MULTI-YEAR PREDICTION OF WHEAT YIELD AS INFLUENCED BY CHANGING AGRO-CLIMATIC INDICES IN KAPILVASTU USING DSSAT CROP MODEL

Submitted to:

Central Department of Hydrology and Meteorology (CDHM)

Tribhuvan University (TU)

Kirtipur, Kathmandu

For the partial fulfillment of requirement for the Master of Science (M.Sc.) degree of Hydrology and Meteorology of Tribhuvan University

Submitted By:

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July, 2020

A thesis report on

MULTI-YEAR PREDICTION OF WHEAT YIELD AS INFLUENCED BY CHANGING AGRO-CLIMATIC INDICES IN KAPILVASTU USING DSSAT CROP MODEL

(For the partial fulfillment of Master of Hydrology and Meteorology)

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DECLARATION

I hereby declare that the dissertation work entitled "**Multi-year prediction of wheat yield as influenced by changing agro-climatic indices in Kapilvastu using DSSAT crop model**" presented herein is my own work, done originally by me and has not been summited elsewhere for the award of any degree. All the reference sources of information have been properly and fully acknowledged.

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RECOMMENDATION

This is to certify that Mr. Devid Dhakal has prepared the dissertation entitled **"Multi-year prediction of wheat yield as influenced by changing agro-climatic indices in Kapilvastu using DSSAT crop model"** under my supervision and guidance. Moreover, I recommend this thesis for final approval and acceptance as a partial requirement for master's degree of science in Hydrology and Meteorology. This thesis bears the candidate's own effort and is not submitted for other degree before. Therefore, I strongly recommended this thesis for approval

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LETTER OF APPROVAL

This dissertation submitted by Mr. DEVID DHAKAL entitled **"Multi-year prediction of wheat yield as influenced by changing agro-climatic indices in Kapilvastu using DSSAT crop model"** as a partial fulfillment of the requirements for the award of Master's Degree of Science in Hydrology and Meteorology under Tribhuvan University has been approved for the final selection.

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ABSTRACT

Central Terai in Nepal is the major production domain of wheat; however, wheat yields have been majorly affected by anomalies of agro-climatic indices like fluctuating maximum and minimum temperatures, solar radiation and rainfall. NASA Power data over 33 years records (1985-2018) were purposively download and compared with the ground station measured data for the study of study by using four years of weather data (1986, 1996, 2006 and 2016) randomly selected years for the multi-year prediction of agro-climatic scenarios on yields of wheat in Kapilvastu district, of Central Terai, Nepal. The relationship between the DHM recorded weather data and the NASA power data was found fairly valid and safe to see the long-term climate change impacts. At Kapilvastu the annual average and maximum temperatures were found to be decreasing by 0.017˚C and 0.046˚C per year, respectively, whereas the minimum temperature was increasing by 0.011˚C. Similarly, the total precipitation was increased by 28.63mm per year and solar radiation was decreasing by 0.035 MJm^{-2} per year. The trend analysis on grain yields of wheat were correlated over the historical records of maximum temperature, minimum temperature, rainfall and solar radiations. A positive correlation was found with minimum temperature and rainfall. However, the yield was found to be negatively correlated with the maximum temperature and solar radiations. Cropping Systems model CERES-Wheat embedded in Decision Support System for Agro-technology Transform (DSSAT) ver 4.7 model was used to study the multi-year prediction of wheat yield over the changing agro-climatic scenarios after following IPCC (2007) scenario using environmental modification section of the DSSAT ver 4.7 models. The data sets to run the CSM-CERES- Wheat models have been taken from the well predicted and validated crop model with WK-1204 cultivar of wheat which is popularly grown in Terai and hills condition of sandy-clay loam soil, resembling the production domain of the project sites. The simulation results using DSSAT model over the 33 years of weather data were found to be very closely agreeing with the observed data of the wheat yield recorded from the Ministry of Agriculture and Livestock Development in Nepal. The trend analysis, regression and correlation studies and from sensitivity analysis using DSSAT, all have resulted the uniform relationship between agro-climatic indices and wheat yields. The different climate change scenarios as advocated by IPCC (2007) for 2020, 2050, and 2080 were studied to simulate the yield performance of WK-1204 cultivar of wheat. Increased in temperature by 1˚C will increase the wheat yield and furthermore increased in temperature decreased the yield under the present levels of agronomic management options. The result showed that the wheat yields for few years can only be sustained by using the present crop varieties and urged for the development of climate change ready crop varieties to feed the increasingly growing population.

Keywords: ***Agro-climatic indices, DSSAT 4.7 crop model, Multi-year prediction, Wheat yield***

Acknowledgement

First of all, I would like to acknowledge all the authors of the papers I reviewed on this study. This study wouldn’t be completed without their research outputs.

I would like to express my deep and sincere gratitude to Dr. Lal Prasad Amgain, Dean, Agriculture, Far-Western University, Tikapur, Kailali, Nepal for his valuable guidance and encouragement which laid a foundation for the success of this research. My sincere gratitude goes to my co-supervisor Mr. Saurav Suman, Data Analyst, UN-WFP-Kathmandu, Nepal for his continuous support and guidance from the beginning until the completion of my research.

I owe my deep respect to Prof. Dr. Deepak Aryal, Head of Department, Central Department of Hydrology and Meteorology (CDHM) for his support and suggestion during the study period. I am thankful to Dr. Binod Dawadi, Associate Professor, CDHM for his valuable comments and suggestion.

I would thank all the teachers and all other faculty members of CDHM for their enthusiasm and cooperation throughout the research period. I would like to acknowledge my colleagues Mr. Binod Dhakal, Mr. Laxman Paneru, Mr. Sagar Subedi, Mr. Biraj Kandel, Mr. Hira Prasad Bhattarai, Mr. Lekhnath Pokhrel and Ms. Nirmala Regmi for their continuous support for this study. I would like to thank all my seniors and juniors from CDHM for their valuable support during this study.

I would like to thank my friend Mr. Shailesh Adhikari for his valuable ideas, suggestions, and continuous support during my research work.

My heartfelt appreciation goes to my brother Mr. Bhanu Bhakta Dhakal, for his support, guidance, and suggestions.

I owe my deep respect and debt of gratitude towards my family for their continuous supports, suggestions, and help during the research work without which I wouldn't have been able to complete this study.

Lastly, I would like to thank all those who directly or indirectly helped me in the course of study and report preparation.

Devid Dhakal

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List of Abbreviations

AGDP: Agriculture Gross Domestic Product
CC: Climate Change
CERES: Crop Environment Resource Synthesis Crop Environment Resource Synthesis
CH_4: Methane Gas
CIMMYT: International Maize and Wheat Improvement Center
CO_2: Carbon dioxide
CSM: Crop Simulation Model
DAP: Diammonium Phosphate
DHM: Department of Hydrology and Meteorology
DSSAT: Decision Support System for Agrotechnology Transfer
FAO: Food and Agriculture Organisation
GCM: General Circulation Model
GDD: Growing Degree Days
GDP: Gross Domestic Product
GHGs: Green House Gaseous
GPS: Genotype-Specific Parameters
IBSNAT: International Benchmark Sites Network for Agrotechnological Transfer
ICIMOD: International Centre for Integrated Mountain Development
IGP: Indo-Gangetic Plain
IPCC: Intergovernmental Panel for Climate change
MOAD: Ministry of Agriculture Development
MoE: Ministry of Environment
N_2O: Nitrous Oxide
NARC: National Agriculture Research Centre
NASA: National Aeronautics and Space Administration
NASA/POWER: National Aeronautics and Space Administration/Prediction of Worldwide Energy Resource radiation
UNEP: United Nations Environment Programme

CHAPTER 1

INTRODUCTION

1.1 Background

Globally wheat (*Triticum aestivum* L.) is grown on more land area than any other food crops (214.3 million ha) as reported (FAOSTAT, 2018). In 2018, world production of wheat was 736.1 million tons (FAO 2018 a, b) making it the second most-produced cereal after maize. Importance of wheat production in world economy is proven by its share of 15% from 1500 million hectares arable land in the world (Kiss, 2018). Wheat is grown on more land area than any other commercial crops and continues to be the most important food grain source for humans. Wheat production leads all crops, including rice, maize and potatoes (FAO, 2018c). Wheat is grown in nearly every region of the world and represents a main source of food and income for millions of smallholder farmers (CIMMYT, 2018). Wheat serves as a first source of protein and second source of calories in the diet of consumers in developing countries. It provides 21% and 20% of the food calories and protein, respectively for more than 4.5 billion people live in 94 developing countries. An estimated 80 million farmers in the developing world depend on wheat for their livelihoods. About 21% of the world's food depends on the wheat crop, which grows on 200 million hectares of farmland worldwide (http://www.fao.org). Although wheat is traded internationally and developing countries are major importers (43% of food imports), the reality is that 81% of wheat consumed in the developing world is produced and utilized within the same country, if not the same community (CIMMYT, 2005).

Wheat occupies 17% of the total cultivated land area of the world and comes to third in Nepal in terms of area, production and consumption (CIMMYT, 2002). It is the staple food of 35% of the world's population and provides more calories and protein in world's diet than any other cereal (CIMMYT, 2002). Wheat is the major winter cereal crop of Nepal occupying 22% (735,850 ha) of total cereal area and contributes 20% (1,879,191 tons) of the total cereal production in the country with productivity of 2.554 tons/ha (MoAC, 2017). Wheat contributes 7.14% in the AGDP share of the country. Terai represents about 66% total wheat area and contributes about 76% total production of wheat in Nepal (Poudel *et. al*., 2013). The present average wheat productivity in Terai is 2938 kg/ha compared to 2177 kg/ha in hill and 1403 kg/ha in mountain with national average 2554 kg/ha (MoAC, 2017). Even though wheat is third important crop of Nepal, it is second important for Kapilvastu district. It is cultivated in 25627 hectares and average productivity is 3.65 tons/ha (MoAD, 2017).

There are several factors responsible for low wheat productivity in Nepal, like poor irrigation facilities, less availability of fertilizer, pesticides and insecticides (Pokherel *et al*., 2007; Devkota, 2013). Agrawal and Karla (1994) explain that in sub-tropical region there will be small decrease in potential wheat yield by 1.5 to 5.8%, but in tropical zone, the decrease will be 17 to 18% indicating that rainfed wheat productivity is likely to suffer more in Terai as compared to the mid-hills environment in a changing climatic scenarios. Several complaints have been made by the farmers over the year about increasing difficulty to plant wheat due to delayed monsoon and factors including population growth, market, deforestation and desertification which have already threatened food security in Nepal (Dahal, 2009). Whether the delayed monsoon and other climatic parameters have already been affecting wheat planting and yield, examining this relation is worth to know whether there has any relation with the changing climate scenario (Dahal, 2009). If the results show any relation of the changing climate scenario, it must be addressed before it is too late.

In Nepal wheat is sown after rice and it grows and survives on the residual soil moisture, late monsoon rains and winter rain (Shrestha *et al*., 2013). Average productivity of wheat is very low as compared to developed countries. The average yield per hectare is maximum in New Zealand (10 tons/ha), followed by Zambia (7 tons/ha) and Mexico (6 tons/ha). Low wheat yield in Nepal is due to late planting of wheat is very common due to an excess or lack of moisture just after rice harvesting, delay in rice harvesting due to late maturing varieties and shortage of labors during rice harvesting time. In late sown wheat high temperature and desiccating winds during the month of April may cause forced maturity resulting reduction in test weight and decrease grain yield (Singh and Dahiwal, 2000). Nepalese agriculture is rain fed dominant and rice cultivation is followed by wheat as the result it faces chilling winter at vegetative stage, anthesis and post-anthesis drought with high temperature stress during later stage of growth. Moreover, the shift in monsoon rainfall from Jestha-Asar to Shrawan-Bhadra due to climate change has pushed the timely sowing of wheat exposing it to the post-anthesis heat stress (Giri, 1998). The problem of lesser growing degree days due to shorter crop duration has aggravated with moisture stress especially in later growth stages is more under conventional system of farming. In late sown wheat due to high temperature and desiccating winds during the month of April may cause forced maturity of late sown wheat, thus resulting reduction in test weight and, hence decrease grain yield (Singh and Dahiwal, 2000). Climate influences plant life in many ways and can inhibit, stimulate, alter or modify crop performance (Amgain *et al*., 2006). Climate components like temperature, solar radiation, rainfall, relative humidity and wind velocity independently or in combination, can influence crop growth and productivity (Amgain *et al*., 2006). With the increasing population and purchasing power, demand on food has also increased which is impossible to meet with the present varieties, technologies and management practices. The deterioration of soil health, threats of climate change, emergence of new weeds and diseases, increase on the labor, energy and water intensive wheat cultivation has aggravated the situation.

Mainly the regression equation, trend analysis and many other methods are used to know about the impact of agro-climatic factors on the yield of wheat in Nepal. A range of technologies has been identified in recent years, which have the potential to increase resource use efficiently, reduce adverse environmental impacts, and increase crop productivity in Asia. It is assumed that evaluation and site-specific adaptation of these technologies can be assisted through crop simulation models. Among several models evolved, the Decision Support System for Agro technology Transfer (DSSAT) is pioneer one. DSSAT was originally developed by an international network of scientists; cooperating in the International Benchmark Sites Network for Agro technology Transfer (IBSNAT) project (Jones *et al*., 1998; Iyanda *et al*., 2014; Kaur *et al.*, 2015; Anar *et al*., 2015). The IBSNAT suites of crop models represent many of the major staple food crops and have been widely calibrated and validated in many countries. Decision Support System for Agro technology transfer (DSSAT) software consisting of Crop Simulation Model

(CSM)-CERES-Wheat, is one of the highly adopted and well-recognized software in the developing world which can investigate the various management and climate change scenarios and can help to identify the best management practices and factor to close the yield gaps and increase the food security (Amgain and Timsina, 2004). This is process based, management-oriented model that can simulate the growth and development of wheat as affected by varying levels of water, nitrogen and cultivar characteristics (Amgain, and Timsina 2004). Several studies have done separately in several stations of various parts of the world, but there is lack of study focusing the impacts on agro climatic indices on productivity of wheat and multiyear prediction on wheat yield in Terai conditions of Nepal and this study was proposed, executed and accomplished with dual aims of studying the following broad and specific objectives:

1.2 General objective

- To observe the multi-year prediction of wheat yield as influenced by various agro-climatic factors in Kapilvastu district.

Specific objectives

- To see the validity of DHM observed weather data with the weather data obtained from the NASA Power,
- To acquaint the trend analysis between historical agro-climatic indices and wheat yield over Kapilvastu district, and
- To test the sensitivity of the CSM- CERES- Wheat (DSSAT Model) over the changing climatic scenarios and weather years in central Terai region.

CHAPTER 2

LITERATURE REVIEW

2.1 Rice-Wheat cropping system

Rice (*Oryza sativa* L.) - wheat (*Triticum aestivum* L.) system, the practice of growing wheat after rice in an annual rotation, is the leading cereal cropping system in the Indo-Gangetic plains (IGP) and vital for the food security, livelihood and employment of millions of people in the region (Timsina and Connor, 2001; Gupta *et al*., 2002). Rice-wheat systems provide the staple grain supply for about 8% of the world's population, making these systems critically important for global food security (Ladha *et al*., 2003b; Timsina and Connor, 2001). In South Asia, rice-wheat systems produce more than 30% of the rice and 42% of the wheat consumed -(RWC-CIMMYT 2003:04) and cover about 14 million hectares of cultivated land, with most of the area located in India and the IGP. It is the dominant cropping system among other cereal cropping production system in Terai and mid hill region of Nepal and is important for food security.

