Meza et al., 2008). There are a wide variety of models, ranging from empirical– statistical models to models based on physiological processes. (Hoogenboom, 2000) classifies the uses of crop simulation models into (i) strategic applications, where models are run to compare crop management scenarios as decision support systems; (ii) tactical applications, where the runs are made using current weather conditions to help producers make management decisions during the growing season; and (iii) forecasting applications, which provide insights about future crop yield outcomes (Meza et al., 2008). Crop simulation models that are run with realizations of growing season weather that represent a seasonal forecast allow agricultural scientists to evaluate the most suitable management alternatives based on the distribution of yield outcomes (Hansen et al., 2006). review methods for coupling crop models with seasonal climate forecasts (Meza et al., 2008).

One strength of using crop models for yield prediction is that the models allow for a sensitivity analysis (Pogson et al., 2012; Saltelli and Annoni, 2010; Wang et al., 2013) of how single input parameters affect crop growth and yield formation (Yu et al., 2014). For supporting drought management, if the weather data can be input into crop models, the drought-induced changes of soil moisture and yield losses can be estimated (Yu et al., 2014). Most of the existing methods of providing future weather data as model inputs are based on historical data. For example, (Du Toit and du Toit, 2003) compared the current weather conditions with historical data to identify the five best fitting years, and used the daily data for the rest of growing season from these five analogue years (Yu et al., 2014). (Bannayan et al., 2003) applied a weather generator based on the stochastic analysis of multiple-year historical data to create future weather data for predicting daily weather data based on k-nearest neighbor approach.

2.6 Advancement in Drought Prediction:

In recent decades, dynamical numerical weather prediction models have considerably improved with advanced model scheme and physics options. Advancement in Numerical Weather prediction and climate forecast at different lead-times ranging from few days to whole season have stimulated substantial interest in predicting the impact of drought on crop growth and its relative yield reduction as a means of improving farm management and policy-level interventions in a manner that reduces risk and enhances livelihoods and food security, particularly in the marginal and rainfed cropping regions.

3. Study area:

3.1 Haryana:

3.1.1 Location and Extent:

Haryana state extends between the latitudes 27° 39’ N to 30° 55’ N and the longitudes 74° 27’ E to 77° 36’ E. It covers a total geographical area of 4,421,000 ha forming about 1.35 percent of the total area of the country. It is bordered by the Union territory of Delhi and the states of Rajasthan, Punjab, Himachal Pradesh and Uttar Pradesh.

3.1.2 Physiography, Relief and Drainage:

The state represents a variety of landscape varying from hills in the northern region to almost level alluvial plains in the central parts and sand dunes in the southern districts. Major part of the state forms a part of Indo-Gangetic alluvial plains. The state has 4 main physiographic regions namely (i) Siwalik Hills, (ii) Alluvial Plains (iii) Aravalli Hills and (iv) Aeolian Plains which have been further subdivided into 11 units.

The general slope of the state is from north to south but the slopes become reverse further south and southwest due to presence of subdued ranges of the Aravallis.

The entire state is drained by Yamuna and Ghaggar rivers and their tributaries mainly Markanda, Saraswati, Chautang and Tangri; and other seasonal streams. Sahibi,Dohan and Krishnawati originating from Aravalli ridges are flowing from south to north.

3.1.3 Geology:

The geological formation range from Precambrian into 3 geological systems.

(i) Aravalli system: These are the oldest formation present in the southwestern parts of the state covering Bhiwani, Mahenragargh and Gurgon districts. They are composed of quartzites, quartizic sandstone, mica schists, phyllites and crystalline limestone.
(ii) Siwalik system: This is located in the northern parts of Ambala districts and is composed of sedimentary rocks. The dominant rocks are sandstones, shales, clays and boulders.
(iii) Indo-Gangetic Alluvial Plains: This is formed by deposition of alluvial sediments between Siwaliks and Aravallis as a part of great Indo-Gangetic plains. They consist of sands, silts, clays and occasional gravel beds.

Wind-blown sand deposits are found in the form of sandy plains and sand dunes over alluvial deposits in parts of Bhiwani, Hisar and Sirsa districts.

3.1.4 Climate:

The climate of the state is subtropical semi-arid to sub-humid, continental and monsoonic type. The annual average rainfall of the state is 650mm which varies from less than 300mm in the south western parts to over 1000mm in the hilly tracts of Siwalik Hills. The state has 3 main climatic regions. The average annual rainfall and air temperature are given below.

(i) Hot Arid Region – 300-500mm – 27 C
(ii) Hot Semi-Arid Region – 500-750 – 26 C
(iii) Hot Sub-humid Region – 750-1050 – 24 C

Average rainfall in the districts and mean temperature, mean relative humidity and mean wind speed for selected stations in Haryana are given in Table. Soil temperature regime is Hyperthermic and the soil moisture regimes are Ustic and Aridic. Water balance diagrams for selected stations are given in the figure.

3.1.5 Agro-Ecological Zones in Haryana:

Based on the soil, physiography, bio climate and length of growing period, the state has been divided into 4 regions, 4 sub-regions and 8 agro ecological zones (NBSS&LUP) 1989. They are briefly described as under:

E 1.2: This zone covers western part of the Aeolian plain. The climate is hot and dry with annual rainfall of 300-350 mm, and growing period of less than 60 days.

E 2.2: This zone covers maximum area of the state in aeofluvial plain. The climate is hot and dry with annual rainfall of 300-450 mm, and growing period 60-90 days.

D 3.2: This zone covers rugged hilly terrain of Aravalli ranges. The climate is hot and semi-arid with annual rainfall of 350-500 mm, and growing period 90-120 days.

D 3.3: This zone covers parts of Yamuna alluvial plain. The climate is hot and semi-arid with annual rainfall of 450-600 mm, and growing period 90 - 120 days.

D 4.3: This zone covers part of alluvial plain. The climate is hot and semi-arid with annual rainfall between 600-700 mm, and growing period 120 – 150 days.

Cd 5.4: This zone covers alluvial plain. The climate is dry sub-humid with annual rainfall between 700-1000 mm, and growing period 150 – 180 days.

Cd 6.1: This zone covers areas of alluvial plain and upper terraces/piedmont plains. The climate is dry and sub-humid with rainfall between 800 – 1000 mm, and growing period 180 – 210 days.

Cm 6.2: This zone covers areas of Siwalik Hills. The climate is dry to moist sub-humid with rainfall of about 1000-1200 mm, and growing period 180 – 210 days.

3.1.6 Natural Vegetation and Forests:

Among the flora of Haryana, the largest of the truly indigenous are “Shisham” *(Dalbergia sisoo)* and “Kikar” (*Acacia Arabica*). The shrub jungle consists of “Jal” (*Salvadora oleodes*), “Jand” (*Prosopis specigera*) and coral flowered leafless “Karir” (*Capris aphylla*), besides other common tress and grasses.

Forest area in Haryana is limited to only 166000 ha (3.7% area of the state) of which 85% is under state forest and rest under private forests. 76% of the state forest is classified as protected forest and 17% as reserved forest. Haryana forests have been divided into three types,

(a) Tropical thorn forests – located in south and southwestern parts of the state,
(b) Subtropical dry deciduous forests – found in central parts.
(c) Subtropical pine forests – covering northern parts of Ambala district in Morni hills.

3.2 Punjab:

3.2.1 Location and Extent:

Punjab state extends between the latitudes 29° 30' N to 32° 32' N and the longitudes 73° 55' E to 76° 50' E. It covers a total geographical area of 50,362 km^2 forming about 1.54 percent of the total area of the country. It is bordered by the Jammu and Kashmir in the North, Haryana in the South, Himachal in the Northeast, Rajasthan in Southwest and Pakistan in the West.

3.2.2 Physiography, Slope and Drainage:

The state of Punjab forms a part of Indo-Gangetic alluvial plain and is composed of sediments of Shiwalik hills and Himalayas brought down and laid by the rivers of Indus system. The exact depth of the alluvium has not been ascertained, though it varies from a few metres to over 2000 metres.

The state represents a variety of landscape varying from hills in the northern region to almost level alluvial plains in the central parts and sand dunes in the southern districts. Major part of the state forms a part of Indo-Gangetic alluvial plains. The state has 4 main physiographic regions namely (i) Siwalik Hills, (ii) the dissected foot-hill zone (iii) the 5 upland plains and the malwa tract and (iv) the flood plains along all the river.

The general slope of the state is from north to south but the slopes become reverse further south and southwest due to presence of subdued ranges of the Aravallis.

The entire state is drained by Yamuna and Ghaggar rivers and their tributaries mainly Markanda, Saraswati, Chautang and Tangri; and other seasonal streams. Sahibi, Dohan and Krishnawati originating from Aravalli ridges are flowing from south to north.

3.2.3 Climate:

It is bounded by western Himalaya in the North and the Thar Desert in the south and south-west which mainly determine its climatic condition. It receives south-easterly current of the summer monsoons coming over the Bay of Bengal. The mean annual rainfall varies from less than 300 mm to about 1400 mm per annum: major portion of which is received as summer monsoon (July to September). From October to the end of next June, dry condition prevail except for some few light showers received from the westerly depression (December to February)

The temperature variations, especially the mean annual temperature over the whole region, are moderate and vary from 23.2º C (Pathankot) to 25.8º C (Abohar). The summers are extremely hot and slightly cool. The mean monthly maximum temperature (June) is as high as 42º C while the mean monthly minimum temperature (January) is as low as 4.7º C. The area generally qualifies for hyperthermic temperature regime and is out of the inter-tropical and temprate zones.

According to the Thornthwaite (1948) classification system, the state of Punjab can be divided into six climate zones (*Seghal 1970*):

1. Arid and Hot Zone (E d, A'_2 a'_2)
2. Semi-arid (dry) and Hot Zone (D_1d, $A'_{2,}$ a'_2)
3. Semi-arid (dry) and Less - hot Zone (D_1d, $A'_{2,}$ a'_2)
4. Semi-arid (semi-dry) and Less - hot Zone (D_2d, $A'_{2,}$ a'_2)
5. Semi-arid (semi-Moist) and Less - hot Zone (D_3d, $A'_{2,}$ a'_2)
6. Sub-humid (semi-moist) and Less - hot Zone (D_1d, $A'_{2,}$ a'_2)

3.2.4 Natural Vegetation:

Because of the centuries of old and intensive cultivation, information about the past vegetation of the area is lacking. Since the natural vegetation depends on existing climatic conditions, therefore, the assumption that present day plants were also growing in the far past is questionable. The natural vegetation is very scanty and varies from *Acacia Arabica* (‘kikar’/’Babul’) in the arid to semi-arid and hot zones, through *Dalbergia sisoo* (“shisham”) in the central sectors representing semi-arid and less-hot zones, to shrubs and thin deciduous forest in the NE sectors representing sub-humid (dry) and less-hot zone.

3.2.5 Geology:

Except for some hills of the Siwalik system situated along its border with Himachal Pradesh in the north, the Punjab state is a vast monotonous plain having an average elevation ranging from 180 to 290m above the mean sea level. The Plain is an outcome of alluvial deposits of Indo-Gagetic systems ranging in age from Pleistocene to Recent periods. The following deposits of alluvium are recognized as: ‘Bhangar’: old alluvium that occupies the higher ground forming small plateau and containing much ‘Kankar’; and ‘Khadar’: newer alluvium that occupies lower level than ‘Bhangar’; these have clays with less ‘Kankar’. The deposition of this alluvium commenced after the final upheaval of the Himalayas (Siwaliks) and continued all through the Pleistocene up to the present. The foot-hills, belonging to the Siwalik system, are composed of weakly consolidated, medium to coarse grained sandstones, siltstones, conglomerates, shales, etc. with occasional organic remains.

3.2.6 Agro-climatic Zones:

Punjab Agricultural University has divided Punjab into 6 agro-climatic Zones, subdividing each of the first five zones into A and B sub-zones based on the soil type. A symbolizing medium to heavy textured soils and B symbolizing light to medium textured soil region are as below:

1. Sub-Mountain Undulating region
2. Undulating Plain region
    a. Undulating Plain region North
    b. Undulating Plain region South
3. Central Plain region
    a. Central Plain region North
    b. Central Plain region South
4. Western Plain region
    a. Western Plain region North
    b. Western Plain region South
5. Western region
    a. Western region North
    b. Western region South
6. Flood Plain region

3.3 The Regions for the Study

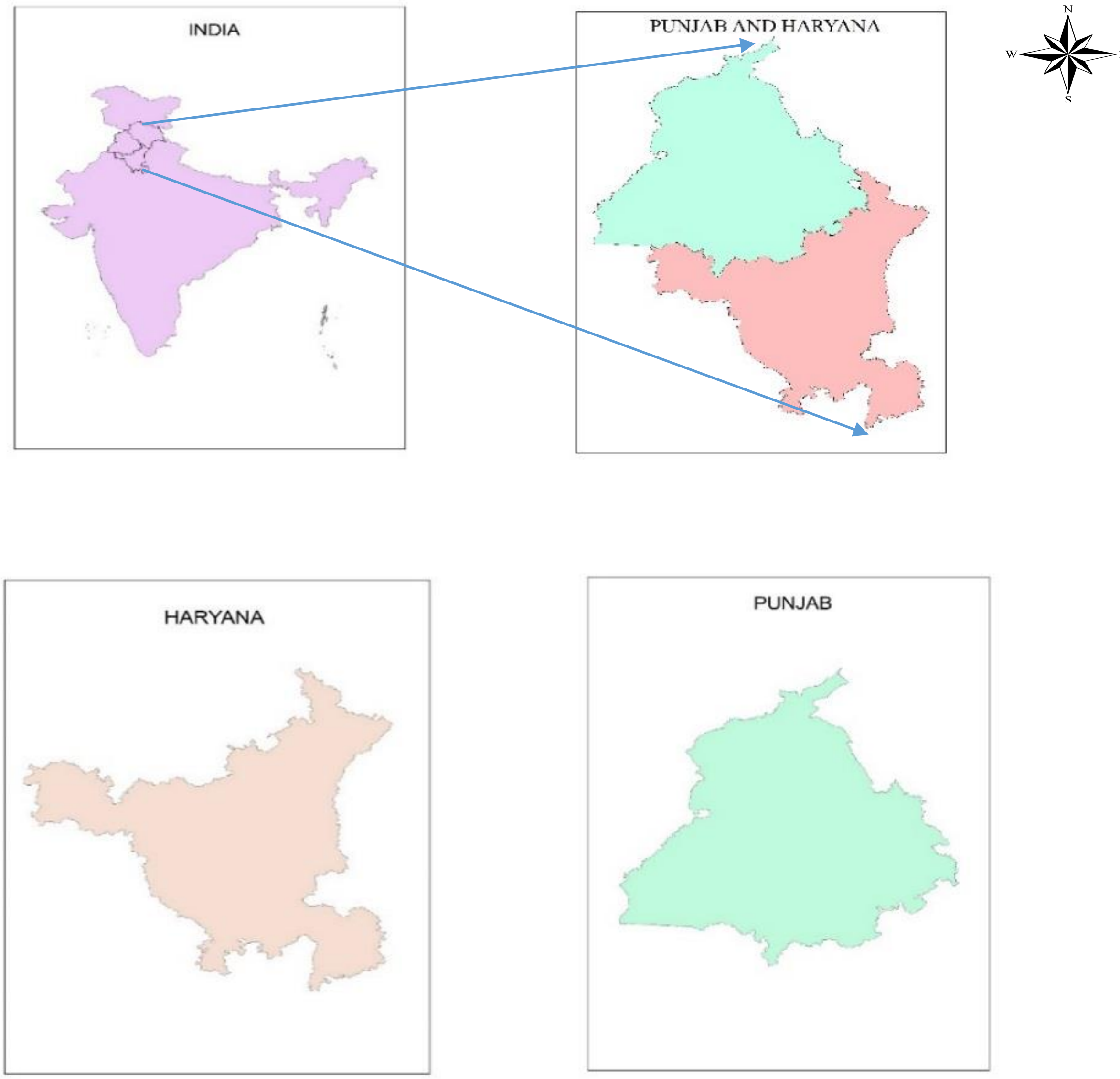


Figure 1 Study Area

4. Materials and Methodology

4.1 Regional Climate Model used:

The regional climate model used in this study is the Advanced Research WRF version 3.6 (ARW) with dynamic core. WRF is a next-generation, limited-area, non-hydrostatic, with terrain following eta-coordinate mesoscale modeling system designed to serve both operational forecasting and atmospheric research needs. Two different simulations for years 2009 and 2014 were conducted to study the impact of drought on crop yield loss. The model configurations, design of experiments and data sets used are discussed in this section