Rice and wheat occupy 1.5 and 0.76 Million ha, respectively and are grown in succession on more than 0.56 Million ha which accounts 37% of the rice and 85% of wheat area in Nepal (Tripathi *et al.*, 2002). Rice-Wheat-System, one of the principle cropping systems in Nepal, occupies one-fourth of the total cropped area and provides food, income and employment to 83 % of the Nepalese populace. Thus, the rice-wheat system is of great importance in assuring food security and enhancing livelihood of the Nepalese people. Rice–wheat system is largely practiced on low land ecosystem where heavier soil texture, excessive soil moisture, and late rice harvest lead to higher production cost and delays in wheat planting. The traditional method of wheat establishment involves excessive tillage which is painstaking, time and energy consuming that further leads to poor plant stand and late planting (Giri, 1997; Hobbs and Morris, 1997; Tripathi, 2002). Residue retention in situ conserves soil moisture; enhance soil organic carbon and N efficiency (Hobbs and Gupta 2003).

In order to feed the growing population the country need to increase the productivity of crops while maintaining the sustainability of the cropping system. Recent studies indicate a slowdown in the productivity of growth in the rice-wheat systems (Kumar *et al.,* 2002a). Evidence from long-term experiments shows that crop yields are stagnating and sometimes declining (Duxbury *et al.,* 2000; Ladha *et al.,* 2003a). The observed yield decline from the long term experiment in rice-wheat system is due to deterioration of soil physical properties and soil fertility (Sharma and Jain, 1997; Ladha *et al.,* 2003).

In addition, environmental degradation, increasing water scarcity, labour shortage and socioeconomic changes are seen as the other major contributors to the stagnation of rice–wheat productivity in the IGP (Erenstein *et al.*, 2007; Rijsberman, 2006). The major sustainability issues are declining soil fertility and organic matter content (Yadav *et al*., 1998; Byerlee *et al*., 2003), micronutrient deficiencies (Nayyar *et al.*, 2001) increasing pest problems (Pingali and Gerpacio, 1997), and rapidly declining groundwater levels (Pingali and Shah, 1999; Singh and Dahiwal, 2000; Hira and Khera, 2000). The fertility status of the Nepalese rice-wheat system has been declined due to poor soil organic matter content and is being consistently depleted of their finite reserve of nutrients by crops.

2.2 Climate change and emissions of Greenhouse gases

Intergovernmental Panel on Climate Change fourth assessment report defines climate change as a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcing such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes. United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as: “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods”.

Climate Change (CC) refers to a change in the state of the climate that can be identified by changes in the mean or variability of its properties and that persists for an extended period, typically decades or longer (IPCC, 2007a). Natural variability or human induced increase in greenhouse gases (GHGs) is the main factors responsible for CC. Carbon dioxide(CO_2), methane(CH_4), nitrous oxide(N_2O), and F-gases such as per fluorocarbons(PFCs), hydro fluorocarbons(HFCs), sulphur hexafluoride(SF_6), and chlorofluorocarbons(CFCs) are the most prominent GHGs that trap heat and cause CC(IPCC, 2007b). Fuel combustion, deforestation, transportation, agriculture, urbanization, and industrialization are the main sources of GHGs emission. Marked increase in the concentration of CO_2 from about 280ppm in pre-industrial value to 379ppm in 2005 has been reported. Similarly, during the same time period concentration of CH_4 and N_2O has increased from 715ppb to 1774ppb and 270ppb to 319ppb, respectively. Total CO_2 equivalent of prominent GHGs is estimated to be around 455ppm, which if not stabilized below 550ppm CO_2 would lead to the most harmful irreversible consequence of CC through temperature rise more than 2˚C (IPCC, 2007a). According to (IPCC, 2007), there has been an unprecedented warming trend during the 20th century. The current average global surface temperature of 15 ºC is nearly 0.6 ºC higher than it was 100 years ago-most of the increase has been the consequence of human activity. A further increase of 1.5-6 ºC is projected for the period to 2100. Fourth Assessment Report of IPCC (2007) concluded that “most of the observed increase in anthropogenic greenhouse gas concentrations.” The average atmospheric CO_2 concentration has increased from 280 ppm in 1850 to 365 ppm at present, and could exceed 700 ppm by the end of the present century if emissions continue to rise at current rates (IPCC, 2007).

Clear indication of CC in the earth has been reported. Over the last few decades, temperature of earth surface has been rising and predicted to rise further if proper attention is not paid. This has caused changes in weather patterns, rise in sea level, and melting of glaciers. In addition, more frequent storm events, increased events of drought, increased number of El-Nino and other adverse climatic situations can also be attributed to the global CC. Prediction shows that rise in 2˚C temperature is inevitable even if emissions are reduced to less than 50% of the current level by 2050. This increase in temperature was determined to be an upper limit beyond which the risks of grave damage to ecosystems, and of non-linear responses, are expected to increase rapidly. However, the current trend of emission i.e., emission well above 2000 levels in 2100, would lead to 4˚C increase in temperature causing unavoidable devastating losses, and excessively higher adaptation costs (IPCC, 2007b). It is expected that up to 2100 this concentration would become 3 times as much as the pre-Industrial time causing 3 to 10˚C hikes in temperature (Tisdell, 2008).

2.3 Climate Change in Nepal

Nepal has an extremely varied and complex climate, driven by the uneven terrain and regional weather systems. Within a few hundred kilometers, the country's elevation changes from the lowland of 70m in the Terai to the top of the world, Mount Everest (8,848m). Nepal is considered as one of the top ten countries most likely to be impacted by global climate change (WFP, 2009) but is one of the least contributors to the emissions of greenhouse gases (GHGs), emits only 0.027% of global share (INDC, 2016). The Observed Climate Trend Analysis Report (2017) prepared by the Department of Hydrology and Meteorology (DHM), Nepal based on temperature and precipitation data from the year 1971 to 2014 finds out that the average annual temperature increase rate of Nepal is 0.056°C. Also studies on temperature trend in Nepal have identified increasing trend in annual mean and annual maximum temperature in high altitude more than that of lower altitude (Baidya *et al.,* 2008). Observations of regional and seasonal variation at different part of the country resulted high rainfall regions and seasons are recording increases in precipitation and becoming wetter, whereas low rainfall regions and seasons are recording decreases in precipitation and becoming drier. The water springs in the mid Hills of Nepal have been drying up in the recent past (Gurung *et al.*, 2009). Climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity (IPCC, 2007). Climate change is expected to affect the agricultural production, thereby affecting the livelihood and food security in poor rural parts of developing countries (Aydinalp *et al.*, 2008, Keane *et al.*, 2009 and Lybbert *et al.,* 2012). In Nepal, the temperature has been increased by 1.8˚C during last 32 years and the average temperature increase was recorded as 0.06˚C per year (Malla, 2008). Warming and rising of temperature in the higher altitude has benefitted some households such as growing maize, and green vegetables (Manandhar *et al.,* 2011).

2.3.1 Change in Precipitation

The annual mean precipitation is around 1800 mm in Nepal but because of greatly diverse topography it ranges from more than 5000 mm in the south to less than 250 mm in the north (Rai, 2007). Because of climate change and the rising temperatures, Nepal could face drier phases during dry seasons with wetter monsoon (as much as three times the current level of rainfall) with chances of flooding and landslides during rainy seasons with subsequent impacts on agriculture and livelihoods (Alan and Regmi , 2005). Rainfall was recorded minimum in the year 1972, 1977, 1992 and 2005 and maximum in the year 1975, 1985 and 1998 respectively (Malla,2009). Traditional rainfalls of Jestha and Ashar (mid-July) have been shifted in Shrawan and Bhadra in Kathmandu and it has affected negatively in the rice production.

Erratic rainfall events i.e., higher intensity of rains but less number of rainy days and unusual rain) with no decrease in total amount of annual precipitation have been experienced. Such events increase possibility of climatic extremes like irregular monsoon pattern, droughts and floods. For example, there were rain deficit in eastern Terai and western regions, normal rain in far western region and heavy rain in the mid-western region creating flood, landslide and inundation (Agrawala *et al.*, 2003). People in Nepal are experiencing more intensive rainfall and subsequent flood and landslide that have direct adverse impact on livelihood assets such as physical, natural, financial, social, and human (Vidal, 2006; Gautam *et al.*, 2007a; Gautam *et al.*, 2007b; Pokhrel,*et al.*, 2007).

Rainy days are decreasing at a rate of 0.8 days per year (Regmi and Adhikari, 2007) leading to a delay in monsoon season and scarcity of water which in turn is causing a change in cropping patterns and crop maturity periods (Regmi and Adhikari, 2007). Additionally high humidity provides a conductive environment for breeding of insects, bacteria and fungi leading to the rise of tropical diseases and also crop destroying pests become more prevalent (Regmi and Adhikari, 2007).

2.3.2 Change in temperature

It already observed such as increase in dry period, intense rainfall, flood, landslides, forest fires and glacial retreats threats (Shrestha, 2007). In Nepal average temperature increase was recorded as 0.06 ºC per year and that in Terai and Himalayas was 0.04ºC and 0.08 ºC per year respectively (Shrestha, 2007). Nepal has experienced the fastest long-term increase in temperature with 1.6˚C increase between 1976 and 2005, which is very high compared to global temperature increase of 0.6˚C in the last three decades (IPCC, 2007b). Negative impacts of climate change have been observed in Nepal. It has been reported that 2006 was the warmest year among the twelve warmest years since 1975 to 2007. Agrawala *et al* (2003) reported that temperature increase faster at higher altitudes than at lower altitudes. Due to the change in climate, soil quality is declining due to increased precipitation and occurrences of intense rainfall leading to higher levels of erosion and sedimentation of fertile land. Temperature is rising at an average of 0.4° C per decade, hence affecting soil moisture because of increased evapo-transpiration.

Developing countries are more vulnerable to the effects of climate change due to its high dependence on climate-sensitive sectors like glaciers, agriculture and forestry, and its low financial adaptive capacity (Karki, 2007). Developing countries like Nepal are more susceptible to the climate change and its impacts due to their limited capacity to cope with hazards associated with the changes in climate.

2.4 Effects of climate change in Agriculture

Weather and climate are the key factors affecting the agricultural productivity. Being open to vagaries of nature, agriculture sector is highly vulnerable to climate change phenomena (Ahmed, *et al.*, 2012). Change in water availability to crops may be attributed to annual rise of 0.3°C in world average temperature, which would lead to limit cereal production (Schneider, 2007). The physiological processes including alleviation of photosynthetic efficiency, oxidative damage, uptake of water and nutrients by crop are severely affected under continuously changing temperature and moisture disparity (Wang *et al.*, 2011). Similarly, climate change in the form of temperature rise and rainfall variability in many parts of world caused countries cereal grain yield stagnation and increased yield variability (Olesen *et al.*, 2011). Hence, plant growth and productivity is severely affected by nature in the form of biotic and abiotic stresses like water stress therefore, physiological and morphological changes in plants needs to be addressed as mitigation approach (Jaleel *et al.*, 2009). Stresses (water & temperature) due to climate change reduce crop growth by affecting various physiological and biochemical processes such as photosynthesis, respiration, translocation and nutrient metabolism (Jaleel *et al.*, 2009).

The impacts on agriculture are the decrease of productive land in some region and increase in other region. So, it is a complex problem to the world (Pathak, 2003a). Rising CO_2 promotes plant growth and if the CO_2 gas doubles, yields will increase by 40%. CO_2 is regarded as the driving factor of climate change, however its direct effect on plant is positive (Warrick, 1988). Changes in precipitation patterns i.e. intensive rain concentrated in particular month have a devastating effects on crop production (Adams *et al.*, 1995). Nepalese agriculture is predominantly rain-fed agriculture. Therefore, any variations in rainfall patterns will have direct impact on Nepalese agriculture. For instance drought condition will result in decreased crop yields thereby total production (Malla, 2007).

Increase in temperature under increased availability of atmospheric CO_2 leads to vigorous growth of food crops and reduce the level of soil organic carbon, soil micronutrient, and enhance decomposition by activating the microbial population in the soil, thereby decreasing agricultural productivity in a long run (Malla, 2003). With the increase in temperature shifting upward of several domestic and wild plants and animals species have been reported in Nepal (Malla, 2007). In general temperature increase will reduce yield and quality of food crops there by exacerbating vulnerability in food supply.

2.5 Effects of climate change on wheat production

Climate influences plant life in many ways and can inhibit, stimulate, alter or modify crop performance (Amgain *et al.*, 2006). It's components like temperature, solar radiation, rainfall, relative humidity and wind velocity independently or in combination, can influence crop growth and productivity. Climatic parameters like rain and temperature strongly affect the growth and productivity of wheat. An experiment conducted in open top chamber at Khumaltar showed the increase of wheat yield by 8.63 and 9.74% even at the increase of the temperature by 6.94˚C and the doubling of CO_2 (Malla, 2007). Wheat production was increased by 41.5% in the Terai plain, 24.4% in the hill and 21.2% in the mountain under the elevated CO_2. The yield however decreased by 1.8% in the Terai but continued to increase by 5.3% in the hill and 33.3% in the mountain at 4˚C rise in temperature under irrigated condition (Malla, 2007). All over the world concerns now exists about the possible climate change caused by an increase in the concentration of the greenhouse gases such as CO_2, CH_4 and N_2O in the atmosphere (Watson *et al.*, 1996). Using general circulation model (GCM), it has been predicted that a doubling of the current CO_2 levels in the atmosphere will cause an increase of 1.5 to 4˚C in average global surface air temperature, with accompanying changes in rainfall pattern by the end of the 21st century (Cohen, 1990; Adams *et al.*, 1995). Warrick (1988) investigated that at higher level of CO_2 in the atmosphere, C3 crops specially wheat would show improvement in water use efficiency through less transpiration, in such case at 2×CO_2 concentration level (680 ppm), wheat production would be increased 10 % to 50 % for mid and high latitude region of Europe and America. However, 2˚C increase in temperature would decrease the production by 3 to 17 % which might be offset by higher level of precipitation. For each degree centigrade increase in temperature would cause to shift the geographical location for crops production to several hundred kilometres towards mid and high latitude (Warrick, 1988).

2.6 Agro climatic indices

Temperature is an important environmental factor influencing the growth and development of crop plants. During growth and development of a cereal crop several growth stages are distinguishable in which important physiological processes occur. Influence of temperature on phenology and yield of crop plants can be studied under field condition through accumulated heat units system (Chakravarty and Sastry, 1984, Rajput *et al.*, 1987 and Bishnoi *et al.*, 1995).

Plants have a definite temperature requirement before they attain certain phenological stages. To forecast the phenology and crop production attributes for large areas, there is need to develop crop model (Doraiswamy and Thompson, 1982). The heat unit system was adopted for determining the maturity dates of different crops (Bierhuizen, 1973). The accurate prediction develops on the assessment of plant development rate at each growth stage during the growing season. However, the phenology and ambient temperature interaction in wheat under late sowing high temperature growing condition is very important in Bangladesh. Because in Bangladesh 60% of wheat areas are planted late due to various reasons and the crop faces high temperature during reproductive stages (Badaruddin *et al.*, 1994).

2.7 Decision Support System for Agro -technology Transfer (DSSAT) and crop simulation model (CSM-CERES-wheat)

The Decision Support System for Agro-technology Transfer (DSSAT4.5) is a comprehensive decision support system (Tsuji *et al.*, 1998; Hoogenboom *et al.*, 2010) that includes the Cropping System Model (CSM)-CERES-Wheat model (Ritchie and Otter-Nacke, 1985; Ritchie *et al.*, 1998). The CSM-CERES-Wheat model can be used to simulate the growth and development of dry land and irrigated wheat across a range of latitudes in northern and southern hemispheres (Jones *et al.*, 2003; Nain and Kersebaum, 2007; Hoogenboom *et al.*, 2010). The model had been evaluated and applied to a range of tropical (Timsina *et al.*, 1995), subtropical (Hundal and Kaur, 1997; Heng *et al.*, 2000) and temperate environments in Asia (Timsina and Humphreys, 2006; Zhang *et al.*, 2013). The decision support system for agro technology transfer (DSSAT) has been in use for the last 15 years by researchers worldwide. Crop growth simulation models (CSM) provide the means to quantify the effects of climate, soil and management on crop growth, productivity and sustainability of agricultural systems (Amgain, 2004). They can potentially provide a scientific approach to study the impact of current and future climate change on agricultural production (Rosenzweig and Parry, 1994; Adams *et al.*, 1995). CSM-CERES-Rice and CSM-CERES-Wheat models are process based, management oriented models that can simulate the growth and development of rice and wheat as affected by varying levels of weather, water, nitrogen, and cultivar characteristics (Jones *et al.*, 2003). The model processes indicate the effects of elevated CO_2 and changed climatic parameters such as increased or decreased temperatures, rainfall and solar radiations. These models have been validated and tested across the world, including many countries in Asia (Timsina and Humphereys, 2003) and in N-W India (Timsina *et al.*, 2004), and hence are suitable for investigating the sensitivity of both rice and wheat yields to CO_2 and climate change parameters.

Crop production system analysis is necessary to identify tillage and residue management practices that affect crop production. Crop production system is influenced by a complex array of factors combining crop, soil water, climate, and management parameters. Although many critical cropping system factors cannot readily be changed, soil and water conditions are greatly influenced by management and cultural practices that are controllable. Tillage is one management tool under direct human control that is used to modify the craw environment (Davidoff, 1992). Tillage practices have been devised through trial and error to provide better soil conditions for seed germination and drop development and growth. Because of the complex interactions among system components, systems analysis is a useful technique for defining cultural practices that optimize crop production strategies (Davidoff, 1992). The conventionally tilled winter wheat (*Triticum aestivum* L.) -fallow system is often water-use inefficient as its fallow phase has frequently less storage efficiency than no-till and organic production practices.

Wheat production is constrained by heat stress for late sowing dates. For optimization of yield, sowing at the appropriate time to fit the cultivar maturity length and growing season is critical (Andarzian *et al.*, 2014). Crop models could be used to determine optimum sowing window for a locality. Research result of simulations showed that the yield of early sowing dates (before 15 November) is lower than the yield of normal sowing date (e.g. 15 November) of decreasing crop growth cycle particularly the time from sowing to the anthesis stage (Andarzian *et al.*, 2014).

The delay in sowing date not only affects yield, but it affects the yield components and other aspects of the growth and development of wheat. It has been reported that decreasing duration of the stem elongation phase (end of tillering to anthesis stages) would result in a lower number of fertile florets (Slafer *et. al.*, 2001).

2.8 Sensitivity analysis of model

Sensitivity analysis is done for the study of the behaviour of model (Jones and Luyten, 1997). This is done to determine how much a change in the value of a parameter influences the important outputs from the model. The model is sensitive to a parameter if a major change in the output occurs when the parameter is changed. Sensitivity analysis is a base line that enables the user to make changes to existing data sets and compare the effects of that change. Sensitivity analysis is valuable in assessing several useful theoretical applications including yield gap analysis, strategic decision making planning and climate change studies (Timsina and Humphreys, 2003). It is important to understand the response of the model to one specific input, such as weather data, cultivars or hybrids, soil data, and values for individual Genotype-Specific Parameters (GSPs). This approach, in which all inputs are kept constant except for one input or parameter, is called sensitivity analysis. DSSAT has a facility to automatically do sensitivity analysis for selected variables.

CHAPTER 3

MATERIALS AND METHODS

3.1 Selection of Study Area

Kapilvastu district lies in Province No. 5, Nepal. Its elevation varies from 93 meters to 1,491 meters above sea level. Geographically, the district can be divided into plain low lands of Terai and low chure Hills. The latitude is 27°32′N and longitude is 83°3′E. It has an area of 1,738 km^2 and a population of 571,936 (Census, 2011).

The summer maximum temperature is 45˚C whereas the minimum temperature during winter is below freezing. The distribution of precipitation also depends on the spatial location and time of the year. The monsoon contributes approximately 80% of the annual precipitation during the summer season (from mid-June to mid-September), and westerly winds deliver winter (December–February) precipitation. During the other two seasons, autumn (September–November) and spring (March–May), the region receives occasional precipitation.

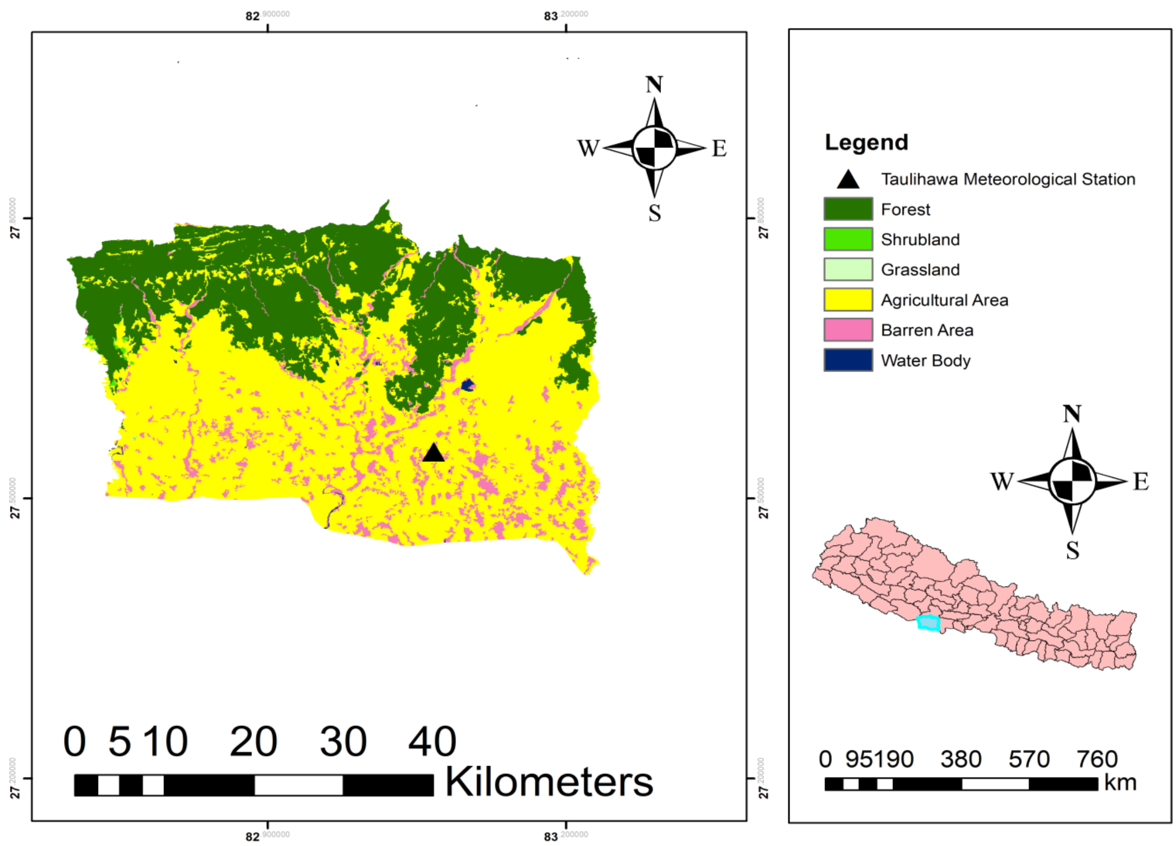


Figure 1: Study Area (Kapilvastu District)

3.2 Data collection

The research primarily depends on datasets that were obtained from several government departments and agencies. Data on historical weather years, crop yield and model data have been taken from the following sources.

3.2.1. Climate database

` Daily data for maximum and minimum temperature, solar radiation, and rainfall of 33(1984-2017) years of Taulihawa, Kapilvastu of 27.55˚ latitude 83.0667˚ longitude were downloaded via the internet from the National Aeronautics and Space Administration (NASA)/Prediction of Worldwide Energy Resource radiation (POWER) site (https://power.larc.nasa.gov/data-access-viewer/). The NASA/POWER project at the NASA Langley Research Center provides daily data for main climatic variables on 0.5° latitude by 0.5° longitude grid cells for the entire globe. The data are widely used in agricultural for modeling crop yields (Bai *et al.,* 2010; van Wart, Grassini, & Cassman, 2013; van Wart *et al.,* 2015), other crop simulation exercises (Ojeda, Volenec, Brouder, Caviglia, & Agnusdei, 2017), plant disease modeling (Savary *et al.,* 2012). Therefore, NASA/POWER products could be used as a source of climatic data for agricultural activities with a reasonable confidence for regional and national spatial scales (Leonardo *et al.,* 2017).

Similarly data for maximum and minimum temperatures and rainfall were also taken from ground Taulihawa, Kapilvastu of 27.55˚ latitude and 83.067˚ longitude with elevation of 94m from sea level station provided by Department of Hydrology and Meteorology (DHM) for the further process in validation.

3.2.2. Wheat yield database

The wheat yield data were obtained from the Ministry of Agricultural Development (MoAD), Nepal. They collected the data from the District Agriculture Development Office Kapilvastu, Nepal. The wheat yield data from 2003-2017 only was available in the MoAD so the required data of yield i.e from 1984-2003 were collected from the International Center for Integrated Mountain Development (ICIMOD) agricultural atlas.

3.3 Weather Data Validation

There is a lot of missing data in ground station (Taulihawa, Kapilvastu) provided by DHM and it is obvious to use satellite data than the data provided by DHM. There are the several methods to fill the gaps of missing data use simply use the simple average method. The model accepts the NASA POWER data that was validated with the ground station. DSSAT requires daily data to run. Before using satellite data, it is important to check how it relates to the observed data and can be used or not. If 10% of the data we collect from ground station is valid with respect to NASA data, then it is considered safe to use. Further minimum temperature, maximum temperature and rainfall data from random 4 years (1986, 1996, 2006 and 2016) were validated between station data and NASA data. Due to lack of solar radiation data on the station we did not do validation these data with NASA derived solar radiation. According to Sayago *et al.,* (2019) NASA-POWER shows potential to estimate solar radiation.

3.4 Trend analysis between historical weather and wheat yield data

Trend analysis was done to see the either climatic indices are increasing or decreasing and to see how wheat yield is related to different weather parameters. For this we find the correlation coefficient of yields and agro climatic indices. Correlations of wheat yield with climatic variables were estimated following an established approach as described in (Bhatt *et al.,* 2014; Lobell and Field, 2007; Lobell *et al.,* 2005; Nicholls, 1997). The correlation results provide initial information on the positive or negative sign of relationships which helps understanding the regression results. The trend line was plotted to determine the relationship between minimum temperature, maximum temperature, rainfall and solar radiation of the 33 years (1984-2017) of crop growing seasons (November to April) along with yield. Similarly, with the yield given by the model, a separate trend line was drawn between the indicators of the weather at the same time.

3.4.1 Correlation coefficient:

According to Simpson and Kafka (2005) "correlation analysis deals with the association between two or more variables". The correlation coefficient measure the degree of relationship between two series of two variables. The value of coefficient of correlation lies between -1 to +1. A correlation coefficient of +1 means that for every positive increase in one variable, there is a positive increase of a fixed proportion in the other. A correlation coefficient of -1 means that for every positive increase in one variable, there is a negative decrease of a fixed proportion in the other. Zero means that for every increase, there isn't a positive or negative increase. The two just aren't related. The calculation of the correlation coefficient is performed using the Equation, in which x represents the independent variable and y represents the dependent variable.

$$\boldsymbol{r} = \frac{\sum(\boldsymbol{X}-\overline{\boldsymbol{X}})(\boldsymbol{Y}-\overline{\boldsymbol{Y}})}{\sqrt{\sum(\boldsymbol{X}-\overline{\boldsymbol{X}})^2(\boldsymbol{Y}-\overline{\boldsymbol{Y}})^2}}$$

Where $\overline{X}$ and $\overline{Y}$ represent the sample mean of x and y respectively.

3.4.2 Regression analysis

According to Morris Hamburg (2005) "The term Regression Analysis refers to the methods by which estimates are made of the values of a variable from knowledge of the values of one or more other variables and to the measurement errors involved to this estimation process." Actually regression is fundamental relationship between a dependent random variable and one or more independent random variables. The general form of the regression function is

$$Y = b_0 + b_1X_1 + b_2X_2 + \ldots\ldots\ldots\ldots\ldots + b_kX_k + c$$

Where (b_0, b_1, b_2,…………….b_k) are the regression coefficient, X and Y are two variables and c is the constant.

3.5 Varietal characteristics of wheat varieties WK-1204 recorded for model testing

It was developed by the combined efforts of CIMMYT Mexico and NARC through production trail, farmers trail and farmer's participatory varietal trails. It was released in

2007 for mid and high- hill region of Nepal (NARC, 2007). It matures in about 169 days and produces an average yield of 6.9 tons/ha. The variety performs better in irrigated and non-irrigated high and mid-hill region of Nepal and has hard oval round white grains. Because of its better quality of non-lodging, high yield, synchronized maturity, easy threshing it is popular among farmers (NARC, 2007). Average height of this variety is 83 cm. It is resistant to yellow rust.

3.6 Cultural operation studied to run the CSM-CERES-Wheat model

To run the model we use the ideal conditions of treatments, we did the fertilizers and irrigations on the following manner on the model.

3.6.1 Fertilizer application

Phosphorus and potash were applied at the rate of 60 and 40 kg/ha through the DAP (Diammnoium Phosphate) and potassium chloride. Nitrogen was applied as per the treatments 100 kg/ha through the Urea. The half dose of nitrogen, full dose of phosphorus and potash were applied as a basal dose. The remaining half dose of nitrogen was applied 30 days after sowing.

3.6.2 Irrigation

Irrigation was applied only three times, as rainfall was sufficient to meet the moisture requirement of the crop. The irrigation was done 15 days, 45 days and 60 days after sowing. In each irrigation 70mm of water was used on flood condition.

3.7 Data required for running DSSAT

DSSAT model requires different data sets. Separate files of different data sets are prepared for running of model.

X-file:

The x-files contained the following data sets. Agronomic management (Tillage, Sowing, Density, Fertilizer, Irrigation, Harvest, etc….) and Initial soil condition (NH4, NO3, moisture, etc…), as shown in Appendix 9.

Weather file (W- file):

Weather file or simply w-file contained the following data sets. Maximum temperature, minimum temperature, rainfall, solar radiation, relative humidity, dew point temperature etc., as shown in appendix 8.

Soil file (S file):

Soil file contained the following data sets. (Drained upper limit (DUL), drained lower (DLL), SAT, Bulk density (Bd), Stone %, Silt %, Clay %, OC %, pH, N%, SRGF, SSKS, SALB, etc….) which is obtained from the World Food Programme.

A-file:

A file contained the following data sets. Performance data (Grain yield (GY), Leaf area index (LAI) max, Anthesis and maturity dates, grain no. grain wt., etc…) as shown in appendix 6.

T-file:

T file contained the following data sets. Time course data (Periodic DM, LAI, Leaf wt, Stem wt, SLA, etc… & HI, GY,…..) as shown in appendix 7.

The X file and W file were prepare by ourselves but remaining data need the experimental files which we do not did so the remaining data were collected from the already calibrated and validated data (Amgain *et al.,* 2019).

3.8 Data requirements for model evaluation

CSM-CERES-Wheat requires a well-defined set of inputs to simulate actual crop conditions (Benioff and Smith, 1994). These include soil and weather conditions, genetic coefficients, planting details, and irrigation and fertilizer schedules. Data requirements depend upon the modeling objectives, larger quantities of accurate data will increase the model accuracy by avoiding parameter and equation based assumptions made by model (Timsina *et al.,* 1995). Descriptions of A-File, T-File, W-File and X-File prepared for the wheat experiments are given in (Appendix 6, 7, 8 and 9) in DSSAT format.

3.8.1 Model calibration

CERES- Wheat uses seven genetic coefficients; three genetic coefficients are related to the plant development (P1V, P1D and P5). The remaining four genetic coefficients are associated with grain yield (G1, G2, G3 and PHINT). Genetic coefficients of wheat cultivar WK-1204 has taken from the already calibrated model (Marasini, 2016). These genetic coefficients of the wheat cultivars were obtained from the different treatment under study by using the CSM-CERES-Wheat model.