4.1.1 Design of experiment and data used:

The model is used in three nested domains with horizontal resolution of 90km, 30 and 10km for 2014. There are 27 vertical levels with the top of the atmosphere located at 10 hPa. The three nested domains used in the model simulation are shown in Fig 1

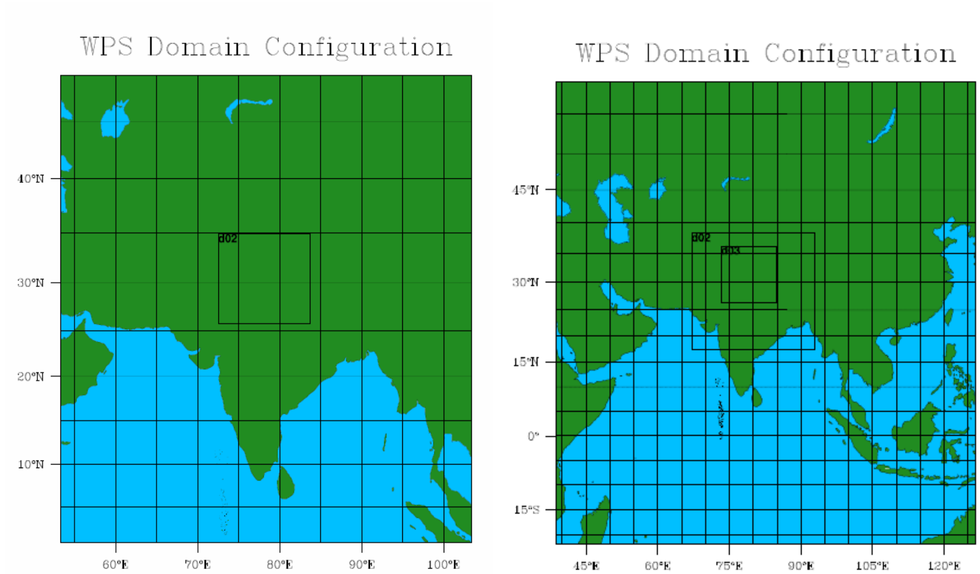


Figure 2 WRF Domain Configuaration

The initial and boundary condition for 2014 simulation are derived from final analysis (FNL) data of 1-degree by 1-degree resolution prepared at National Centre for Environmental Prediction *(NCEP, n.d.)*. The lateral boundary condition (LBC) are updated every six hours. At lower boundary condition the observed sea surface temperature data are used. For this purpose, the daily, real-time global, sea surface temperature analysis that has been developed at NCEP/Marine Modelling and Analysis Branch (MMAB) was used. The daily SST product is produced on half-degree (latitude, longitude) grid, with a 2D variation interpolation analysis of recent 24-hours buoy and ship data, NOAA-17 AVHRR - derived SST data. The model was initialized on 1st may 2014, initial condition and the model was integrated from 1st May to 30th November 2014. The first month simulation has been considered as spin up time, and therefore not used for the present analysis.

For 2009 simulation, two nested domains with horizontal resolution of 30 and 10km are used, with 37 vertical levels. The two domains used in the model simulation are shown in Fig .CFSR reanalysis data of 0.5º x 0.5º resolution prepared at NCEP (National Centre for Environmental Prediction) is used as initial and boundary condition for 2009 simulation (*Saha et al., 2010)*. The lateral boundary condition (LBC) are updated every six hours. At lower boundary condition the observed sea surface temperature data are used. For this purpose, the daily, real-time global, sea surface temperature analysis that has been developed at NCEP/Marine Modelling and Analysis Branch (MMAB) was used. The daily SST product is produced on half-degree (latitude, longitude) grid, with a 2D variation interpolation analysis of recent 24-hours buoy and ship data, NOAA-17 AVHRR - derived SST data. The model was initialized on 1st may 2009, initial condition and the model was integrated from 1st May to 30th November 2009. The first one month simulation has been considered as spin up time, hence not used for the present analysis.

4.1.2. Physical Parametrization:

The physical parameterization schemes utilized in the models are the microphysics scheme of Lin *et al*, WRF Single-Moment 5-class (WSM5) for surface layer, Yonsei university scheme for PBL, RRTM scheme for long wave radiation and Dudhia scheme for short wave radiation in this experiment. For surface physics, the unified Noah land surface model has been used, which consists of one canopy layer and four soil layers with thickness of 0, 30, 60 and 100cm from top to down and which employ Reynolds number based approach for the determination of the ratio between the roughness lengths for momentum and heat transport. Betts Miller Janjic scheme has been used for convective parameterization. The model simulation results were archived every 6 hours during the simulation time period.

4.1.4. Land use Land cover Data:

The default land use and land cover data used in the WRF model are based on 1992 – 1993 USGS data and do not exactly reflect the land surface conditions of 2009 and 2014. IRS P6 AWiFS derived LU/LC data compatible with MM5 & WRF models at 30 arc second resolutions downloaded from http://bhuvan.nrsc.gov.in site is used in this study. Indian region of USGS data is replaced with AWiFS derived LU/LC data, in order to represent the accurate land surface condition in the WRF models.

4.1.3. Vegetation parametrization:

Weather research and forecasting (WRF) model uses green vegetation fraction (fg) as a dynamic tool to represent vegetation phenology. The current fg data was derived from the AVHRR satellite data during 1986 – 1991 with spatial resolution of 0.144º degrees and monthly temporal resolution.

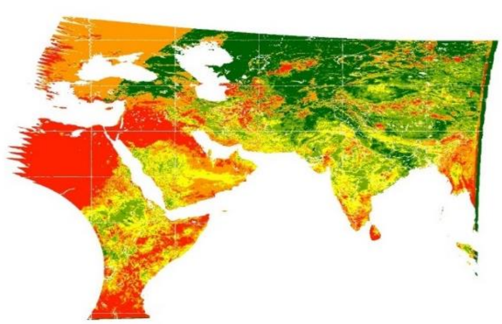


Figure 3 INSAT Vegetation Fraction

Hence, the data cannot represent recent changes in land and impacts on vegetation on weekly or bi-weekly scale from extreme events. In order to represent the inter-annual variability of vegetation, 10 days composite of vegetation fraction derived from INSAT NDVI data is used for 2009 simulation.

Indian geostationary satellite (INSAT 3A) observes the earth surface with continental (Asia) coverage at high temporal frequency (half-an-hour) with spatial resolution 1 km x 1 km. INSAT 3A is the only geostationary satellite which scans Asia with multi-spectral bands. It covers whole Asian continent in a single snapshot. The CCD payload specifically designed to monitor snow cover and vegetation conditions over Asia regularly at 1 km × 1 km spatial resolution. The three optical bands are red (0.62–0.68 m), near infrared (0.77–0.86 m), and short-wave infrared (SWIR) (1.55–1.69 m). The NDVI derived from INSAT at 10 days interval provides better green vegetation fraction than the AVHRR-based climatology data currently used in WRF. For estimation of the VF, the mosaic-pixel model proposed by (*Zu Liang et al)*. is carried out in this study.

4.1.5. Verification strategy:

The daily precipitation simulated by the model re-gridded at 25km x 25km resolution is compared with the daily gridded rainfall data of TRMM for 2014 and observed IMD gridded data for 2009 simulation. To quantify the model deficiency in the spatio-temporal distribution of rainfall the bias contributed from different rain rate categories to the total rain are also computed. The daily temperature is validated against the ISRO meteorological station data. CRU monthly gridded data obtained from CRU TS3.21 is used for monthly minimum and maximum temperature validation. Verification measures such as RMSE, MAPE, index of agreement and MAD are used to evaluate the model performance. The equations used to compute various statistics used in this study are given below.

4.2 Crop model used:

4.2.1 Decision Support System Agrotechnology Transfer (DSSAT)

The decision support system for agrotechnology transfer (DSSAT) has been in use for the last 15 years by researchers worldwide *(Jones et al., 2003)*. The DSSAT package facilitates the evaluation and application of the crop models for different purposes by incorporating models of 28 different crops. Thus, the DSSAT crop models have become very difficult to maintain due to the variation in the codes used for varying crop types and hence have been re-designed and programmed to facilitate more efficient incorporation of new scientific advances and applications. The basic premise for the new DSSAT cropping system model design is its modular structure which allow easy replacement or addition of modules*(Jones et al., 2003)*. It incorporates, weather, crop module, soil module and a module for dealing with competition for light and water among the soil, plants, and atmosphere. Crop module can help in simulating various crops by defining species input files.

4.2.2 CERES Rice Model:

The CERES v3. (Crop Estimation through Resources and Environmental Synthesis version 3) model (*Timsina and Humphreys, 2006)* for rice crop as incorporated in the DSSAT software is used in the study. The CERES-Rice *(Alocilja, 1987)*; is a process-based model of rice crop which simulates crop growth, development and yield, taking into account the effects of soil water, weather, genetics, irrigation, planting, nitrogen and carbon. The minimum inputs required for this model are daily weather, soil information, crop genetic coefficient, and management practices. The following flow chart in fig 4.2 describes the DSSAT CERES rice process.

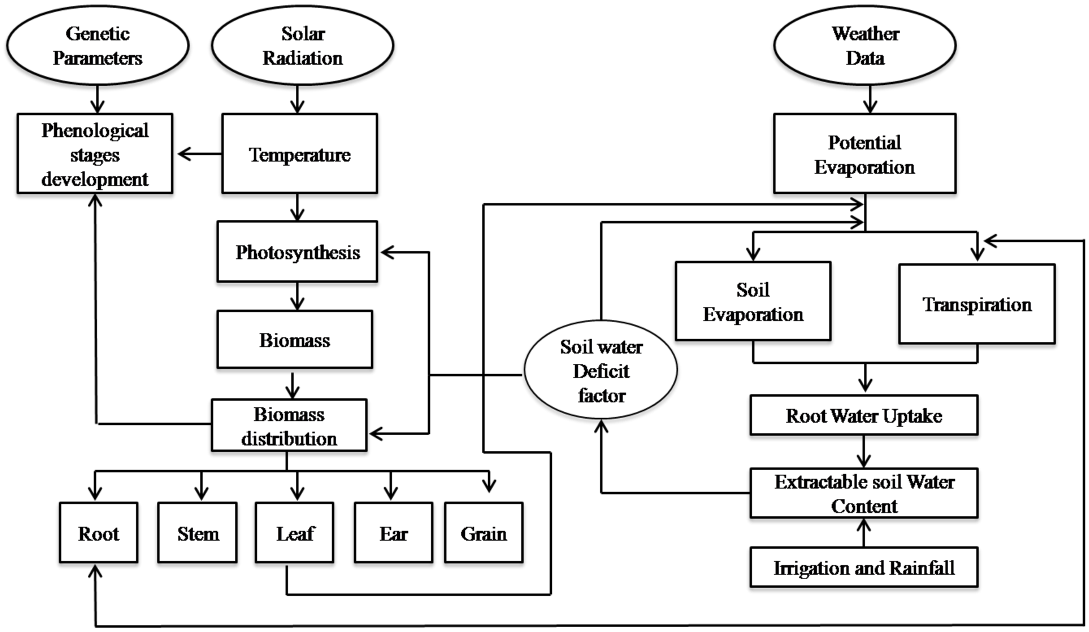


Figure 4 DSSAT model process

4.2.3 Input data preparation:

4.2.4 Weather data:

The minimum weather inputs such as rainfall, solar radiation, maximum and minimum temperature are required to run the CERES rice model. The high resolution data obtained from the WRF simulation for the year 2009 and 2014 are used as weather input for crop model. CDO, NCO and NCL tools are used to extract the daily weather variables from the WRF outputs. The extracted weather variables from WRF outputs are converted into DSSAT weather file format (.WTH) using python programming.

4.2.5 Soil data:

Soil map prepared by the NBSS & LUP at 1: 250000 scale is used to identify the particular taxonomical unit for Punjab and Haryana. The detailed profile information for the taxonomical unit are collected from NBSS & LUP publications on soil series of Punjab and Haryana book and field survey. Fig depict the soil map of Punjab, Haryana and Himachal Pradesh.

The gathered profile data is loaded into the DSSAT soil module which integrates information from four sub modules: soil water, soil temperature, soil dynamics, soil carbon and nitrogen. The missing values in the soil profile are calculated by DSSAT soil module based on the given information. The output of soil module is stored in DSSAT soil file format (.SOL). A program written in python is used to assign soil file spatially for study area.

The management data are collected from farmers and research associates from agriculture research stations of various districts during the field visit. The parameters derived are irrigation times and dates, depth of irrigation, type of irrigation, type, amount and date of fertilizer application, sowing depth, row spacing of plants, plant population, etc.

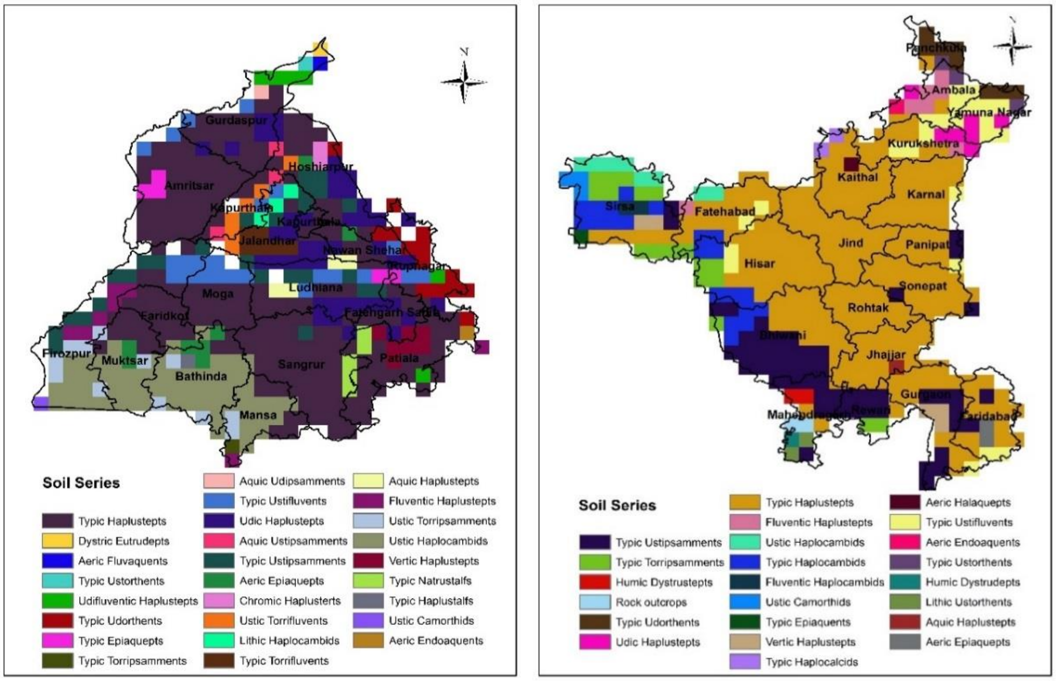


Figure 5 Soil Map

4.2.6 Management file for Rice:

Planting time	First fortnight of June
Population	33plants /hill
Seeding depth	5cm
Row spacing	15-20cm
Irrigation dates	Day 1(day of Transplantation) - 50 mm 20th & 35th day - 50mm 50th & 60th day - 80mm 85th day - 60mm 100th & 120th day - 80mm
Irrigation Type	Flood Depth
Fertilizer	Urea 120 kg /3 splits
Time	June 6th – Sowing June 26th – Transplantation November 1st week - Harvest

Table 3 Rice Management Practice

4.2.7 Cultivar file (PR114):

Variable	Description	Value
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.	650
P2O	Critical photoperiod or the longest day length (in hours) at which the development occurs at a maximum rate. At values higher than P2O developmental rate is slowed, hence there is delay due to longer day lengths.	200
P2R	P2R Extent to which phasic development leading to panicle initiation is delayed (expressed as GDD in℃) for each hour increase in photoperiod above P2O.	520
P5	Time period in GDD℃) from beginning of grain filling (3 to 4 days after flowering) to physiological maturity with a base temperature of 9℃.	12
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.	59
G2	Single grain weight (g) under ideal growing conditions, i.e. nonlimiting light, water, nutrients, and absence of pests and diseases.	0.025
G3	Tillering coefficient (scaler value) relative to IR64 cultivar under ideal conditions. A higher tillering cultivar would have coefficient greater than 1.0.	1
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.	1

Table 4 Cultivar

4.3 Methodology for Time series analysis of yield departure due to drought:

In general, an increment in harvest yield from year to year may be explained by progressive enhancements in technological innovation while other variable, for example, weather condition, pests and diseases, are all kept constant or under control.

In order to understand the weather variability in the historical yield data, the effect of non-climatic components such as technological improvement, policy intervention and innovation in management should be removed from the time series. Setting up a decent arrangement of yield information requires the utilization of some detrending insights to get the detrended yield.

The goal of detrending is to get a good long-year record of yields that can be used to compare against water balance results from DSSAT CERES model. The hypothesis is that an upward (downward is not very likely) trend in yields shown in Fig caused by the technological factor is eliminated from the statistics. Once the detrending process done, yield recorded 15 years ago will still have predictive value for the current season.

Detrending yield requires two steps. The first step involves the fitting of a smooth curve through the yield statistics. In a second step the actual detrended yield is calculated. The linear detrending method is employed in this study to remove the trend component. Linear detrending is the most common trend identification approach consists in fitting a straight line to the time series. The corresponding detrending process by which the straight line trend, $T(t) = a0 + b0t$, subtracted from the time series, gives a zero mean residue. Finally, the detrended yield departure and yield anomaly based on detrended yield and average yield are used to study the yield reduction due to water stress condition

4.4 Overall Methodology:

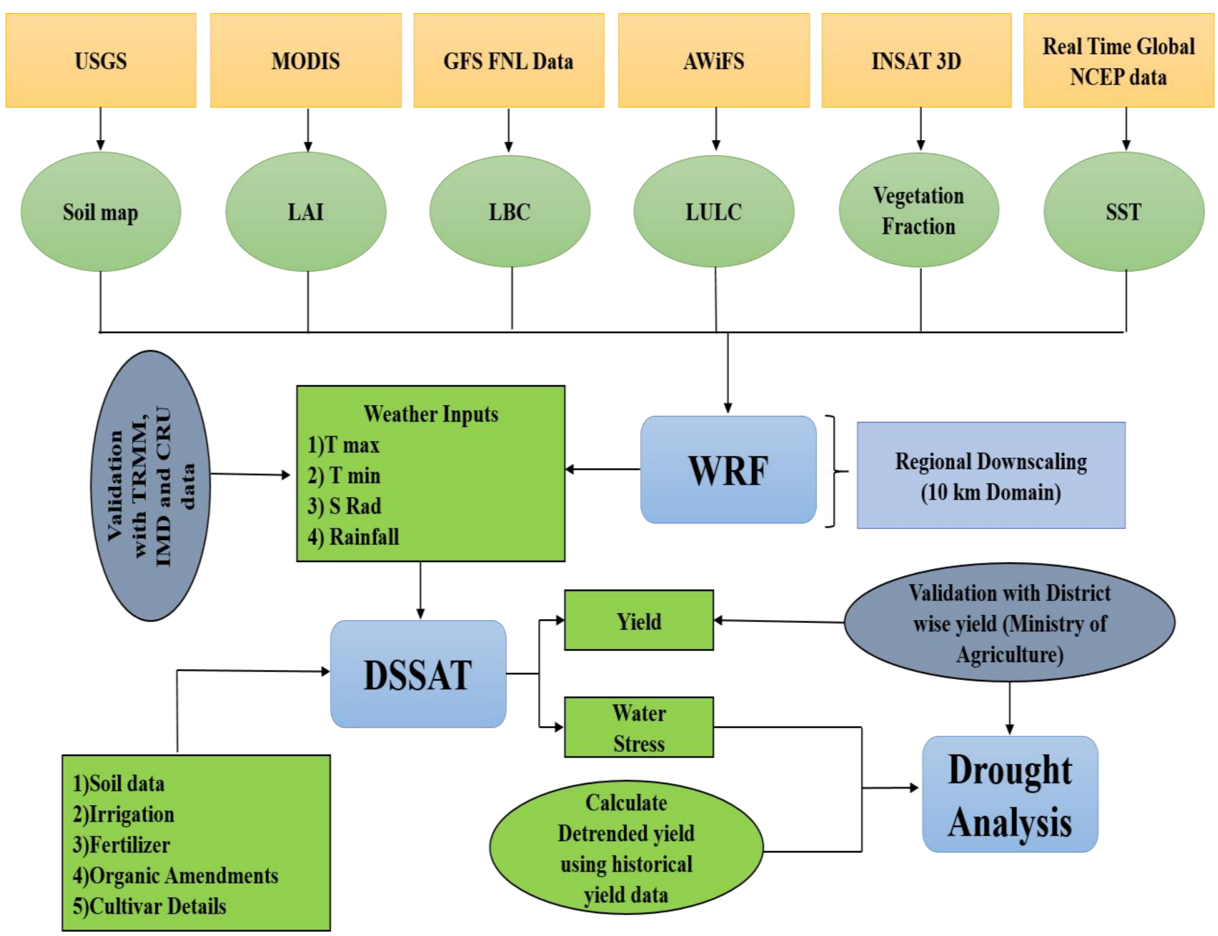


Figure 6 Flow Chart

5. Results and Discussion

5.1 WRF model simulations:

The results of regional climate simulation of summer monsoon over Punjab and Haryana for predicting rice yield losses due to drought in 2009 and 2014 was conducted in this study, are presented in this chapter. The regional climate simulation of India summer monsoon over North India for 2009 and 2014 was conducted using WRF regional climate model at 1:3:3 nested domain with horizontal resolution of 90 km, 30km and 10 km. The results such as rainfall, minimum and maximum temperature are validated with the observed data. To have a better monsoon simulation in the model, the model must have a better representation of land surface condition. The land surface condition obtained from the satellite data were used to study the summer monsoon in high resolution.

5.1.1 Rainfall simulations by WRF during 2014:

The observed IMD daily gridded (0.25º x 0.25º) data and TRMM daily gridded (0.25º x 0.25º) data were used for precipitation validation for 2009 and 2014 respectively. The model precipitation is brought to the same grid (0.25º x 0.25º) as that of the observations for validation. The spatial pattern of observed monthly precipitation (June to November for 2014) from TRMM gridded (0.25º x 0.25º) data over the WRF nested domain are shown respectively in Fig.

The observed TRMM rainfall shows a rainfall maxima over eastern region during the month of July and August, while in the North West India it shows a deficit in rainfall during June, July, and August. During September, there is an increase in rainfall amount in the northern parts of Himalayas due to the torrential rain in Kashmir valley.

Although the model capture spatial structure, the amplitude of variability in rainfall is slightly underestimated, when compared to TRMM observation. Individual months rainfall simulated by the model are compared with TRMM observation. However, an overestimation of rainfall over Eastern Himalayas region is seen in almost all months in the WRF simulated rainfall. Overall, rainfall maxima and minima over the Eastern region of India and North western arid and semiarid region are realistically simulated in WRF model, indicates that the northward propagation of the monsoon convection has a good representation in the model.