The meaning of the various genetic coefficients for wheat cultivars were presented as below:

P1V : Days, optimum vernalizing temperature required for vernalizaion
P1D : Photoperiod response
P5 : Grain filling (excluding lags) phase duration
G1 : Kernel number per unit canopy weight at anthesis
G2 : Standard kernel size under optimum conditions
G3 : Standard, non-stressed mature tiller wt (including grains) (wt dwt)
PHINT : Interval between successive leaf tip appearance (0C.d)

Table 1: Genetic Coefficient of wheat varieties

Cultivars	**P1V**	**P1D**	**P5**	**G1**	**G2**	**G3**	**PHINT**	**Simulated values**		
								A	**PM**	**GY**
WK-1204	3.0	39	315	40	71	0.9	64	119	152	3556

Measured values;
WK-1204 : A – 118 days, PM – 152 days and GY – 3556 kg/ha
A= anthesis days, PM: - physiological maturity GY- grain Yield
These genetic coefficients were then used for validation of the model.

3.8.2 Model validation

Validation of the model involves comparison of predicted and simulated data from crops that were not used for the calibration. They must be validated for the sites and regions of interests. Validation involves subjective judgment. It is a measure of accuracy or closeness of fit established for the state variable such as crop yield. The model were evaluated using the root mean sum square (RMSE) and index of agreement (d-stat) statistics (Willimott, 1985). The d-stat of a 'good' model should approach unity and the RMSE approach zero. The RMSE is considered the 'best' overall measure of model performance as it summarizes the mean difference in the units of observed and predicted values (Toit and Toit, 2003).

The CERES-Wheat model was tested and validated by using the above determined genetic coefficients of four wheat varieties. Model was validated using treatments except those used for model calibration for all wheat varieties. Observation on grain yield was used for the model validation. Predicted grain yield was well agreed with observed yield (RMSE=734.299, d-stat =0.631). These validation results showed that the CERES-wheat model could be safely used as a tool for simulation of different agronomic and climate change parameters under western mid hills condition. (Unpublished thesis, Marasini, S, 2016)

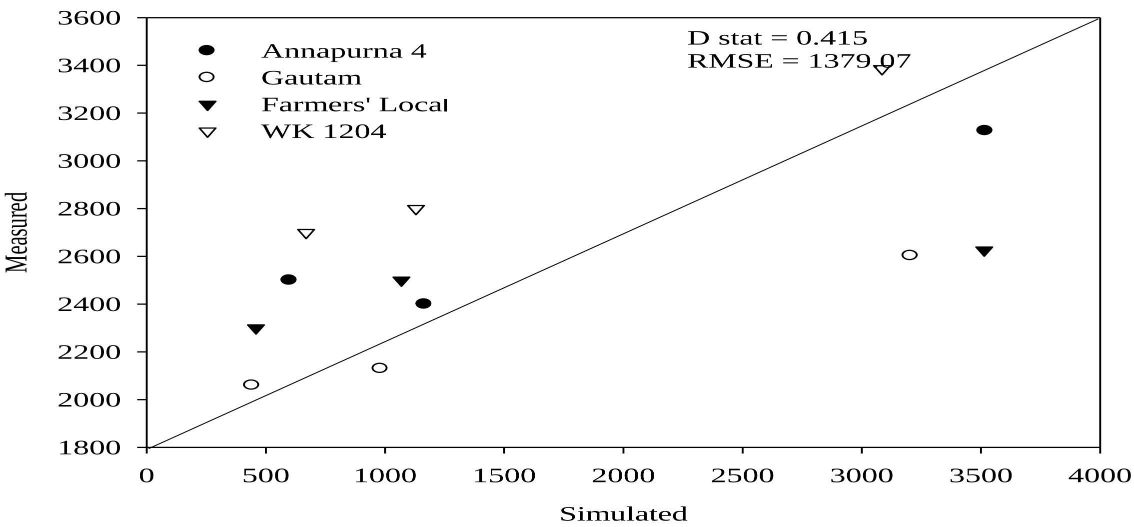


Figure 2 : Simulated and measured yield for farmer's local, WK-1204, Annapurna-4 and Gautam taken from Marasini (2016)

3.9 Sensitivity analysis

The purpose of sensitivity analysis is to study the behavior of the model (Jones and Luyten, 1997). Sensitivity analysis is a base line that enables the user to make changes to existing data sets and compare the effects of that change. Sensitivity analysis is valuable in assessing several useful theoretical applications including yield gap analysis, strategic decision making planning, and climate change studies (Timsina and Humphreys, 2003). DSSAT has a facility to automatically do sensitivity analysis for selected variables.

3.10 Multi-year prediction of wheat yield with changing agro-climatic scenarios

Simulation to different scenarios of climatic parameters was accomplished by comparing the growth and yield performance of wheat genotypes for various weather years (1984/85, 1991/92, 1998/99, 2005/06 and 2014/15). The proportionate increase or decrease in maximum and minimum temperature, solar radiation and increase of CO_2 concentration on the input file (File-X) of wheat was done by changing their respective magnitude to predict the growth and yield performance of wheat as advocated by IPCC (2007) for 2020, 2050 and 2080 scenarios. The scenarios given are in the range of increase of 2-4˚C temperatures, of CO_2 concentration of 420 to 570 ppm and of increase of 1 $MJm^{-2}day^{-1}$for those periods, respectively (Abdul Haris, 2010).

CHAPTER 4

RESULTS AND DISCUSSIONS

The results obtained during the research are presented in this chapter with the help of Tables and Figurers wherever necessary. The results obtained are discussed with possible reasons and with supporting literature.

4.1 Comparison of NASA/POWER- derived and measured weather data from DHM

Figure 3, 4 and 5 shows a comparison of NASA/POWER- derived daily weather data with the ground-measured daily data for 2017 at Taulihawa, Kapilvastu, Nepal. Measured daily maximum temperatures were slightly higher than NASA-derived temperatures, especially during the wet season from June to November, but the temperatures were similar during the dry and winter season. Although the measured daily minimum temperatures were higher in the wet season, there were fewer variations compared with maximum temperatures. In the dry season, the measured daily minimum temperatures were lower than NASA-derived minimum temperatures. Highly extreme rainfall events measured by a rain gauge were not captured by NASA. Due to lack of measured daily solar radiation values we simply used the NASA derived solar radiation. These types of comparisons are also done by Timsina *et al* (2011).

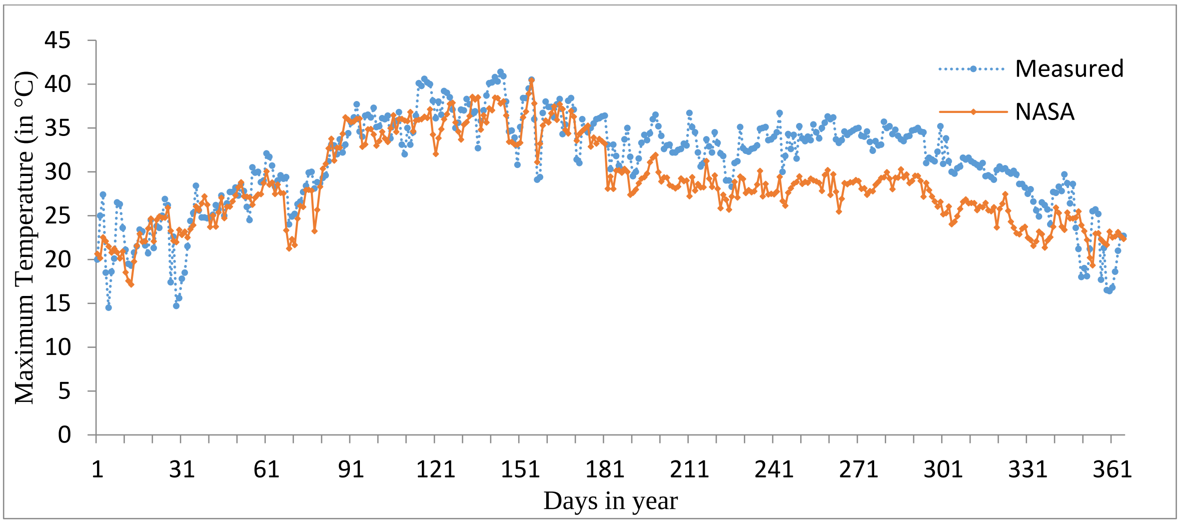


Figure 3: Maximum temperature during 2017 at Taulihawa, Nepal, using ground measured and satellite-derived NASA data

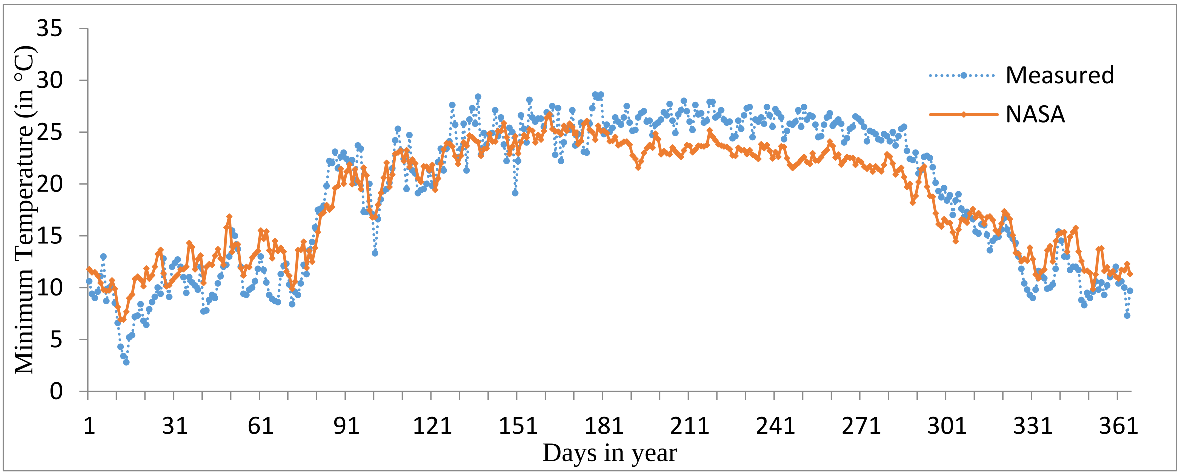


Figure 4: Minimum temperature during 2017, Taulihawa Nepal, using ground measured and satellite derived NASA data

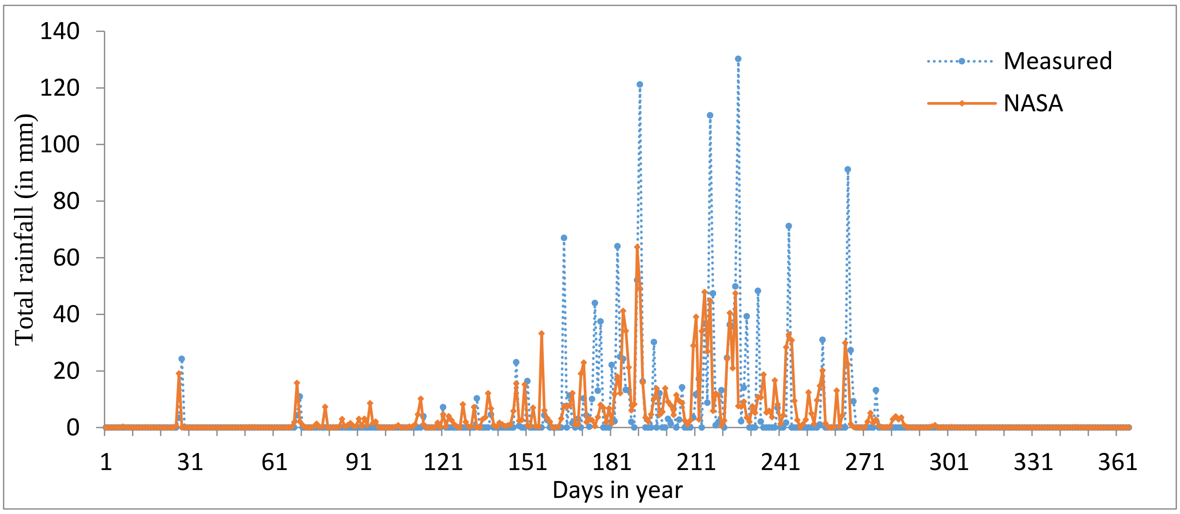


Figure 5: Total rainfall during 2017, Taulihawa Nepal, using ground measured and satellite derived NASA data

Figure 6, 7 and 8 shows comparison between NASA-derived daily maximum, minimum temperature and rainfall and ground-measured data for the different four years (1985/86, 1995/96, 2005/06 and 2015/16) at Taulihawa Kapilvastu, Nepal. The maximum temperature for NASA data range from 13°C to 43.24°C whereas, the measured temperature ranged from 8.3°C to 45°C. The corresponding NASA-derived and measured minimum temperature ranged from 2.41°C to 28.97°C and 0°c to 32.6°C, respectively. The overall mean maximum temperature reflected in NASA data was 2°C cooler than that given by the measured data; values of mean minimum temperature were almost the same for both source of data. Although mean daily rainfall was quite similar (2.96 mm vs 3.86 mm for NASA and measured data), there were large variations in individual daily rainfall (0 – 157.21 mm for NASA data; 0 – 298.5 mm for measured data). R^2 values for maximum temperature for year 1986, 1996, 2006 and 2016 were 0.78, 0.75, 0.63 and 0.71 respectively. Similarly R^2 values for minimum temperature were 0.86, 0.84, 0.87 and 0.90 for respective year. R^2 values for the mention period shows the satisfactory agreement between NASA-derived and ground measured data. For rainfall, R^2 values was least satisfactory, it was 0.21, 0.31, 0.29 and 0.30 for 1986, 1996, 2006 and 2016 respectively. Although the, R^2 values were less than desired, the scatter diagram show similar trends and patterns, indicating a close relationship between NASA-derived and actual ground measured data, especially for temperature (Timsina *et al.*, 2011)

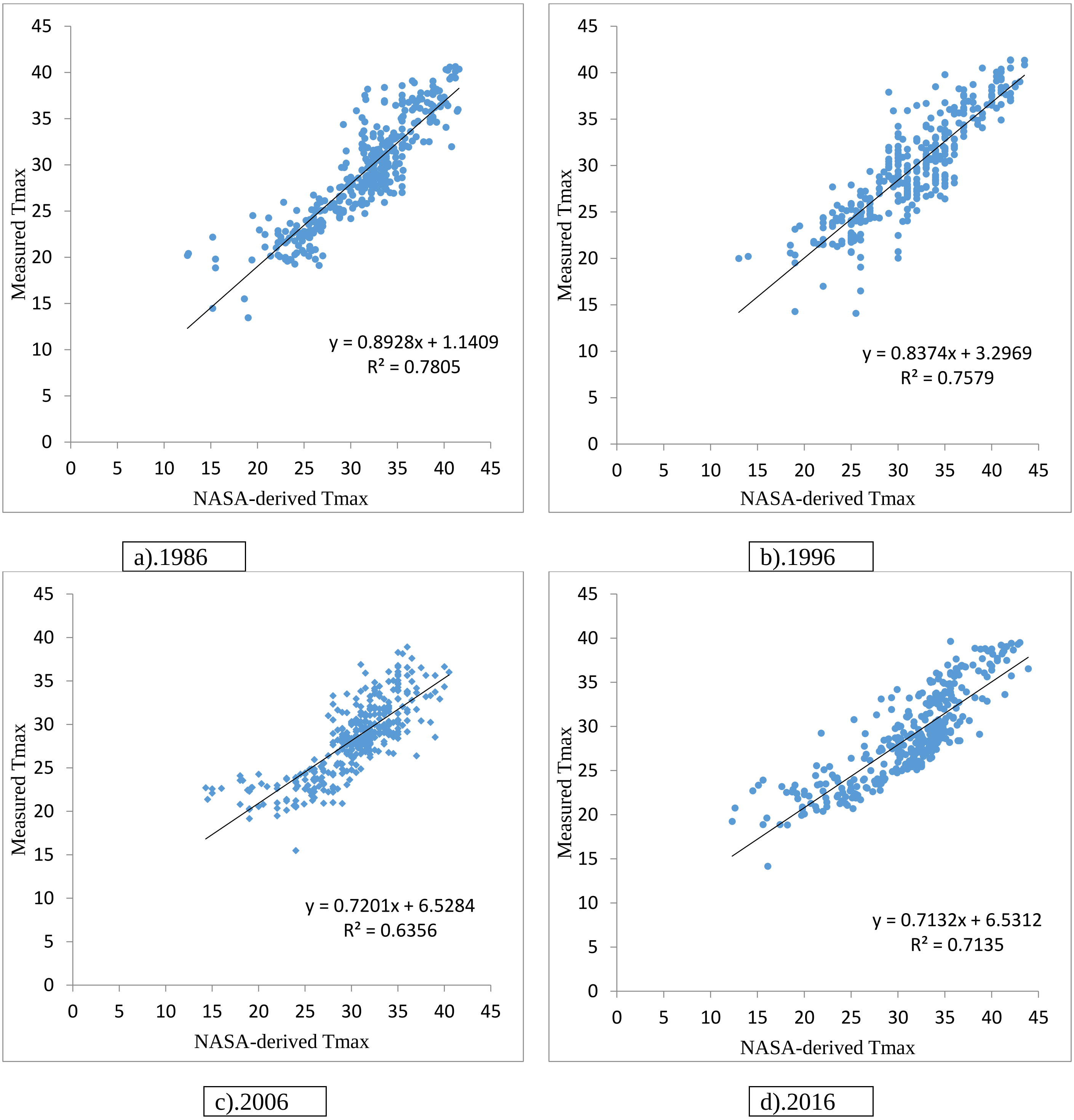


Figure 6 : (a,b,c,d) Comparison of NASA-derived and measured maximum temperature of four different years (1986, 1996, 2006 and 2016) at Taulihawa, Kapilvastu Nepal.