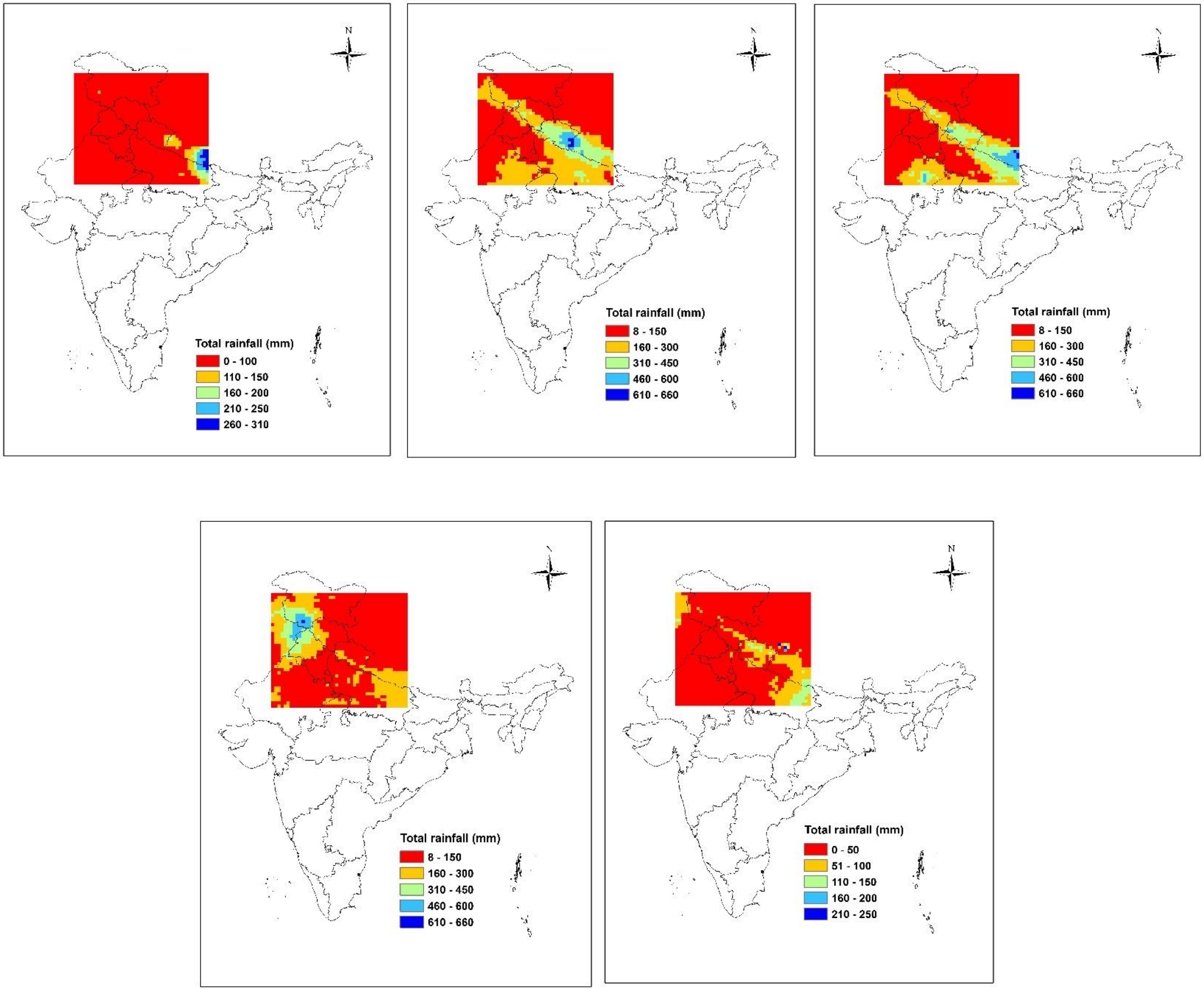


Figure 7TRMM total monthly rainfall from June to September

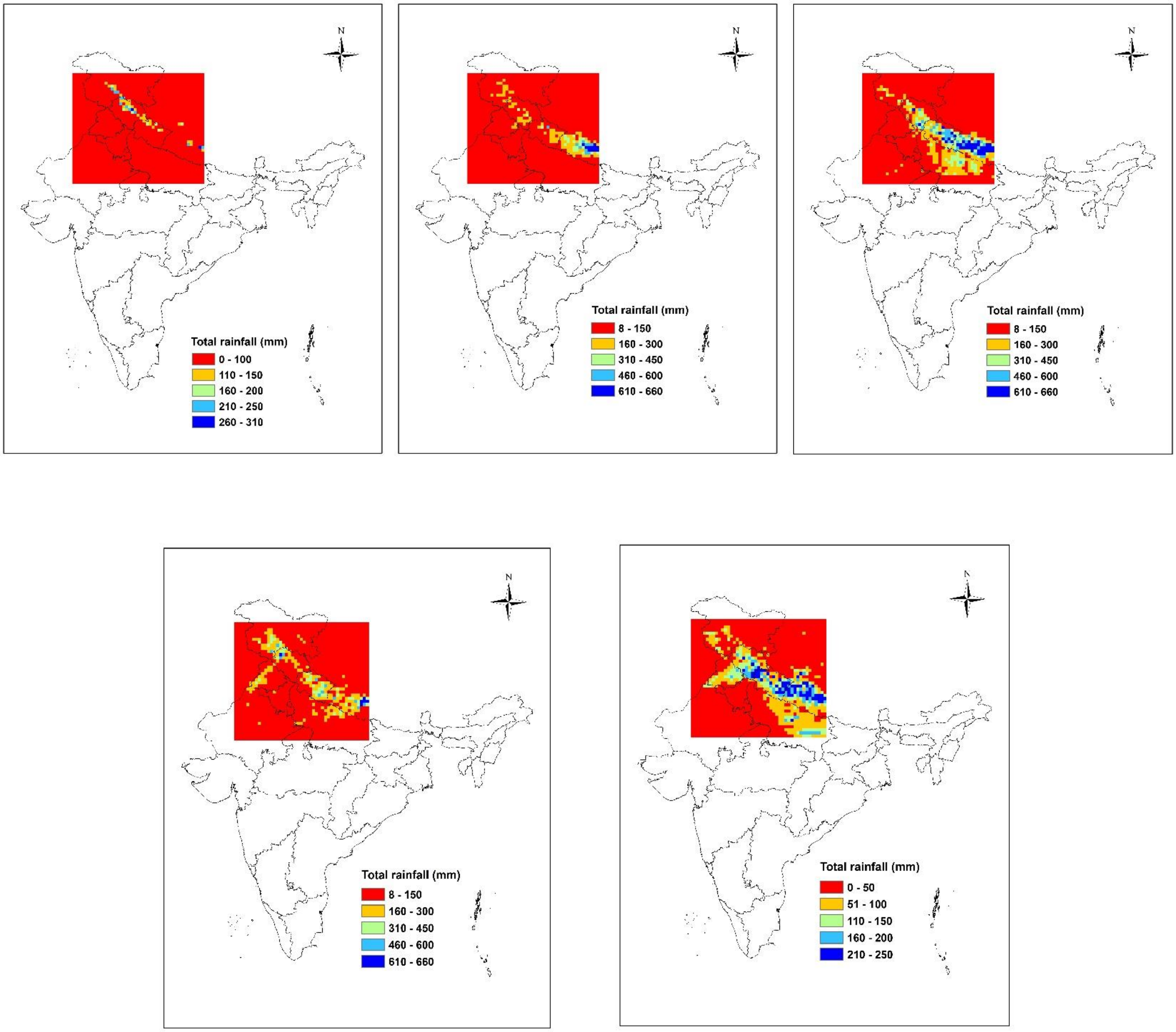
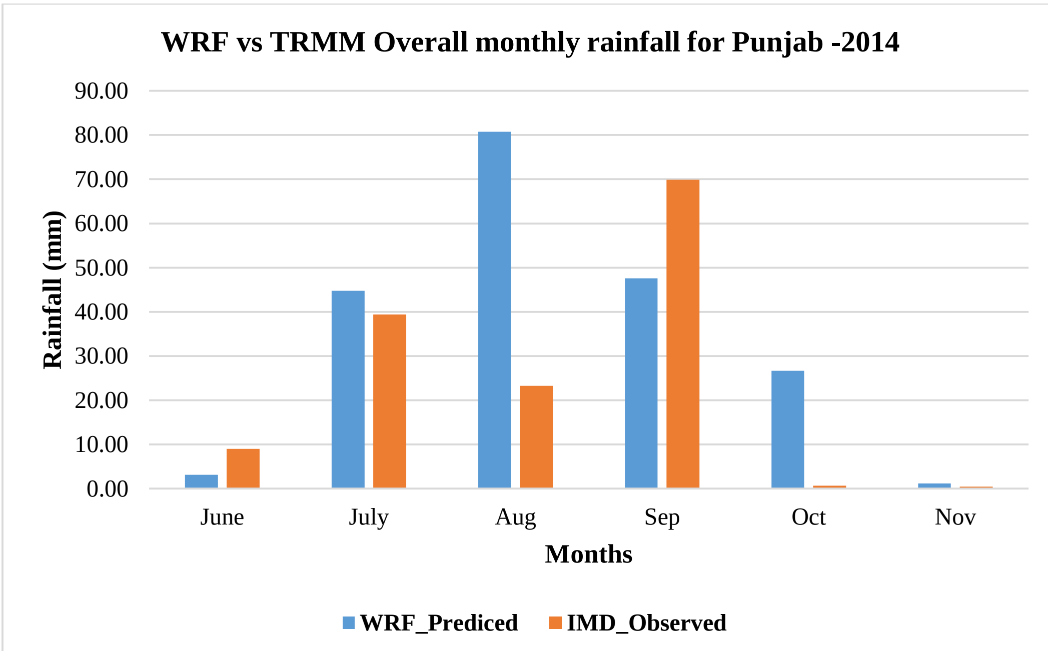


Figure 8 WRF total monthly Rainfall from June to September

5.1.2 Regional validation of WRF monthly rainfall with TRMM during 2014:

The overall simulated monthly rainfall during 2014 for Punjab and Haryana region were compared with TRMM total monthly rainfall to explain the variability in simulated total monthly rainfall. Fig shows the comparison of WRF vs TRMM monthly rainfall for Punjab and Haryana respectively. The total monthly rainfall simulated by the model were fairly consistent with observed rainfall over Punjab and Haryana in most of the months. The graphs clearly shows the model overestimated the August rainfall in both the region.



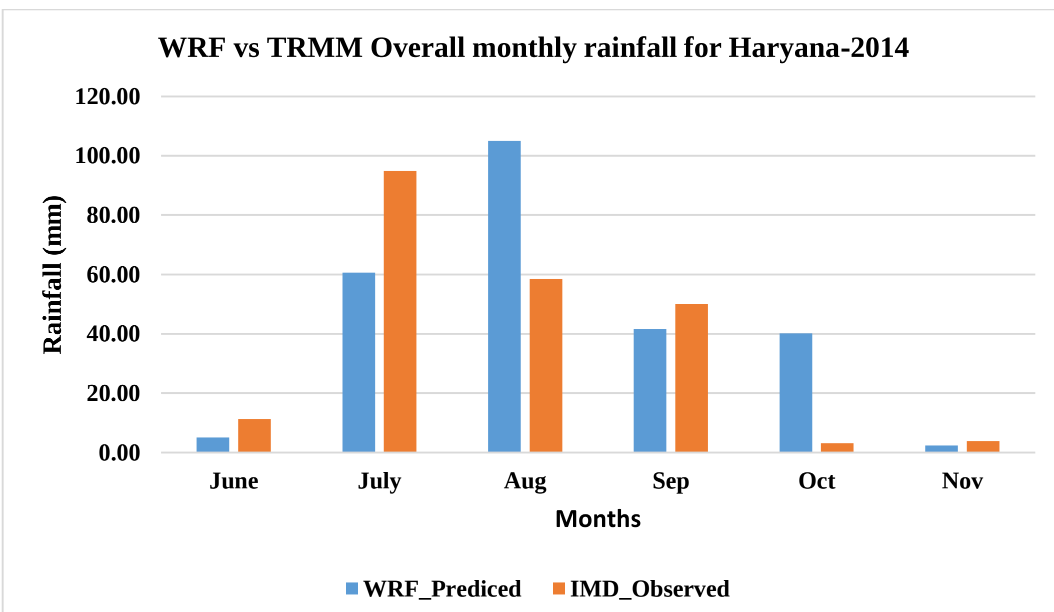


Figure 9 WRF monthly validation with TRMM - 2014

5.1.3 Regional validation of WRF daily rainfall with TRMM during 2014:

The spatially averaged daily rainfall over Punjab and Haryana region of TRMM and WRF simulation were compared to study the daily rainfall variability over the Punjab and Haryana region. The Table shows error statistics and verification measures of WRF simulation regional daily rainfall against TRMM over Punjab and Haryana. The results shows 16.32mm variation in daily rainfall over Haryana and 20.14 mm variation over Punjab with an agreement index of 64 and 61 percentage respectively.

Statistics	Haryana	Punjab
RMSE	16.32	20.14
Agreement Index	64.21	61.93
Bias	-13.51	-20.65

Table 5 Model performance Statistics for Rainfall

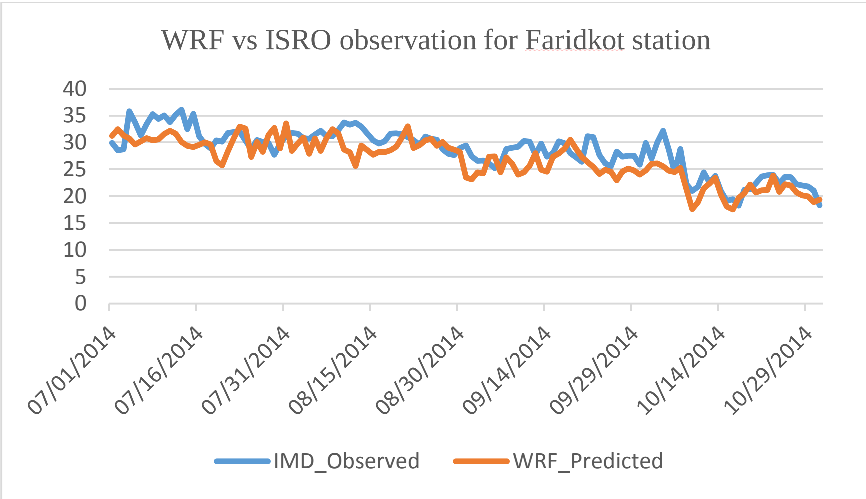
5.1.4 Temperature Simulation by WRF during 2014:

The daily average, minimum, maximum temperature observed from 9 ISRO meteorological stations were used to validate the model output. The Table show the error statistics and verification measures for minimum, maximum and average temperature. RMSE error was found in the order of 2.3 to 3.1 degree Celsius for average temperature for the moist of stations. However across all stations, RMSE was in higher order for maximum temperature. Agreement index was found to be higher for average temperature followed by minimum and maximum temperature.

Station Name	RMSE			Agreement Index		
	T_{avg}	T_{min}	T_{max}	T_{avg}	T_{min}	T_{max}
RS.SF.PAU.Kapurthala	2.54	3.33	6.75	85.58	80.47	52.12
KVK.Bahowal.Hoshiarpur	2.96	3.97	6.93	37.25	41.23	14.41
RRS.Kandi Area.Balachaur.Nawan	2.34	3.53	6.92	85.58	77.44	50.46
KVK.Langroya.Nawan Shahar	2.27	3.47	6.80	87.67	77.45	55.21
Agromet dept.PAU campus.Ludhiana	4.44	4.67	8.37	64.81	67.56	39.32
KVK.PAU farm. Samrala.Ludhiana	3.08	2.81	6.62	43.27	52.12	32.13
KVK.Mallewal Farm. Ferozepur	3.05	3.38	6.10	81.69	81.30	59.20
RRS.PAU farm.Abohar.Ferozpur	2.86	3.80	5.74	83.94	76.88	65.95
KVK.VPO.Goniana. Muktsar	2.94	2.42	7.39	86.58	91.54	54.20
Overall Average	**2.94**	**3.49**	**6.85**	**72.93**	**71.78**	**47.00**

Table 6 Temperature Validation 2014

The simulated results shows 2 to 5 degree Celsius variability in temperature. However, the occurrence of high mean temperature value during October month is under predicted by model. This shows that there is a cold bias in the warmest temperature. The Fig represents the cold bias in the model. This phenomenon of cold bias of warmest temperature and warm bias of the coldest temperature (as observed in Fig) is not a new one. It is one of the common model errors that had been shown by earlier studies. The cold bias is a phenomenon that might be occurring due to problems in Planetary Boundary Layer (PBL) parameterization schemes just because it allows full PBL mixing, thus causing an under estimation of turbulent mixing. (Welsh et al., 2003; Das et al., 2008; Hanna et al., 2010; Flaounas et al., 2010; Manju Mohan and Shweta Bhati, 2011).



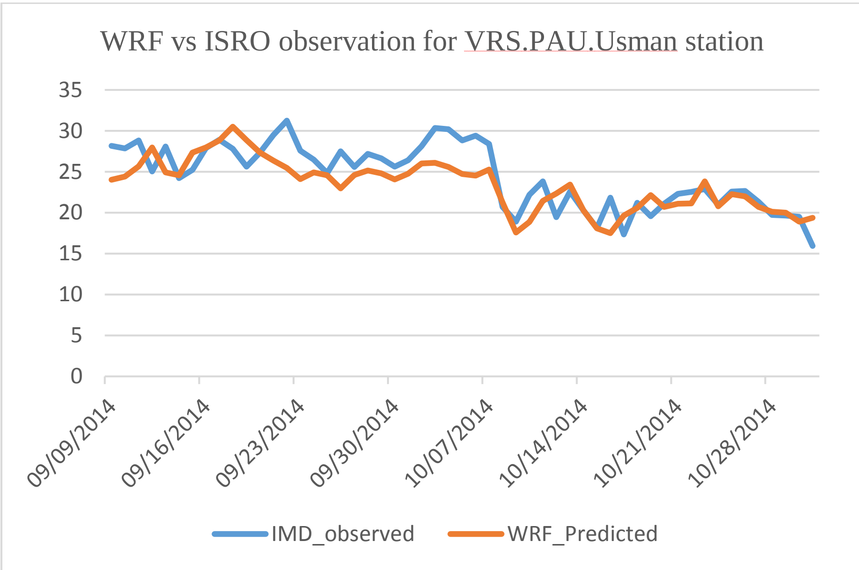


Table 7 Cold Bias in the Model - 2014

5.1.4 Temperature simulation by WRF - 2009:

The maximum and minimum temperature obtained from the WRF simulation for the 2009 were compared against the CRU monthly maximum and minimum temperature gridded (0.5º x 0.5º) data. The model results were resampled to same resolution as that of observed data (0.5º x 0.5º) using bilinear interpolation technique for validation. The observed and simulated maximum and minimum temperature are shown in the figures for the months June, July, August, September and October during 2009.