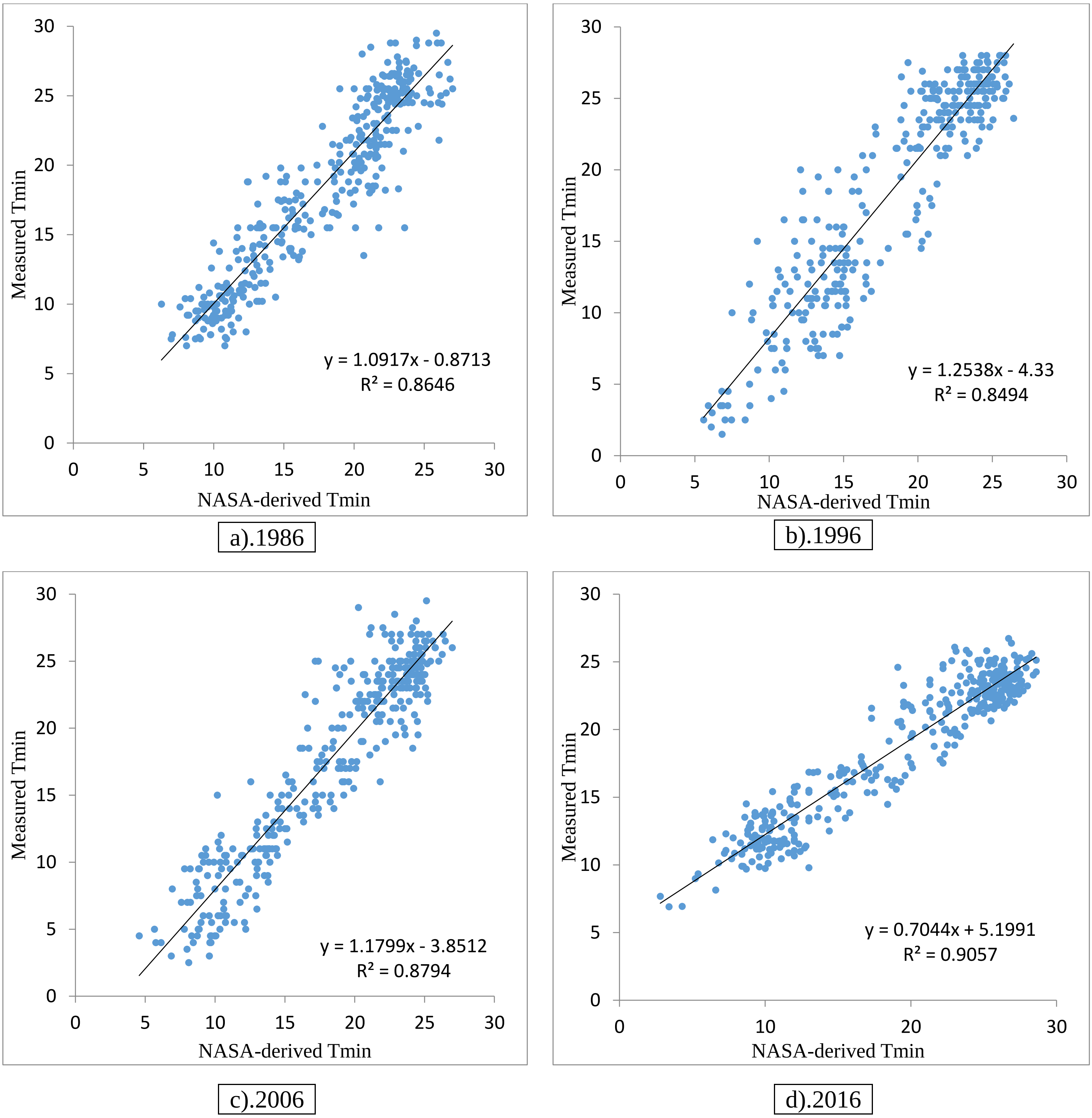
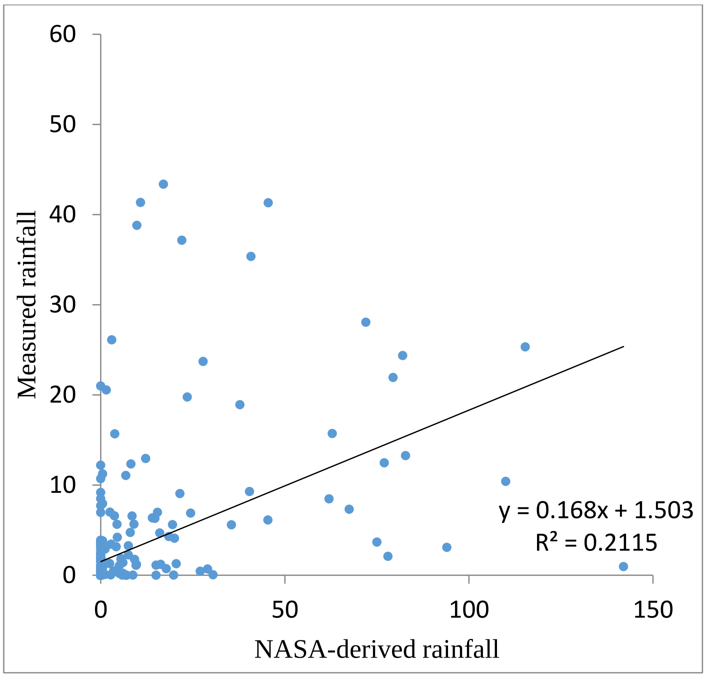
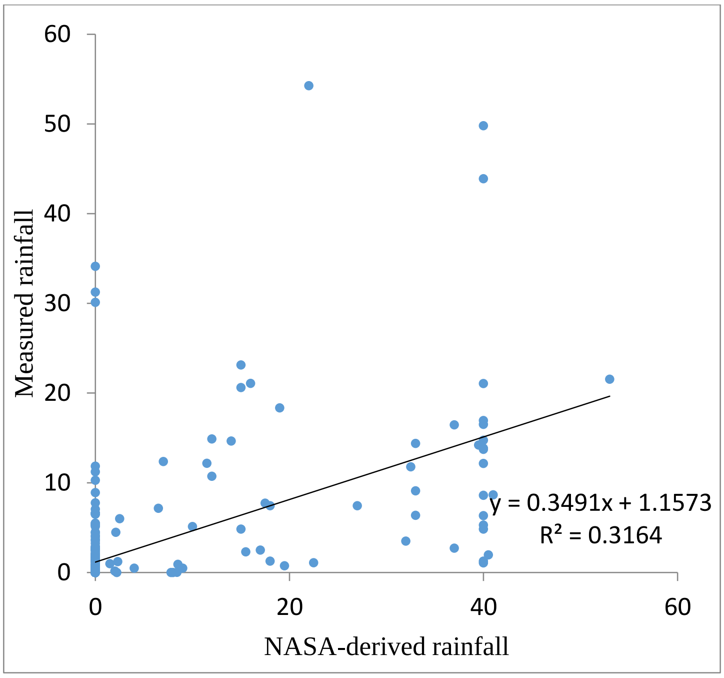


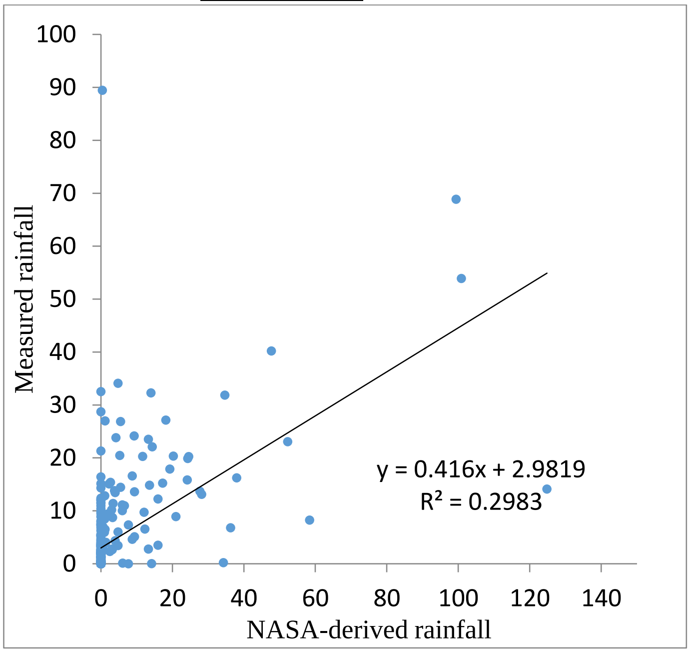
Figure 7 : (a,b,c,d) Comparison of NASA-derived and measured minimum temperature of four different years (1986, 1996, 2006 and 2016) at Taulihawa, Kapilvastu Nepal.



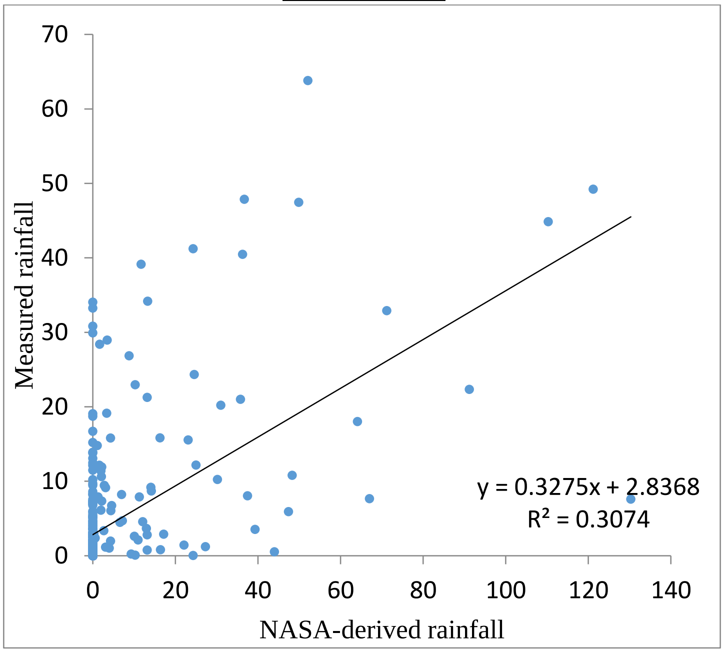
a).1986



b).1996



c) 2006



d). 2016

Figure 8 : (a,b,c,d) Comparison of NASA-derived and measured rainfall of four different years (1986, 1996, 2006 and 2016) at Taulihawa, Kapilvastu Nepal.

4.2 Trend analysis of historical agro-climatic indices and wheat yield

4.2.1 Analysis of Temperature

4.2.1.1 Mean temperature

Average temperature records from 33 years (1984-2017) shows decreasing trends at the Taulihawa, Kapilvastu district. Over the last 33 years the mean temperature decrease by 0.017˚C per year and the highest and lowest values of mean temperature are 24.5 in 2002 and 22.4 in 2013 respectively. Similarly the mean temperature at wheat growing seasons (October to April) of the 33 years also shows the decreasing trends. In this seasons mean temperatures decreases by 0.013˚C per year. According to Chand *et al.*, (2019) rate of increase of mean annual temperature ranges from 0.028 C to 0.035 C per year in Nepal. The time series of annual mean and mean temperature of wheat growing seasons including linear trends are depicted in figures 9 and 10.

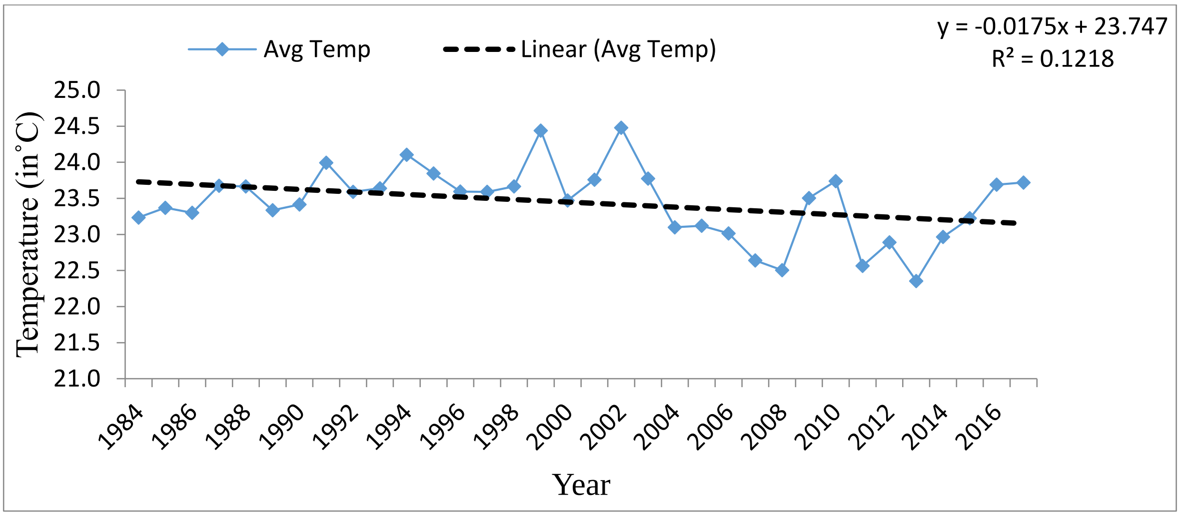


Figure 9: Average temperature of Taulihawa, Kapilvastu of 33 years (1984 to 2017)

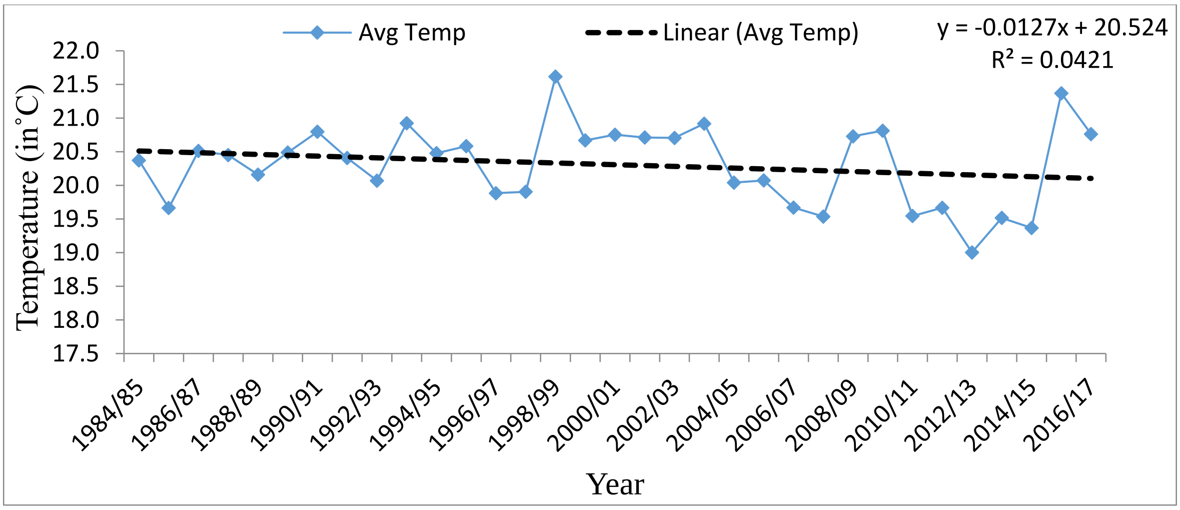


Figure 10: Average temperature of wheat growing seasons of Taulihawa, Kapilvastu of 33 years (1984 to 2017)

4.2.1.2 Maximum temperature:-

Both the annual and seasonal maximum temperature records from 33 years (1984-2017) shows decreasing trends. Over the last 33 years both annual and seasonal maximum temperatures are decreases by 0.046˚C per year and 0.042˚C per year respectively. The time series of annual mean and mean temperature of wheat growing seasons including linear trends are depicted in figures 11 and 12.

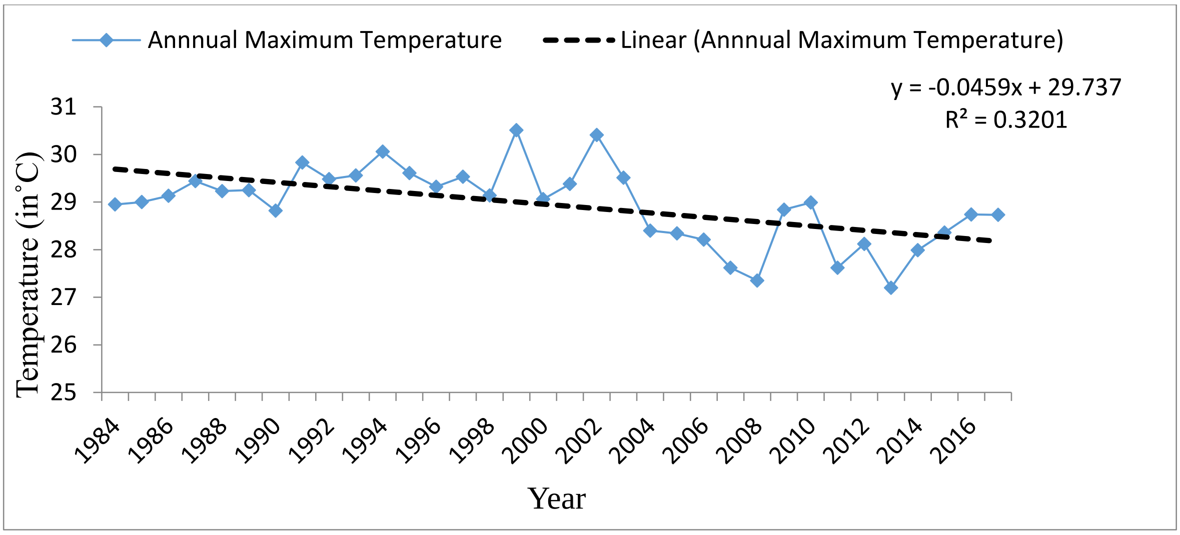


Figure 11: Annual maximum temperature of Taulihawa, Kapilvastu of 33 years (1984 to 2017)

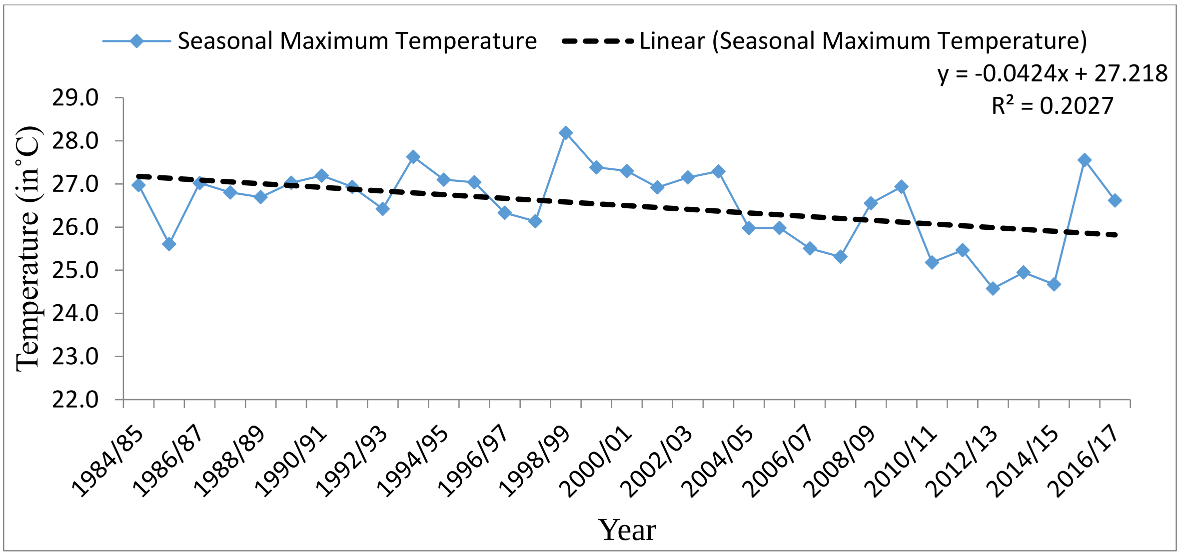


Figure 12: Seasonal maximum temperature of wheat growing seasons of Taulihawa, Kapilvastu of 33 years (1984 to 2017)

4.2.1.3 Minimum temperature:-

The minimum temperature of both annual and wheat growing season shows the increasing trends. The minimum annual and seasonal temperatures were increased by 0.011˚C per year and 0.016˚C per year respectively. The time series of annual minimum and minimum temperature of wheat growing seasons including linear trends were depicted in figures 13 and 14.

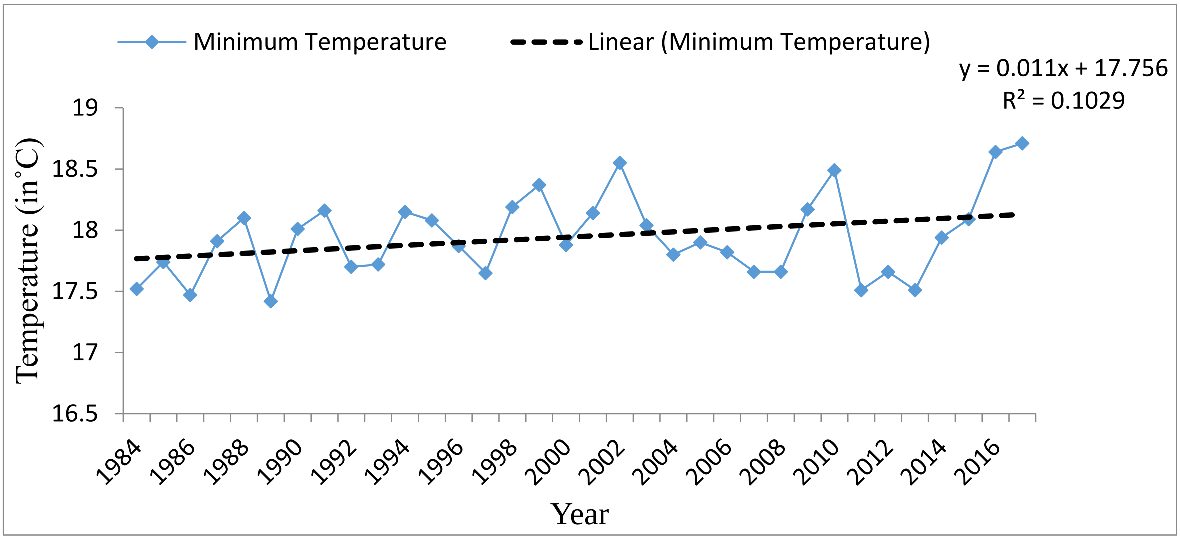


Figure 13: Annual minimum temperature of Taulihawa, Kapilvastu of 33 years (1984 to 2017)

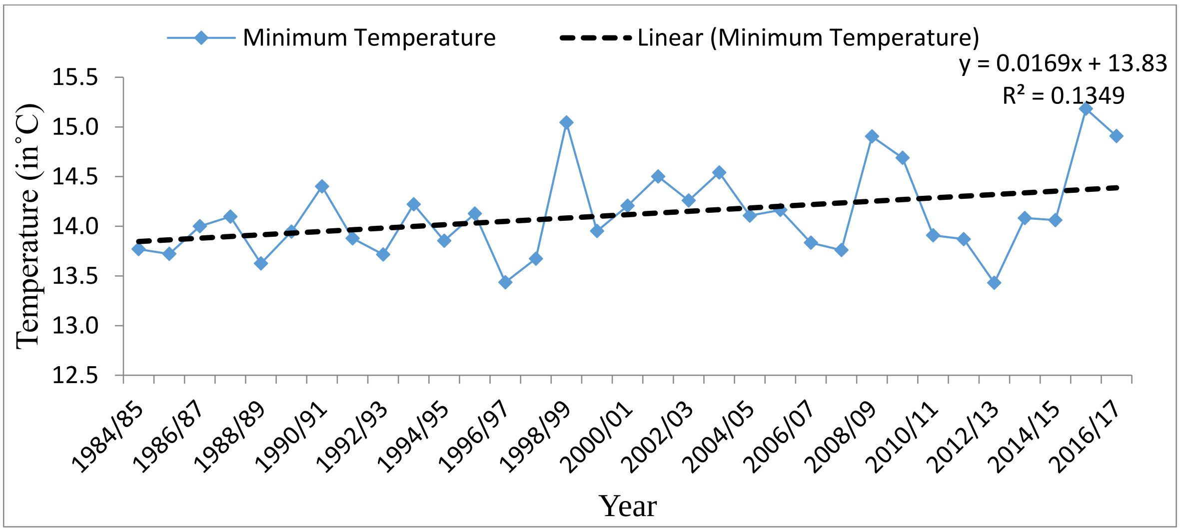


Figure 14: Seasonal minimum temperature of wheat growing seasons of Taulihawa, Kapilvastu of 33 years (1984 to 2017)

The mean, maximum and minimum temperatures were increasing in the case of Nepal. But maximum temperature trend was decreasing for Kapilvastu by 0.022˚C per year. Minimum temperature trend was found increasing 0.024˚C per year in Kapilvastu (Bhandari *et al.*, 2015).

4.2.3 Analysis of precipitation

The mean annual precipitation and mean precipitation of wheat growing seasons (October to April) was found as 1080.00 mm and 118.4 mm respectively. The precipitation of both annual and wheat growing season shows the increasing trends. The annual precipitation and seasonal precipitation were increased by 28.63mm per year and 3.68mm per year respectively. Annual precipitation in Nepal has increased with a rate of 8.7 mm/year with a major increase in monsoon season by 7.67 mm/year from 1979 to 2016

(Shrestha *et al.*, 2019). The time series of annual precipitation and precipitation of wheat growing seasons including linear trends were depicted in figures 15 and 16.

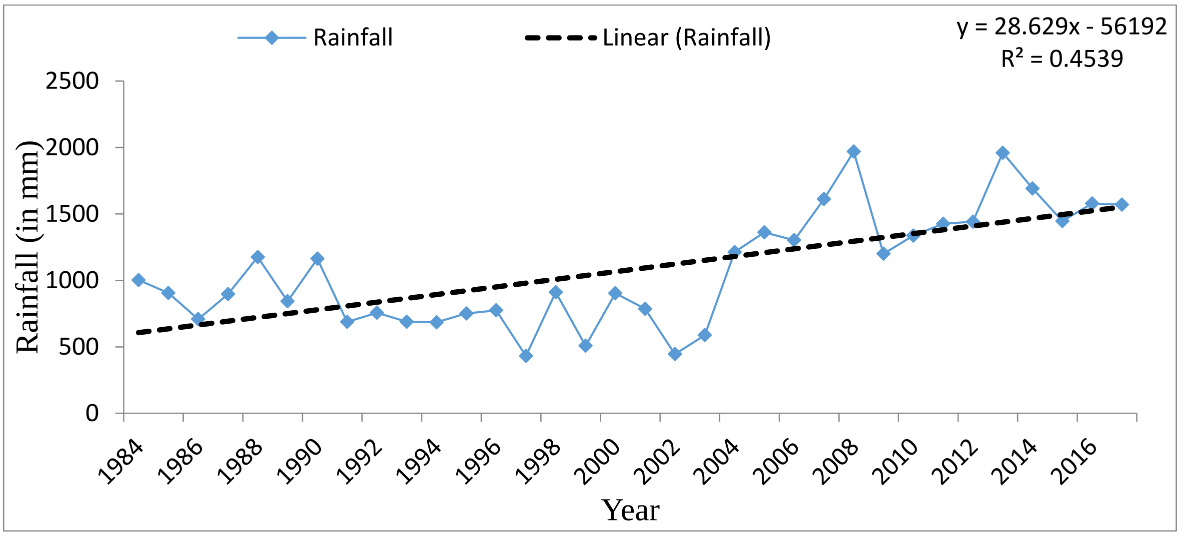


Figure 15: Annual precipitation of Taulihawa, Kapilvastu of 33 years (1984 to 2017)

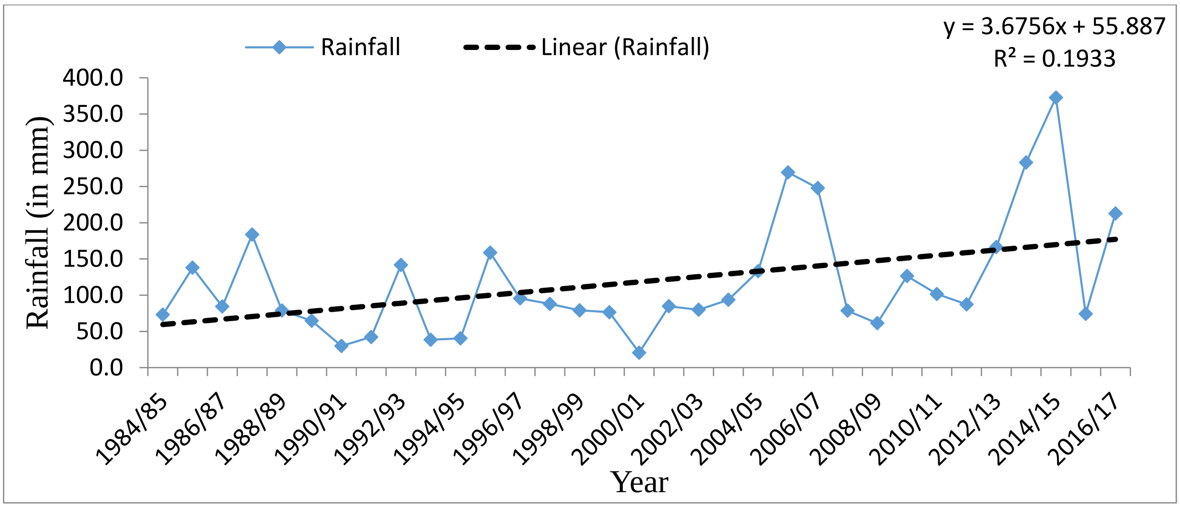


Figure 16: Seasonal precipitation of wheat growing seasons of Taulihawa, Kapilvastu of 33 years (1984 to 2017)

4.2.3 Analysis of solar radiations:-

Both the annual and seasonal solar radiations records from 33 years (1984 -2017) shows decreasing trends. Over the last 33 years both annual and seasonal radiations were decreases by 0.035 MJm^{-2} per year and 0.036 MJm^{-2} per year respectively. The time series of annual solar radiations and solar radiations of wheat growing seasons including linear trends were depicted in figures 17 and 18.