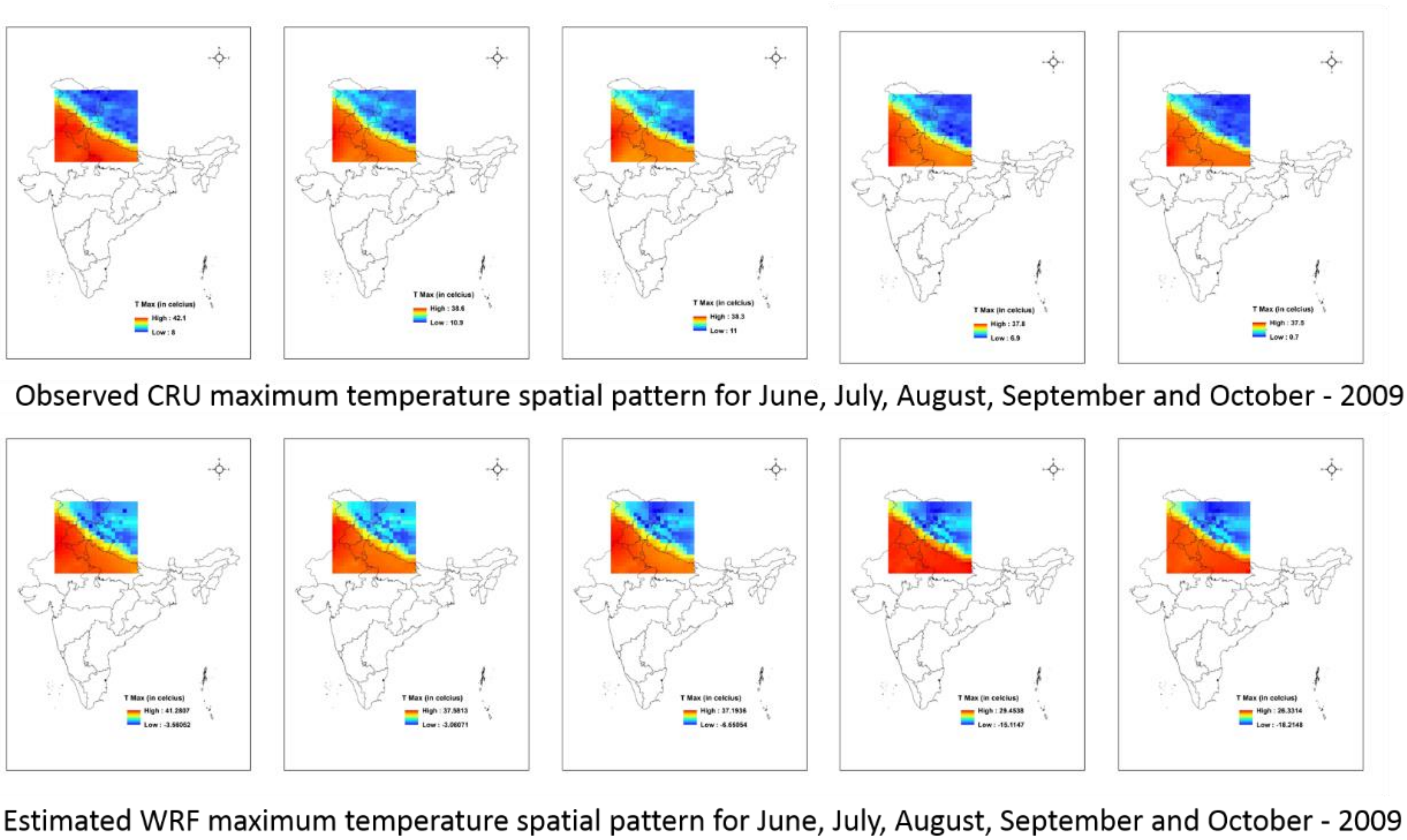
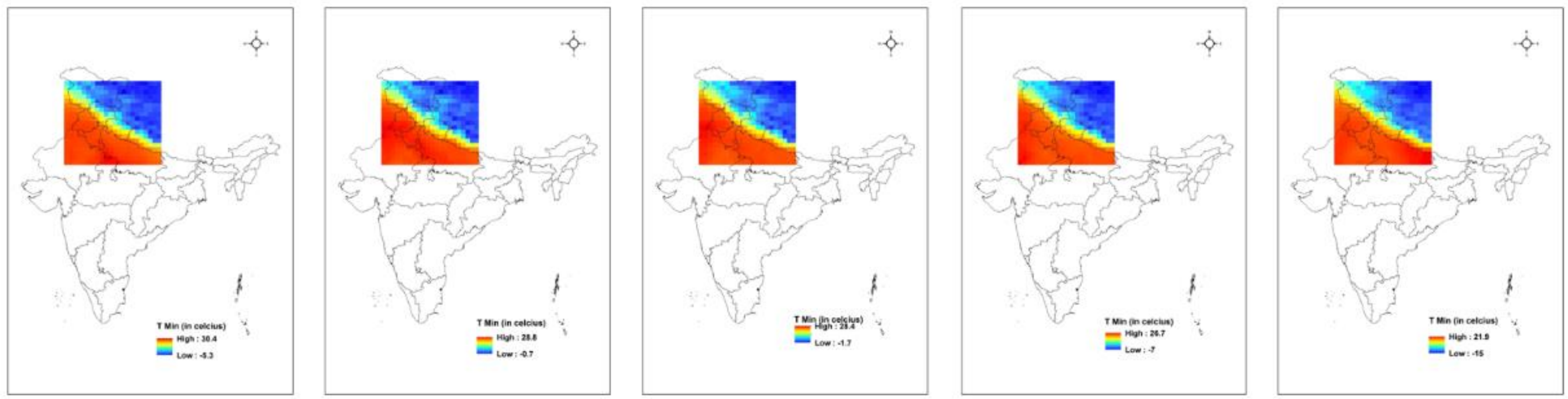
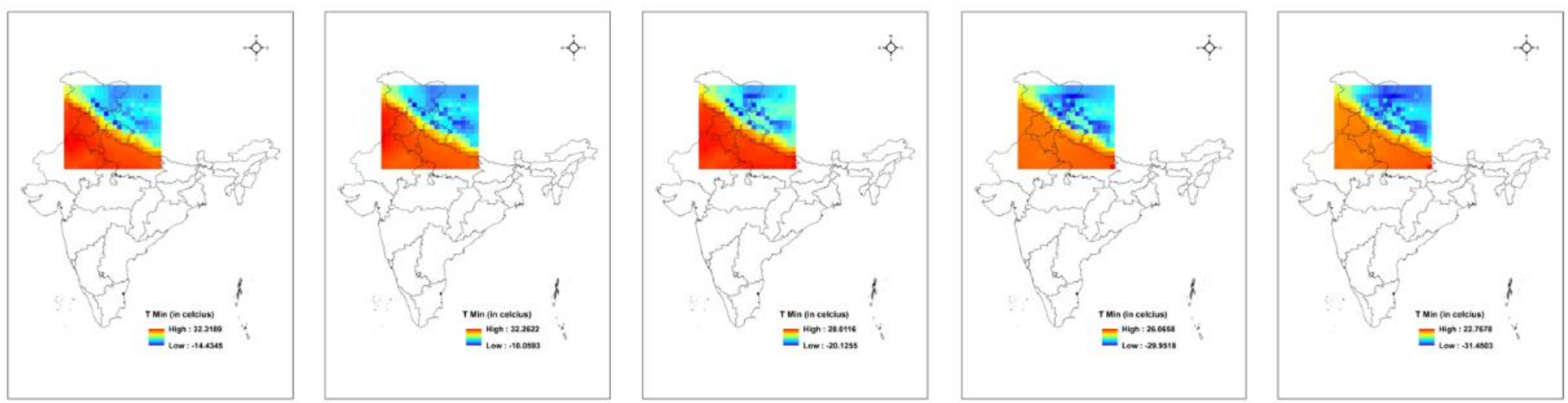


Figure 10 Maximum Temperature comparison with TRMM 2009



Observed CRU minimum temperature spatial pattern for June, July, August, September and October - 2009



Estimated WRF minimum temperature spatial pattern for June, July, August, September and October - 2009

Figure 11WRF Minimum Temeprature Comparison with TRMM -2009

The comparison with monthly CRU data shows a slight overestimation for minimum temperature and underestimation for maximum temperature. Although the result shows variation in maximum and minimum temperature, the model prediction was fairly consistent over Punjab and Haryan

5.2 Crop model simulations:

The DSSAT CERES rice model was used to estimate the harvested yield, components of the water balance, and water productivity for whole Punjab and Haryana region. The high resolution weather data obtained from WRF is served as the weather input for crop model. The soil files generated from NBSS & LUP were assigned to each grid. The coefficient for major rice cultivar (PR-114) obtained from PAU agricultural research center for Punjab and Haryana were used in model. The irrigation and fertilizer management mentioned in Packages of practices for the crops of Punjab and Haryana published by PAU (Punjab Agricultural University) along with field observations were used in this study. The harvested yield, PET (Potential Evapotranspiration) and AET (Actual Evapotranspiration) from CERES Rice model are used for the further analysis

5.2.1 Yield simulation of Rice:

The simulated rice yield obtained from the DSSAT model are shown in Fig over Haryana and Punjab for the years 2009 and 2014.The rice yields simulated by the model were fairly consistent with the typical range of yields reported for the area. Simulated rice yields varied with soil type and were higher in sandy clay loam soil than in the sandy loam soil. The simulated yield is validated against observed district wise yield obtained from Ministry of Agriculture. The table below shows the DSSAT estimated district wise rice yield for the years 2009 and 2014.

Overall the rice yield estimated for the year 2014 is higher than 2009 in Haryana and the district such as Hisar and Fatehabad showed less yield compared to 2009. In Punjab, Amritsar, Kapurthala, Gurdaspur, Hoshiarpur, Jalandhar showed a high yield compared to 2009 and the other districts shows less yield. The information on simulated yield particularly in Haryana reveals that those districts having lesser yields of rice in 2009 than 2014 had experienced severe drought due to delayed monsoon causing mortality of seedlings. The Fig shows the yield map of Haryana and Punjab during the year 2009.

Haryana

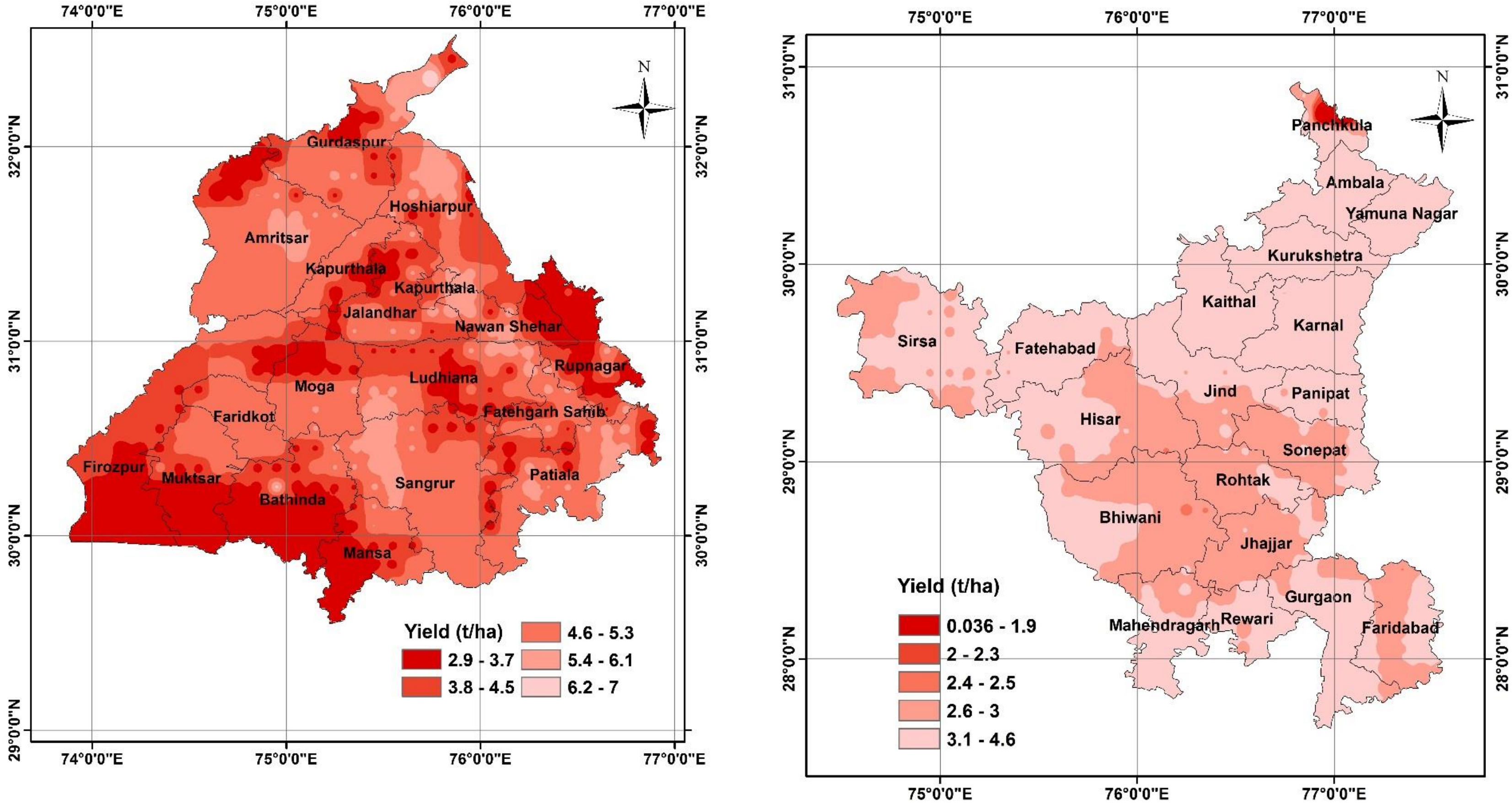
Districts	2014	2009
Ambala	3.41	3.36
Bhiwani	3.11	2.31
Faridabad	3.33	2.71
Fatehabad	3.28	3.98
Gurgaon	3.13	2.70
Hisar	2.94	2.97
Jhajjar	3.26	2.88
Jind	3.49	2.21
Kaithal	3.86	2.68
Karnal	3.83	2.90
Kurukshetra	3.72	3.64
Mahendragarh	2.99	2.75
Panchkula	3.37	2.04
Panipat	3.70	2.87
Rewari	3.36	1.74
Rohtak	3.27	3.08
Sirsa	2.84	2.15
Sonepat	3.39	3.12
Yamuna Nagar	3.78	3.36

Punjab

District	2014	2009
Amritsar	4.46	3.04
Bathinda	3.59	3.85
Faridkot	4.39	4.89
Fatehgarh Sahib	3.89	4.62
Firozpur	3.52	3.93
Gurdaspur	4.30	3.24
Hoshiarpur	3.95	3.57
Jalandhar	3.91	3.87
Kapurthala	4.19	3.47
Ludhiana	3.90	4.41
Mansa	3.84	4.05
Moga	4.11	4.54
Muktsar	3.83	4.04
Nawan Shehar	3.67	4.42
Patiala	4.15	4.78
Rupnagar	3.37	3.75
Sangrur	4.41	4.94