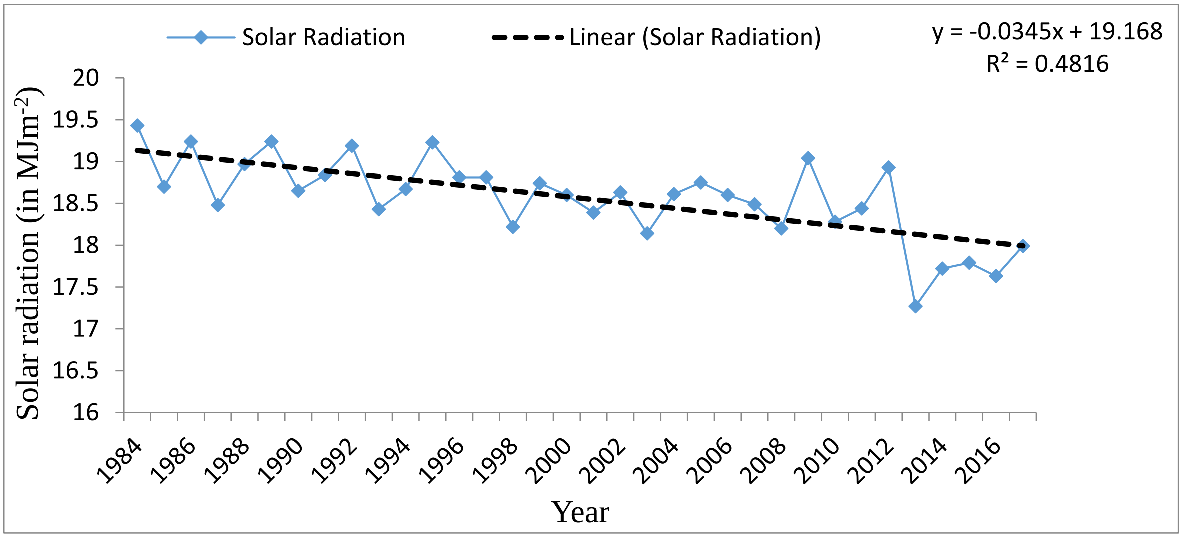


Figure 17: Annual solar radiation of Taulihawa, Kapilvastu of 33 years (1984 to 2017)

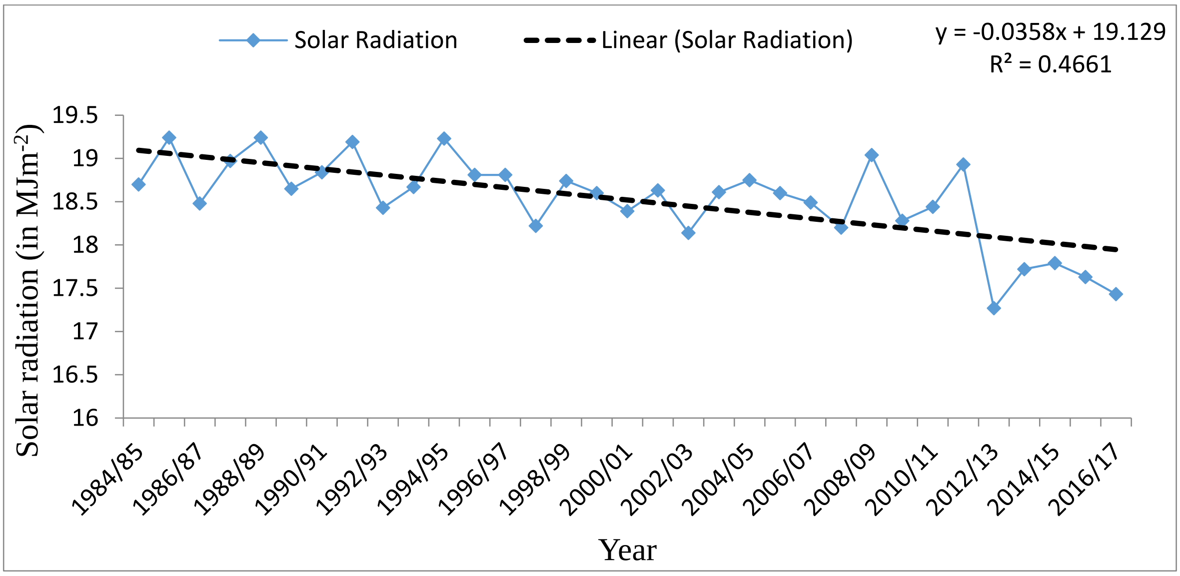


Figure 18: Seasonal solar Radiations of wheat growing seasons of Taulihawa, Kapilvastu of 33 years (1984 to 2017)

4.3 Impact of climatic indices on wheat yield

The study attempted to determine the impacts of climatic indices on wheat. The study focuses the correlation analysis between observed wheat yield and climatic indices of the wheat growing seasons (minimum and maximum temperature, rainfall and solar radiations). Similarly the yields obtained from the DSSAT also correlated with the same climatic indices.

4.3.1 Variability in temperature

The relationships between maximum and minimum temperature and wheat yields from observed and DSSAT simulations were analyzed. A relationship between wheat yield (both observed and DSSAT simulated) and temperature (both maximum and minimum) were shown in figure 19-22. It is well noticed that the effect of wheat yield is more dependent in minimum temperature then maximum temperature. Wheat yields showed the negative correlation for the maximum temperature. The correlation between the maximum temperature and observed wheat yield and DSSAT simulated yields were -0.461 and -0.208. That means increase in maximum temperature has large negative impacts on net wheat yield. Similarly correlations between the observed and simulated wheat yield and minimum temperature showed positive correlations; and values were 0.363 and 0.164 respectively.

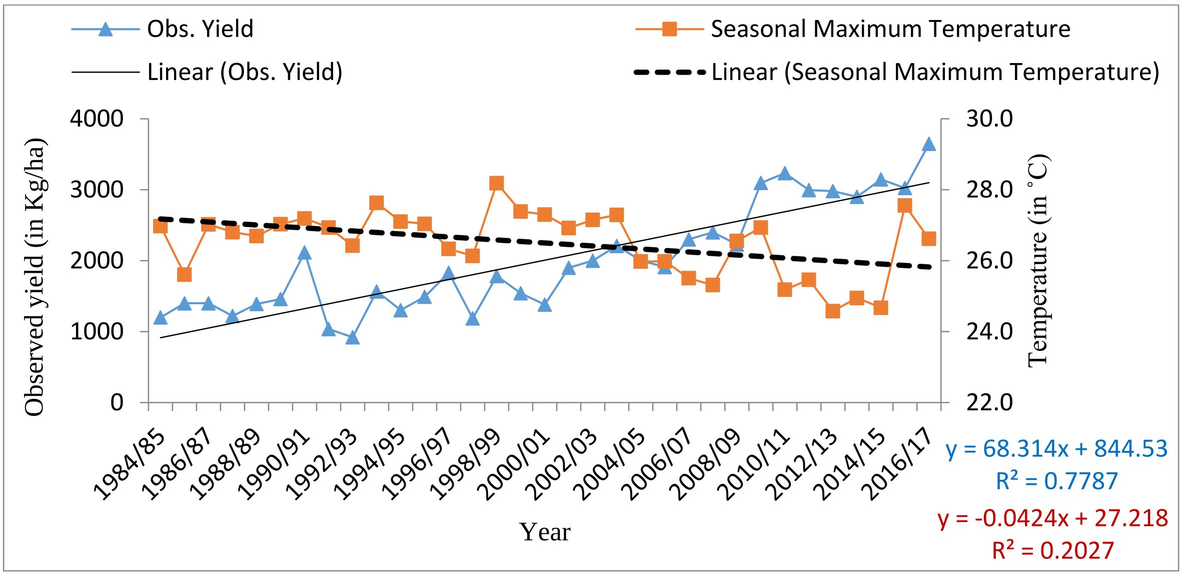


Figure 19: Relation between observed wheat yield and maximum temperature

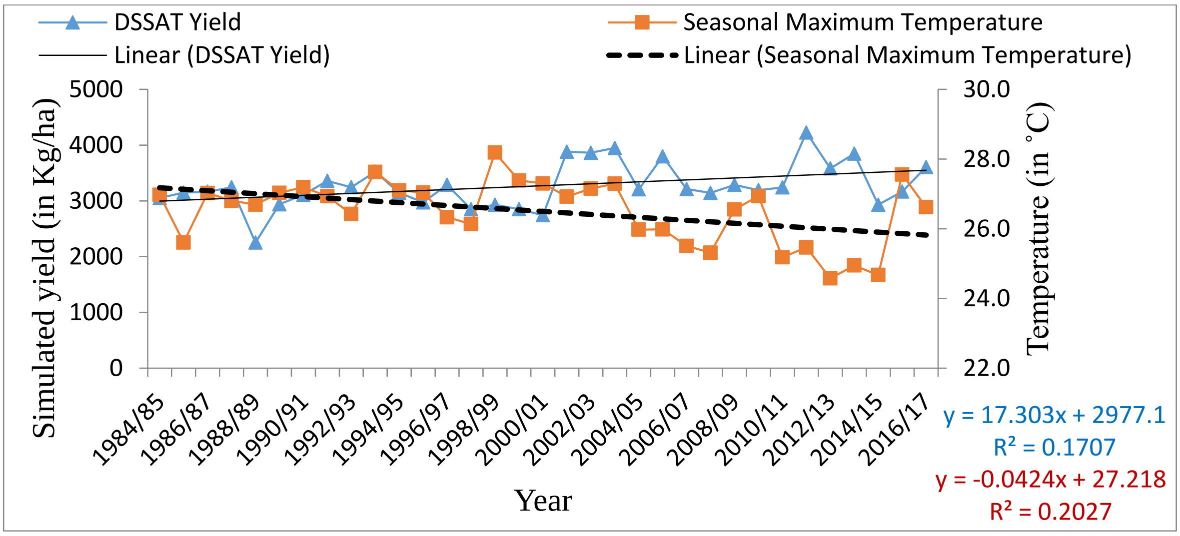


Figure 20: Relation between DSSAT simulated wheat yield and maximum temperature at Taulihawa, Kapilvastu

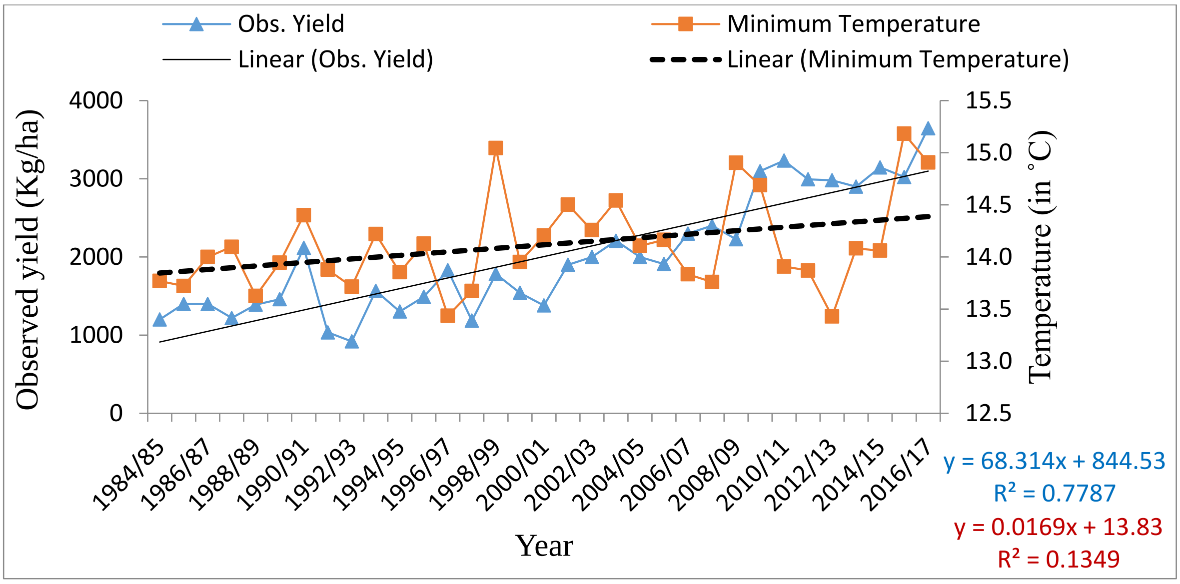


Figure 21: Relation between observed wheat yield and minimum temperature at Taulihawa, Kapilvastu

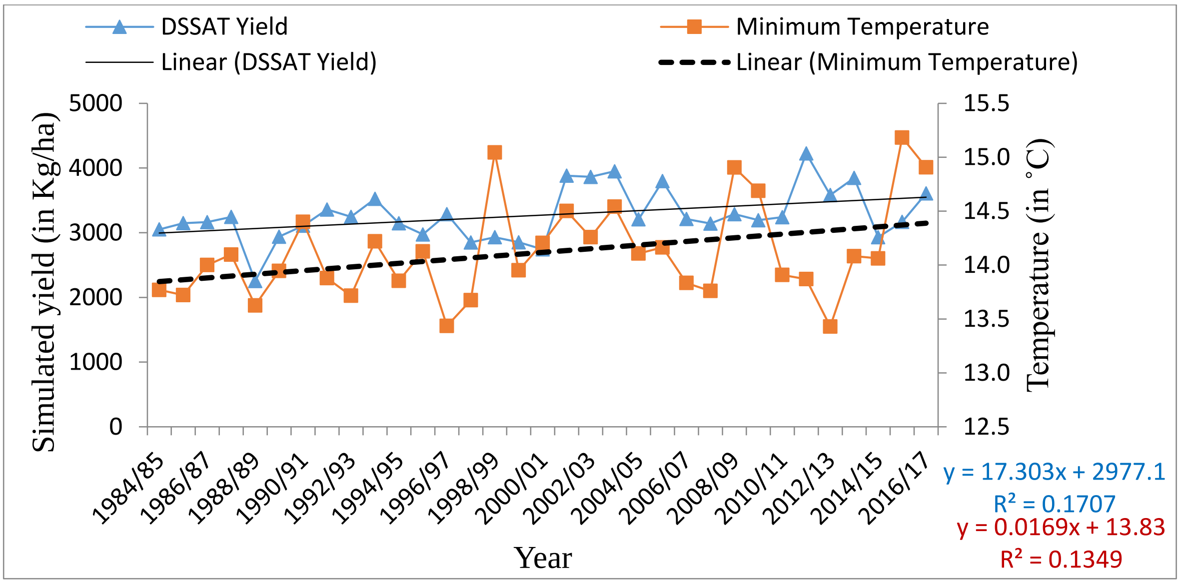


Figure 22: Relation between DSSAT simulated wheat yield and minimum temperature at Taulihawa, Kapilvastu

4.3.2 Variability in rainfall

The relationship between rainfall and wheat yield both observed yield and DSSAT simulated yields were analyzed. It was well noticed that the effect of wheat yield was depend on rainfall. Wheat yields showed the positive correlation for the rainfall. The observed yield showed the strong positive correlation in compare to the wheat yield from DSSAT simulation. The correlation between the rainfall and observed wheat yield and DSSAT simulated yields were 0.423 and 0.184. That means increase in rainfall had positive impacts on net wheat yield. A relationship between wheat yield (both observed and DSSAT simulated) and rainfall were shown in figure 23 and 24.