Table 8 District level simulated Rice productivity during 2009 and 2014

Figure 12 Rice yield productivity over Punjab and Haryana - 2009



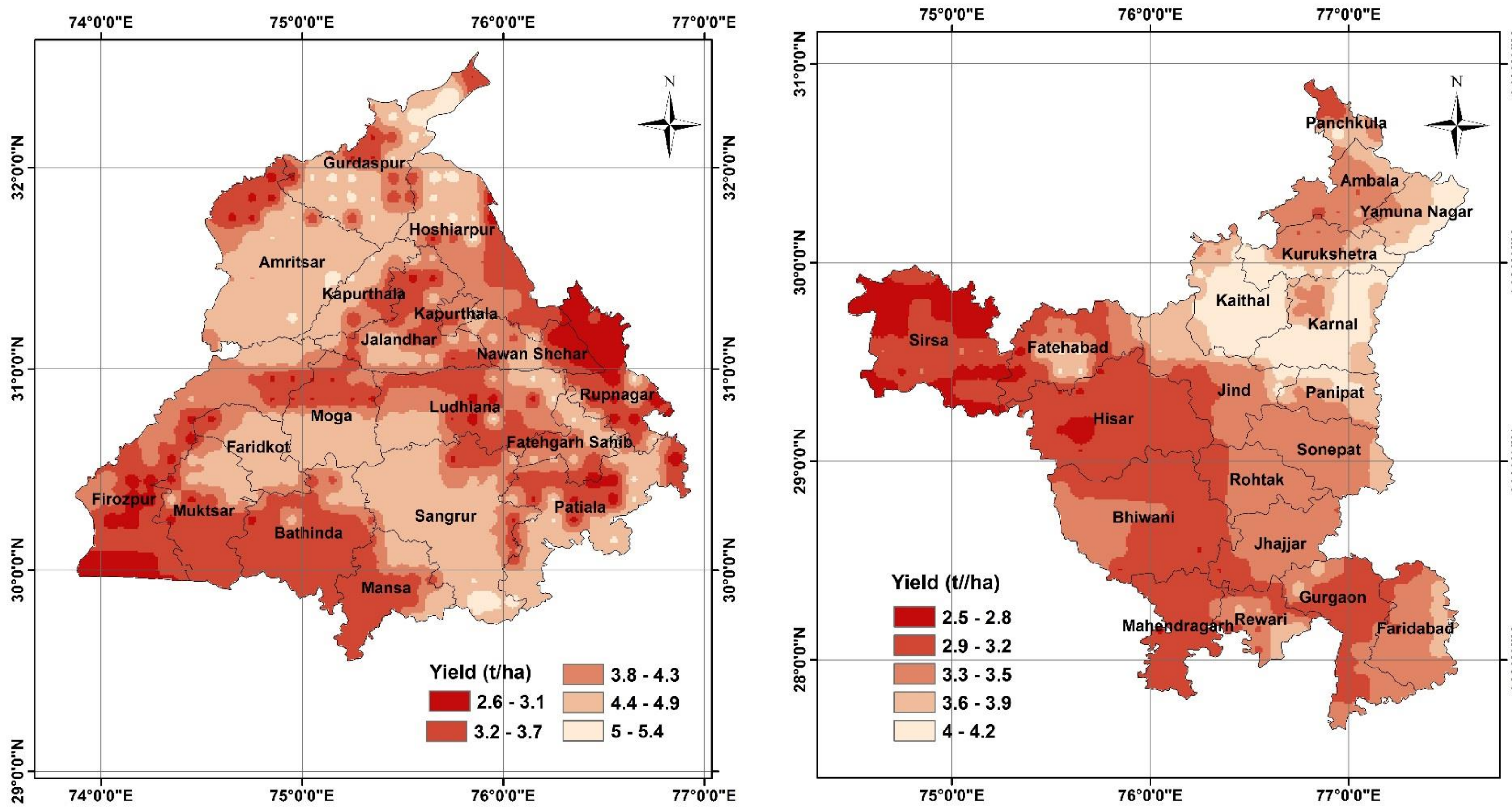


Figure 13 Rice yield productivity over Punjab and Haryana - 2014

5.2.2 Crop yield validation for 2009:

The simulated crop yield is validated against observed district wise yield data obtained from Ministry of Agriculture. The data pertaining to observed and simulate rice productivity are given in Table. Crop yields were satisfactorily simulated for both Punjab and Haryana with a reasonable R^2 value of 0.74 and 0.62 respectively. The plot shows the validation of predicted yield against observed yield for the year 2009 in Punjab and Haryana.

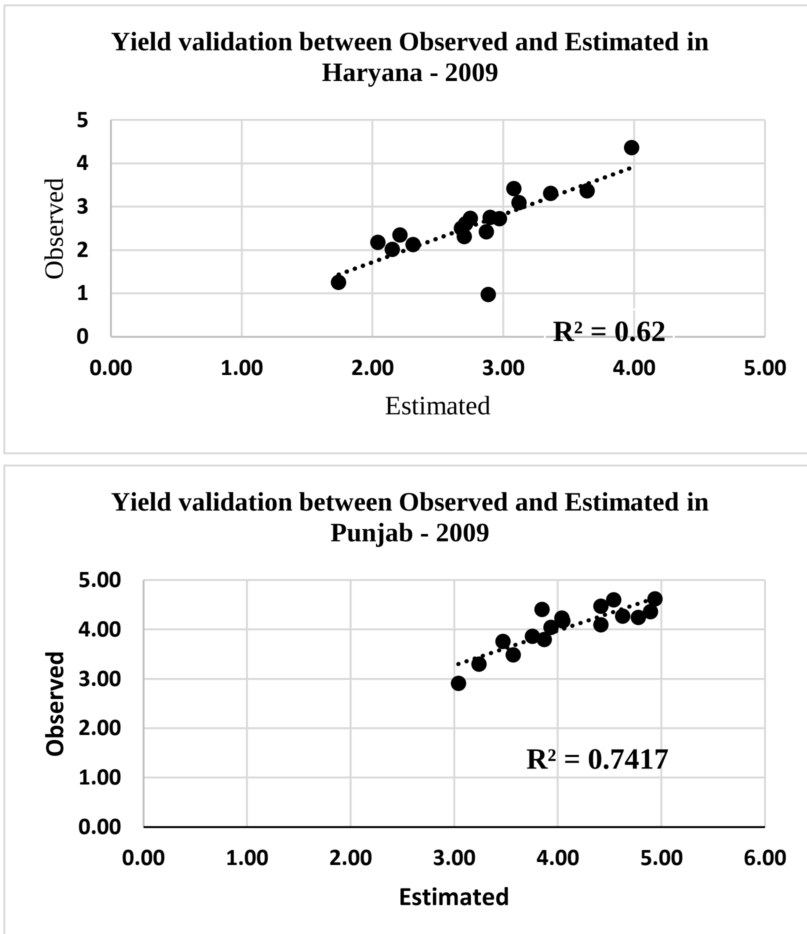


Figure 14 Rice yield Yield Validation 2009

5.2.3 Spatial pattern of PET and ET at three different stages of Rice crop during 2009:

Information on water balance components is crucial to understand the contribution of yield reduction due to weather variability. DSSAT gives various water balance components such as Evapotranspiration, Potential Evapotranspiration, and soil water availability at daily interval. To study the impact of drought at different stages, Evapotranspiration and Potential evapotranspiration were calculated at three different stages (1-60, 60-120,120-146 days). The Figures show the total Evapotranspiration and Potential evapotranspiration at three different stages (1-60, 60-120,120-146 days) for Punjab and Haryana during 2009.

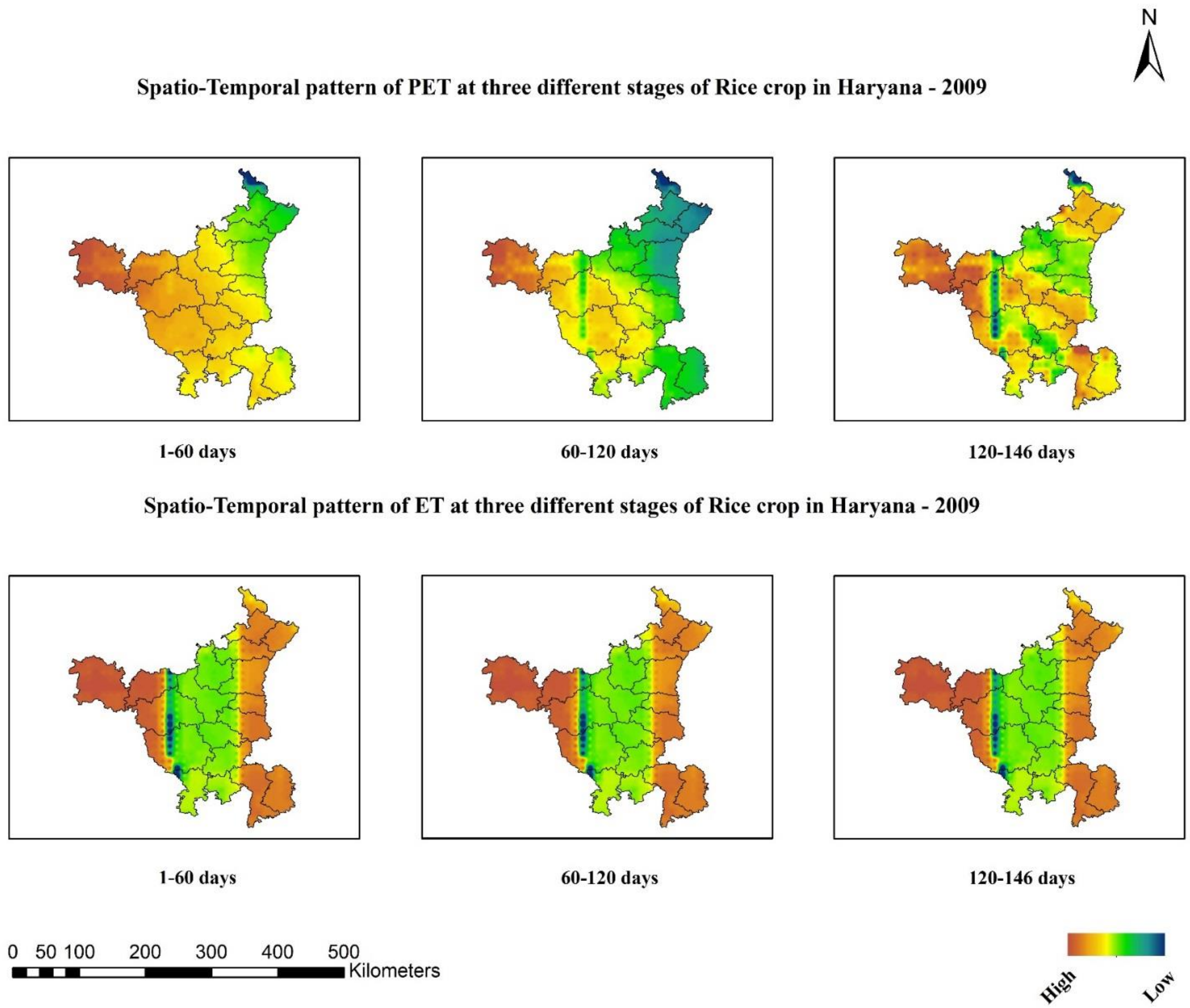


Figure 15 PET at three different stages over Haryana - 2009

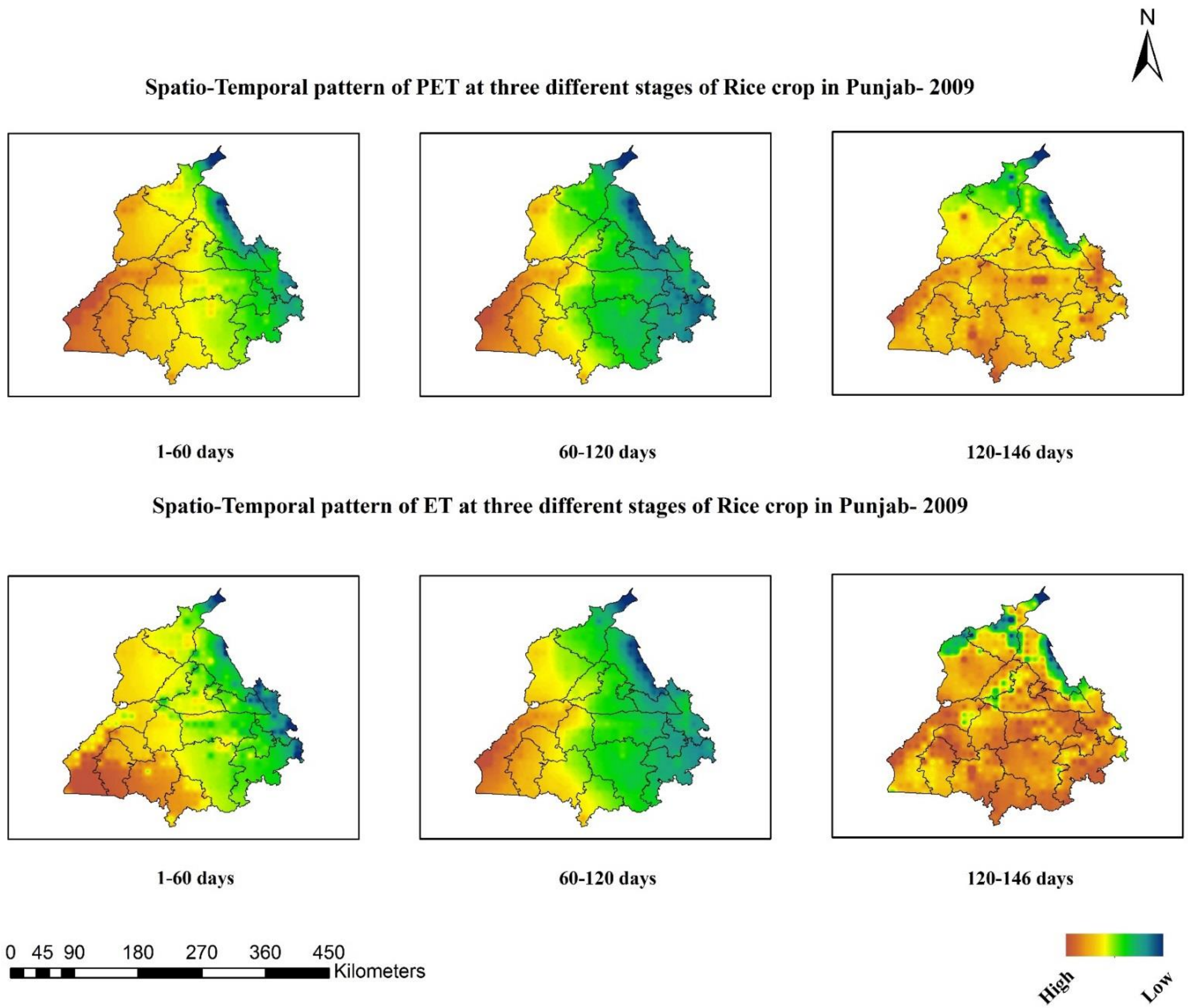


Figure 16 ET at three different stages over Punjab - 2009

5.2.4 Estimation of drought induced yield loss during 2009:

The yield anomaly based on the detrended yield and average yield for rice productivity were calculated to estimate the yield departure due to climatic variability. The Fig and Fig shows the district wise rice yield anomaly based on average yield and detrended yield over Haryana and Punjab respectively during 2009. From the figures it is clear that the severity of drought was comparatively high in Haryana than Punjab during 2009. Almost all districts in Haryana were affected by drought, particularly districts such as Jhajjar, Rewari, Rohtak, and Gurgaon have the deleterious effects of drought condition which reduced the rice productivity around 51, 27, 26 and 22 percent respectively. Although the drought impact was severe, the district such as Fatehabad, Faridabad, Hisar and Sirsa shows positive yield anomaly which reflects an increase in rice productivity. The graph shows the percentage of yield loss due drought for Haryana during 2009

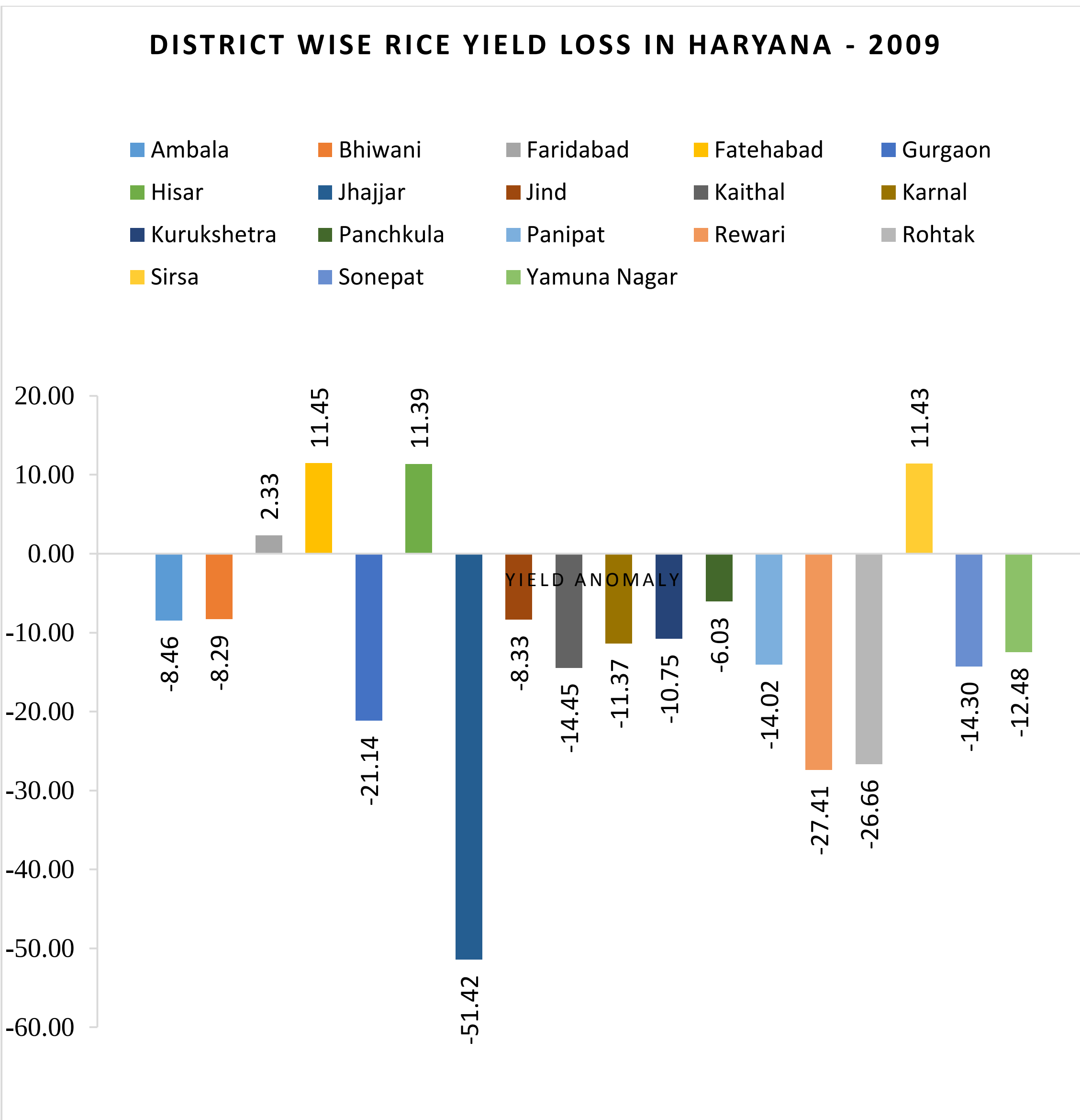


Figure 17District level Yield anomaly based on average yield in Haryana -2009

In Punjab, the scenario was totally different, where the crop productivity was surprisingly high during drought years. The Fig reveals the increases in the rice productivity for most of the districts in Punjab for during 2009. The productivity of rice is least affected because of large scale practice of growing drought tolerant varieties and assured irrigation through pumping of ground water to save paddy crops. In addition to that, the increase in number of sunny days with adequate water during drought years creates a favorable condition for rice production. Although, the drought during 2009 do not have any direct impact on crop production, it affects overall economy of state due to increased cost of diesel and decline ground water table for succeeding crop.

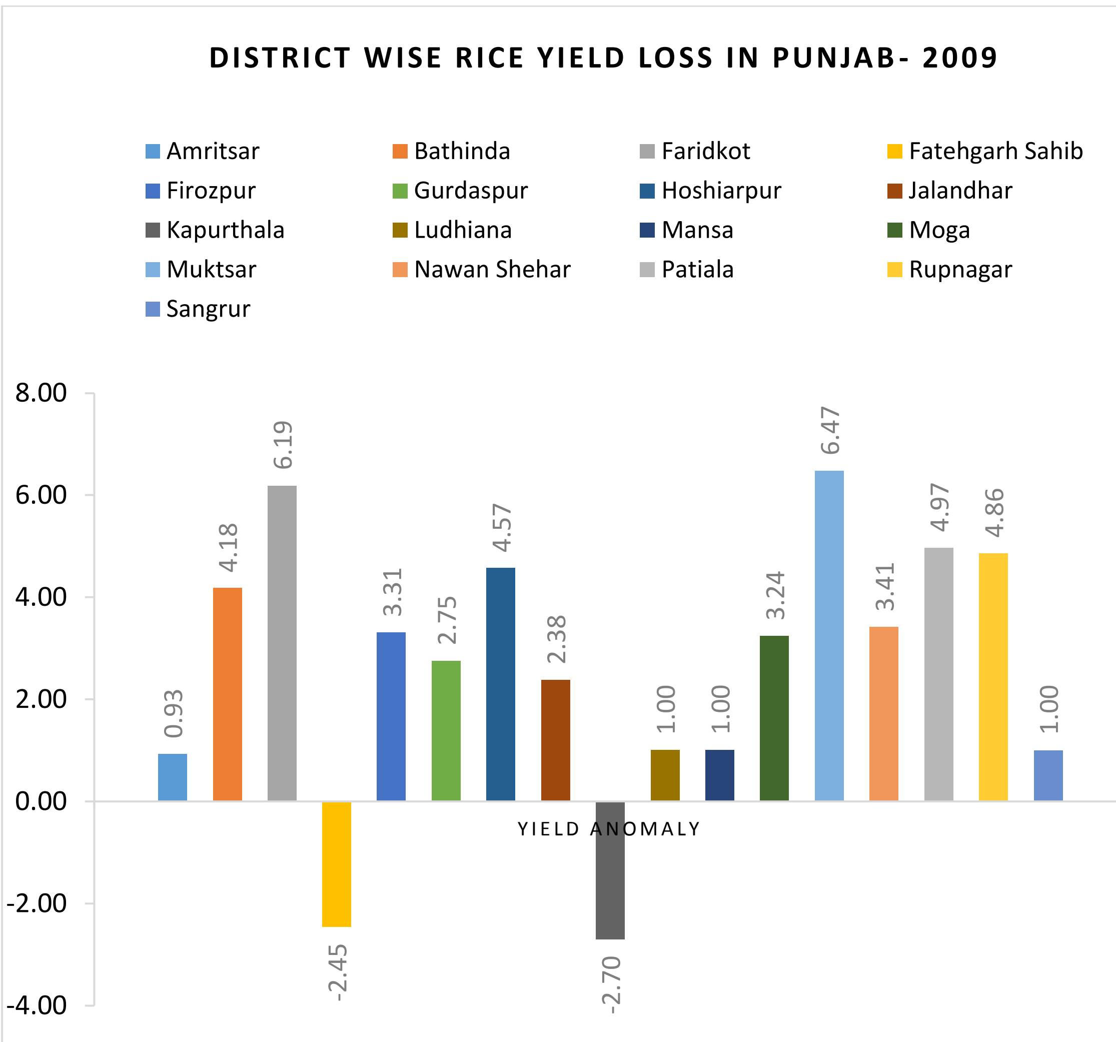


Figure 18 District level Yield anomaly based on average yield in Punjab -2009

Haryana -2009

Districts	Yield Anomaly (%)
Ambala	-8.46
Bhiwani	-8.29
Faridabad	2.33
Fatehabad	11.45
Gurgaon	-21.14
Hisar	11.39
Jhajjar	-51.42
Jind	-8.33
Kaithal	-14.45
Karnal	-11.37
Kurukshetra	-10.75
Panchkula	-6.03
Panipat	-14.02
Rewari	-27.41
Rohtak	-26.66
Sirsa	11.43
Sonepat	-14.30
Yamuna Nagar	-12.48

Punjab - 2009

Districts	Yield Anomaly (%)
Amritsar	0.93
Bathinda	4.18
Faridkot	6.19
Fatehgarh Sahib	-2.45
Firozpur	3.31
Gurdaspur	2.75
Hoshiarpur	4.57
Jalandhar	2.38
Kapurthala	-2.70
Ludhiana	1.00
Mansa	1.00
Moga	3.24
Muktsar	6.47
Nawan Shehar	3.41
Patiala	4.97
Rupnagar	4.86
Sangrur	1.00

Table 9 Yield anomaly Haryana and Punjab -2009

5.2.5 Comparison of yield anomaly and crop water stress obtained from DSSAT for 2009:

Graphs on yield anomaly against simulated crop water stress factor at different stages of crop growth i.e. 1-60 days (vegetative), 60-120 days (reproductive) and 120-146 days (maturity) is presented in figure Results reveal that drought or water stress in vegetative growth stages (1-60 days) and reproductive growth stages (160-120 days) was found to be significantly related to yield anomaly of rice in 2009.

Relationship between water stress factor and yield anomaly at vegetative and reproductive stages of crop had R^2 value of 0.64 and 0.52 respectively for Haryana and 0.73 and 0.68 respectively for Punjab. A poor association was found between crop water stress at maturity stage and rice yield anomaly of both Punjab and Haryana. The degree of fit of relationship is similar for both Punjab and Haryana. This implies the initial and middle stages drought contribute more yield losses in rice crop than the later ones.

However, yield reduction due to drought stress was found to be lower in Punjab as compared to Haryana reflecting slight effect of drought stress on rice crop in Punjab. It is interesting to note that water stress occurred in early stages (vegetative phase) caused large reduction in rice crop of Haryana as compared to water stress occurred during reproductive phase. The devastating effect of water stress of even lower magnitude in early stages on rice crop in 2009 was attributed to large scale mortality of seedlings and reduced tiller due to delayed onset of monsoon.

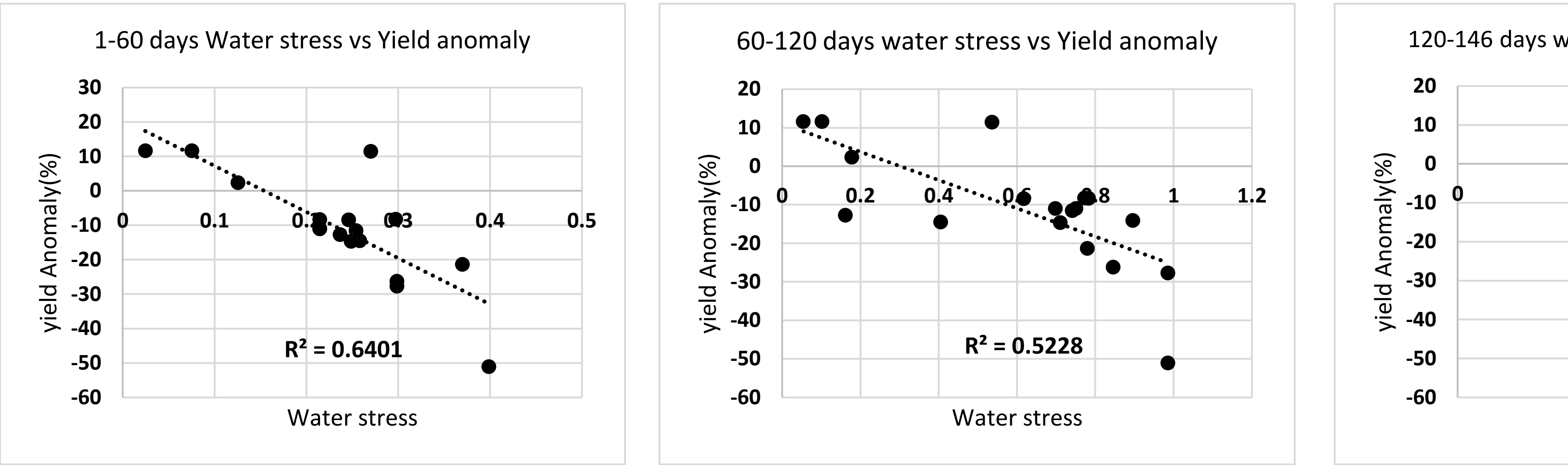


Table 100 Yield anomaly vs Water stress over Haryana at three different stages -2009

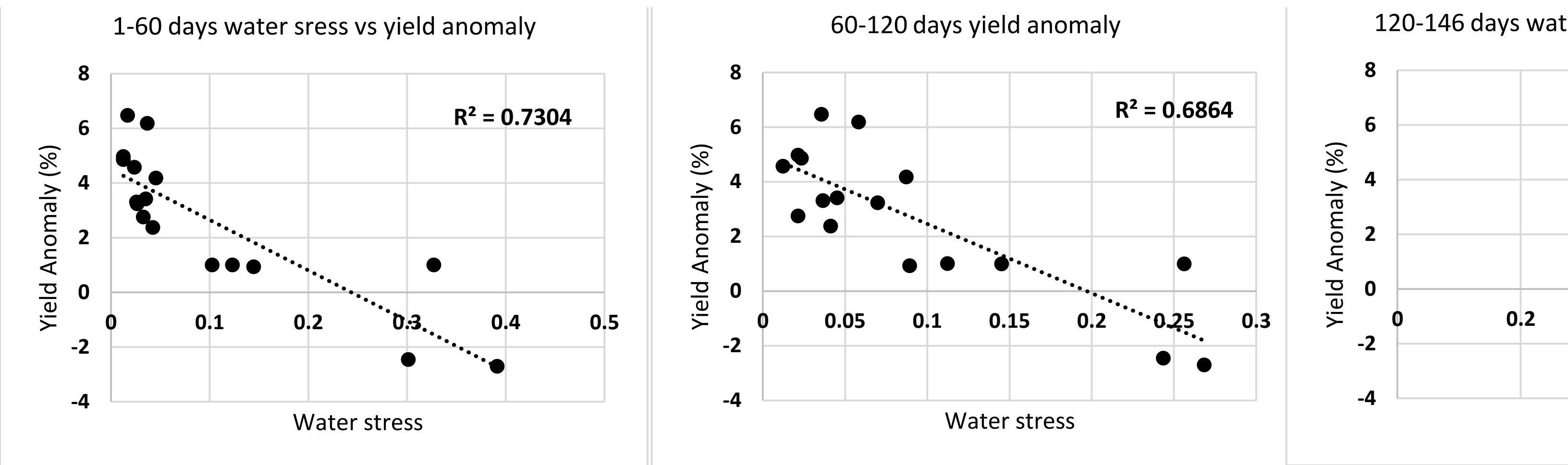


Table 11 Yield anomaly vs Water stress over Punjab at three different stages -2009

5.2.6 Spatio – Temporal pattern of Rice crop water stress during 2009 (10 day basis):

In order to understand the evolution of drought in crop growing season, the crop water stress was estimated using PET and ET at 10 days interval. The fig shows the spatio-temporal pattern of crop water stress at 10 day interval for Punjab and Haryana during 2009. The water stress was high in Haryana where it ranges from 0 to 1, where as in Punjab it range from 0 to 0.5. This indicates the drought condition was more severe in Haryana than in Punjab during 2009. The crop water stress evolve gradually in the initial stages and then it starts declining in the central districts of Haryana. This represent drought condition during the initial stages of rice due to the delayed onset of monsoon. The central parts of Haryana also shows a sudden increase in water stress during reproductive stages (60-120 days), this attribute, the drought condition due to the deficient rainfall and high evaporative demand in the month of august during 2009. This confirm the drought was severe in Haryana due to delayed onset with inadequate rainfall months during 2009.

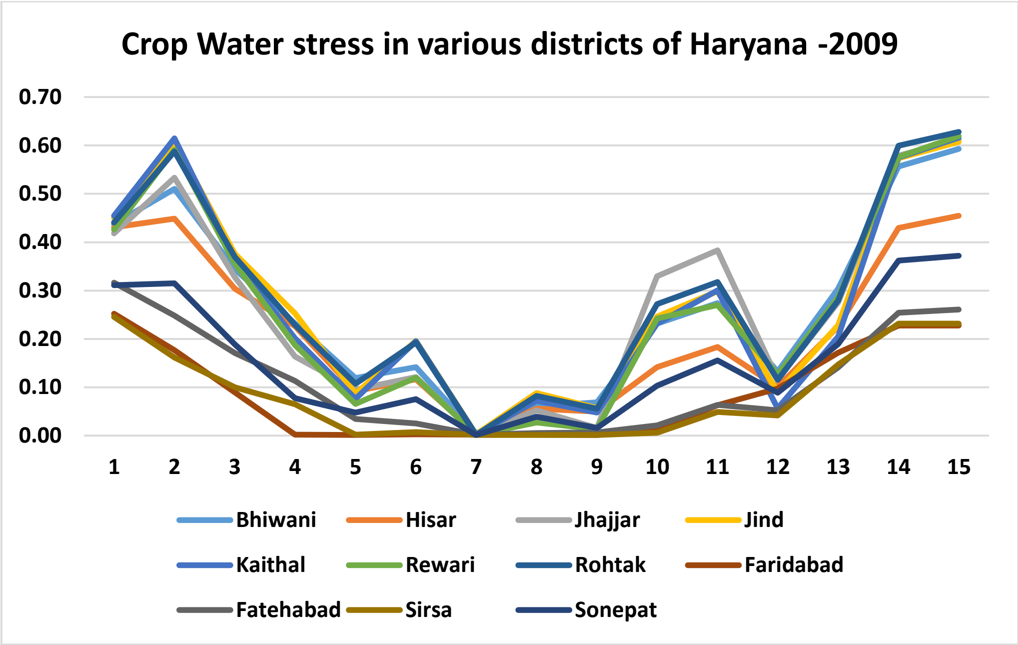
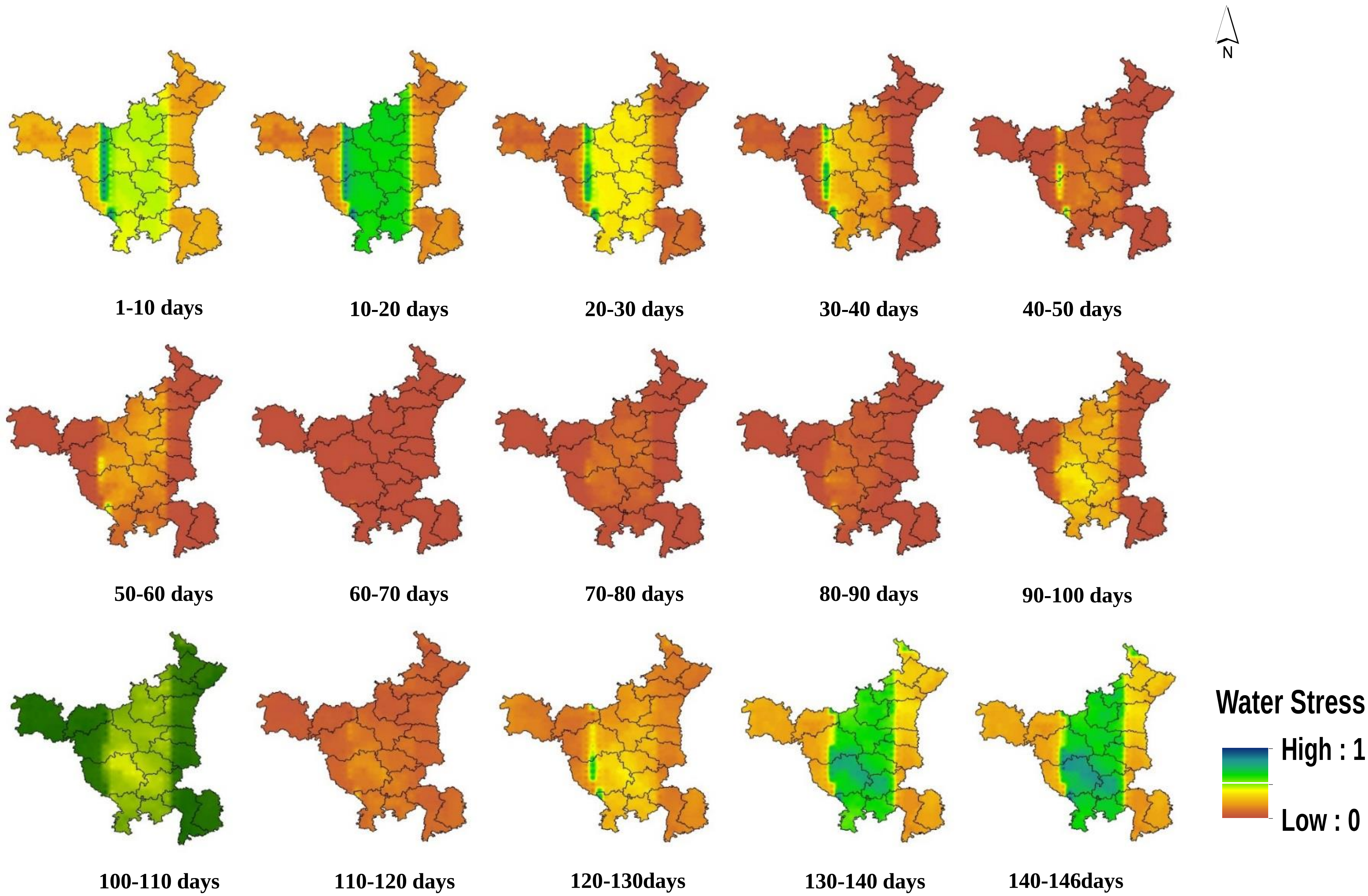


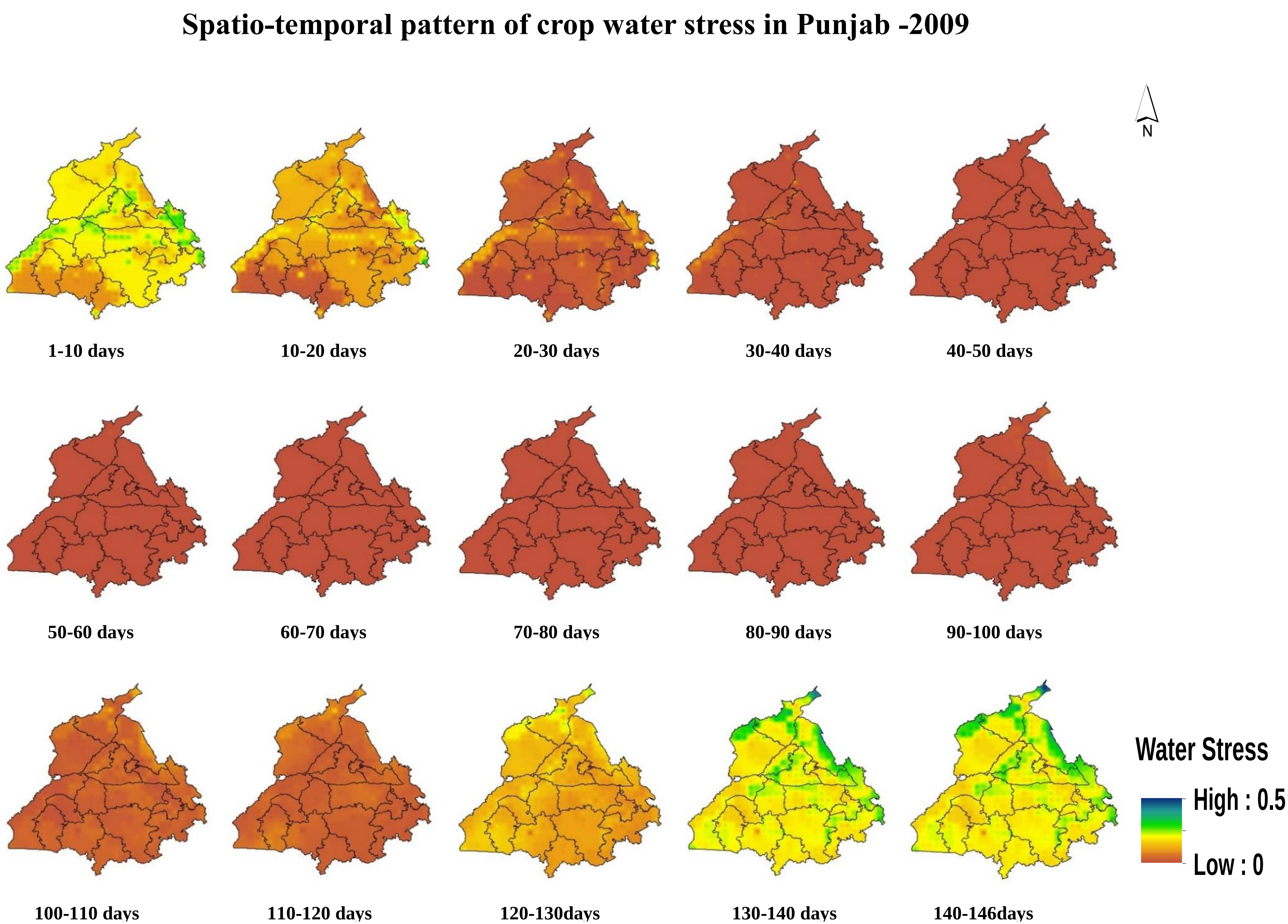
Table 12 Crop water stress over various district in Haryana -2009

The districts such as Jhajjar, Rohtak, Rewari, Gurgaon, Bhiwani, Hisar, Sonepat shows severe water stress during 10-20days and moderate water stress during 20-30 days and 30-40 days 90-100 days, and 90-100 days. Also, the yield anomaly of those district shows a drastic negative change which reflects the water stress during vegetative and reproductive stages have profound impact on rice productivity.

In Punjab, the crop water stress value is very less where it ranges from 0 to 0.5. The spatial pattern shows a minimal stress in the initial stages with water stress values around 0 to 0.2. This indicate that there is no drought condition in Punjab during 2009. Although the drought condition during 2009 in Punjab, do not have any direct impact on rice productivity, it affects overall economy of state due to increased cost of diesel and decline ground water table for succeeding crop.

Spatio-temporal Pattern of crop water stress at 10 days interval




Spatio-temporal pattern of crop water stress in Punjab -2009
N
1-10 days
10-20 days
20-30 days
30-40 days
40-50 days
50-60 days
60-70 days
70-80 days
80-90 days
90-100 days
100-110 days
110-120 days
120-130days
130-140 days
140-146days
Water Stress
High : 0.5
Low : 0

5.2.7 Severity of drought stress at different growth stages:

The observed yield anomaly and spatial averaged water stress at different crop rice stages in drought affected districts were compared to study severity of drought during various stages. The plot in fig shows the comparison of crop water stress at vegetative (1-10 days, 10-20 days, 20-30 days, and 30-40 days) and reproductive (90-100 days, 100-110 days) stages against yield reduction. Water stress at 90-100 days and 100-110 days i.e flowering to maturity stage shows high degree of fit with yield anomaly. This implies the high sensitivity of rice to water stress with any intensity (mild or sever) during the reproductive stage have most serious and devastating effects on yield. The initial stage water stress shows a moderate association with yield anomaly reflects moderate impact of drought in rice production. A poor association was found between crop water stress at maturity stage and rice yield anomaly of drought affected districts in Punjab and Haryana.

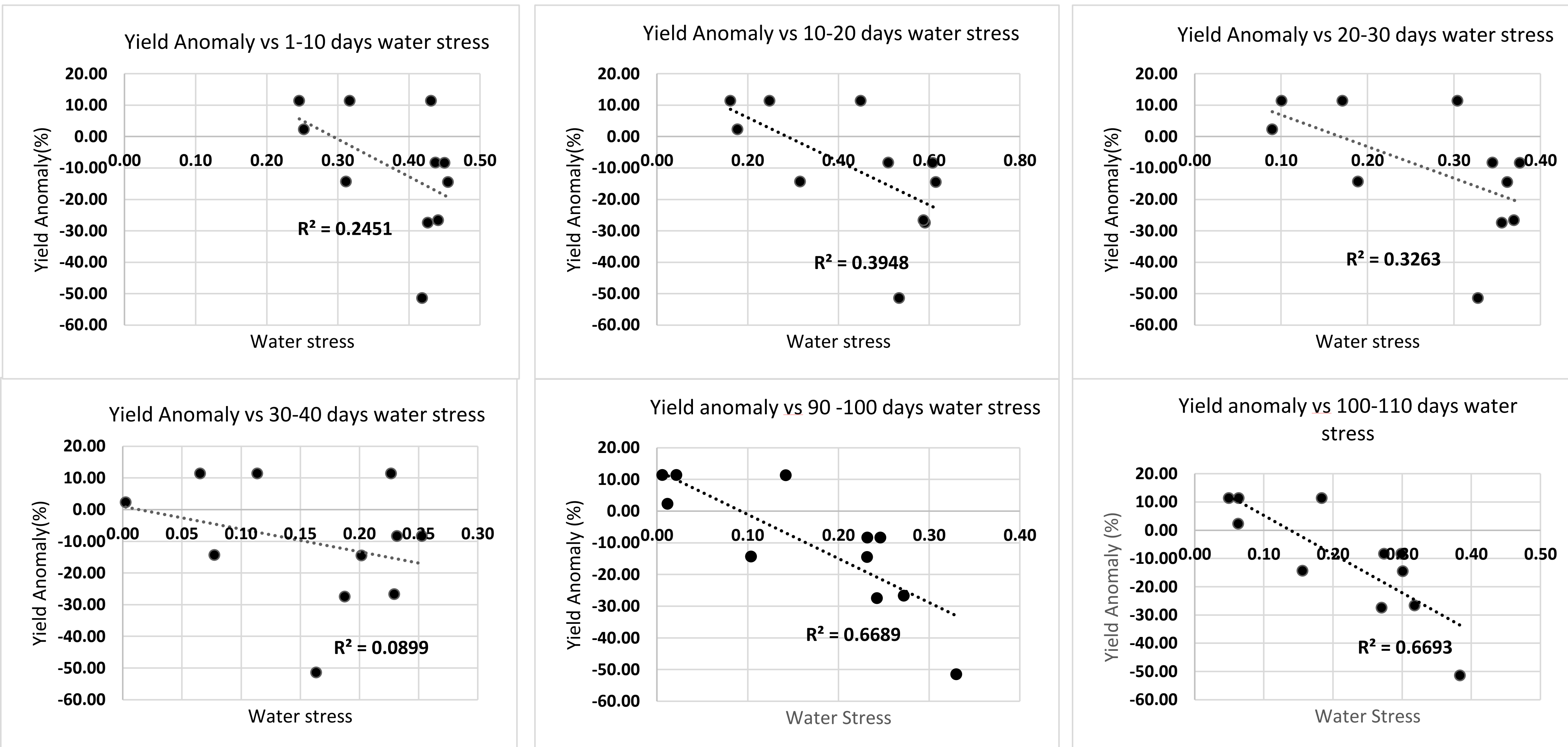


Table 14 Yield anomaly vs Water stress at various crop stages for drought affected district in Haryan -2009

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