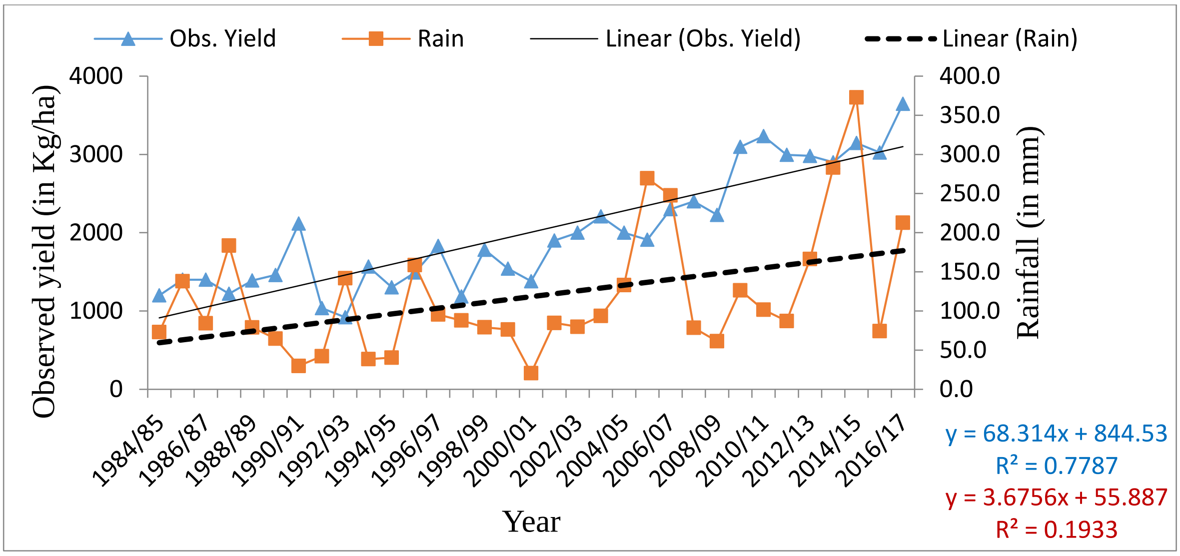


Figure 23: Relation between DSSAT simulated wheat yield and rainfall at Tauliwaha, Kapilvastu

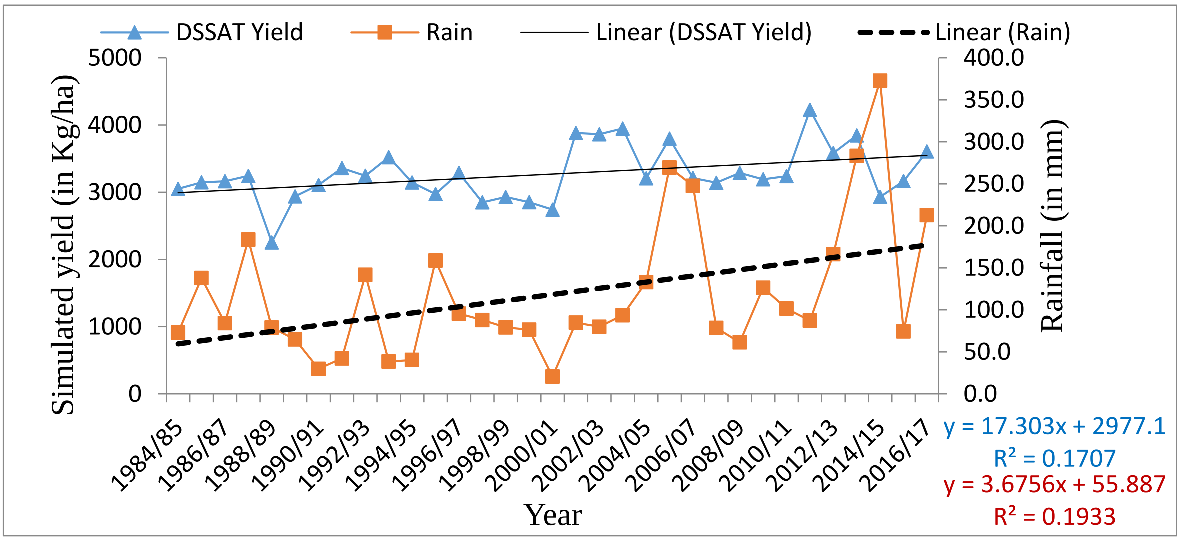


Figure 24: Relation between observed wheat yield and rainfall at Tauliwaha, Kapilvastu

4.3.3 Variability in solar radiations

The relationship between solar radiation and wheat yield both observed yield and DSSAT simulated yields were analyzed. It was well noticed that the effect of wheat yield was depend on solar radiation. Wheat yields showed the negative correlation with the solar radiation. The observed yield showed the strong negative correlation in compare to the wheat yield from DSSAT simulation. The correlation between the solar radiation and observed wheat yield and DSSAT simulated yields were -0.650 and -0.217. That means increase in solar radiation had negative impacts on net wheat yield. A relationship between wheat yield (both observed and DSSAT simulated) and solar radiation were shown in figure 25 and 26.

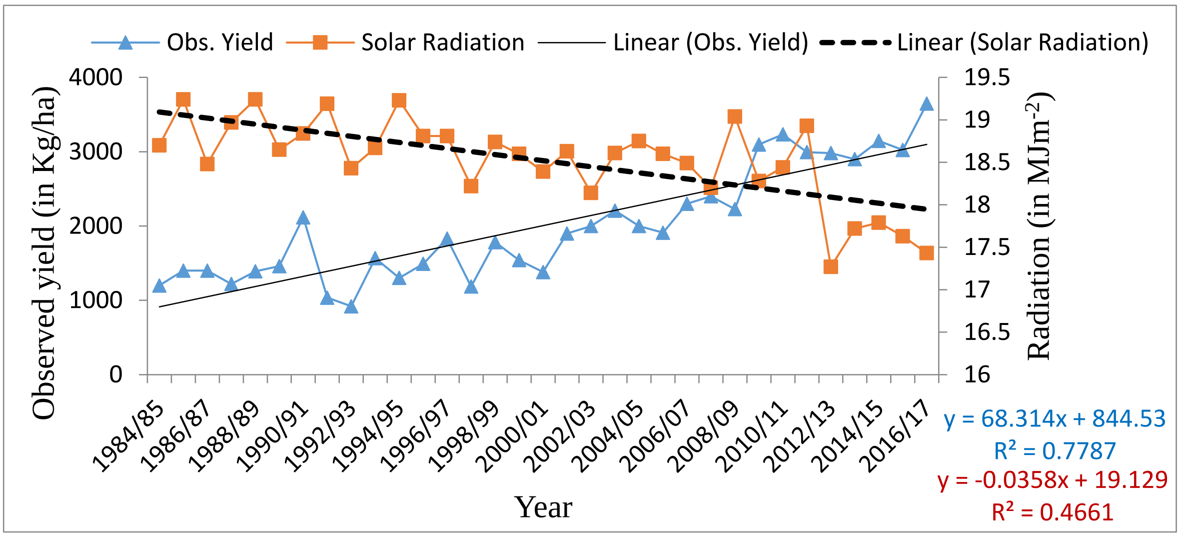


Figure 25: Relation between observed wheat yield and solar radiation at Tauliwaha, Kapilvastu

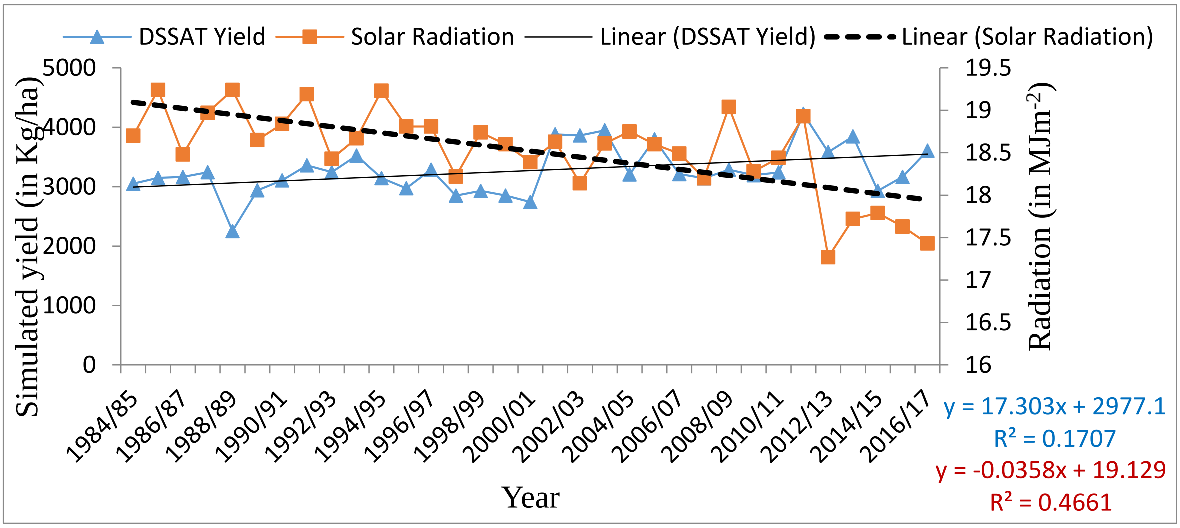


Figure 26: Relation between DSSAT simulated wheat yield and solar radiation at Tauliwaha, Kapilvastu

4.4 Sensitivity analysis

CERES-Wheat was run for to study sensitivity analysis to different weather years and climate change scenarios. For this WK-1204 variety f wheat was used.

4.4.1 Sensitivity to weather years

CERES-Wheat was run for the standard treatment using 5 years of weather data (1984/85, 1991/92, 1998/99, 2005/06 and 20014/15) (Table 2, Figure 27, 28, 29). The simulated yields were sensitive to various weather years. It was revealed that there was 30% yield increased was observed in the year of 2005/06. It was revealed that there was 2% yield declined in WK-1204 in the year of 1998/99. In 1991/92 increased yield 15% was observed in WK-1204. Similarly only 4% yield was observed in the year 1984/85 which was lower in comparison of other years. It was found that average temperature was lower in the year of 2005/06, which increased maturity days of WK-1204. Similarly Rainfall and Solar radiation was highest in 2005/06 which resulted in highest yield. Singh and Padila (1995) reported that decreased temperature increase wheat yield significantly.

Table 2: Sensitivity of simulated yield and phenology of wheat cultivar WK-1204 to weather years

	Weather years	Simulated yield (kg/ha)	Percent yield
WK-1204	20014/15[a]	2931	100
	2005/06	3798	130
	1998/99	2852	98
	1991/92	3359	115
	1984/85	3051	104

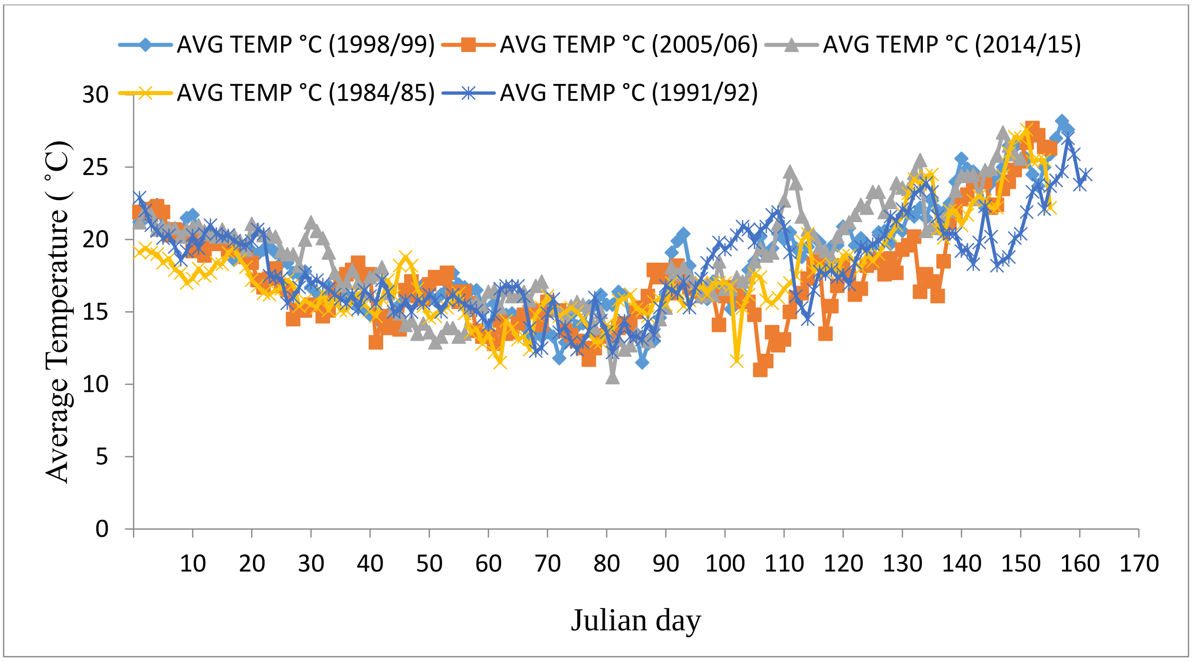


Figure 27: Daily average temperature (˚C) during wheat growing season

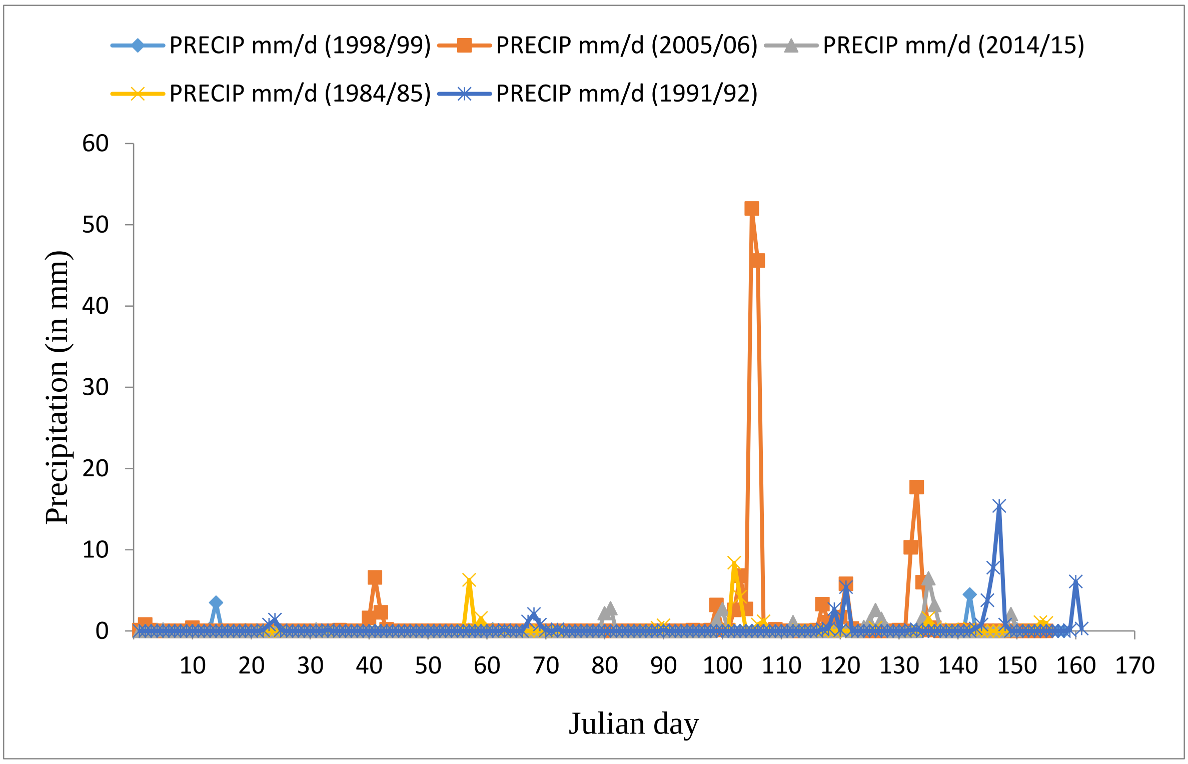


Figure 28: Daily rainfall (mm) during wheat season

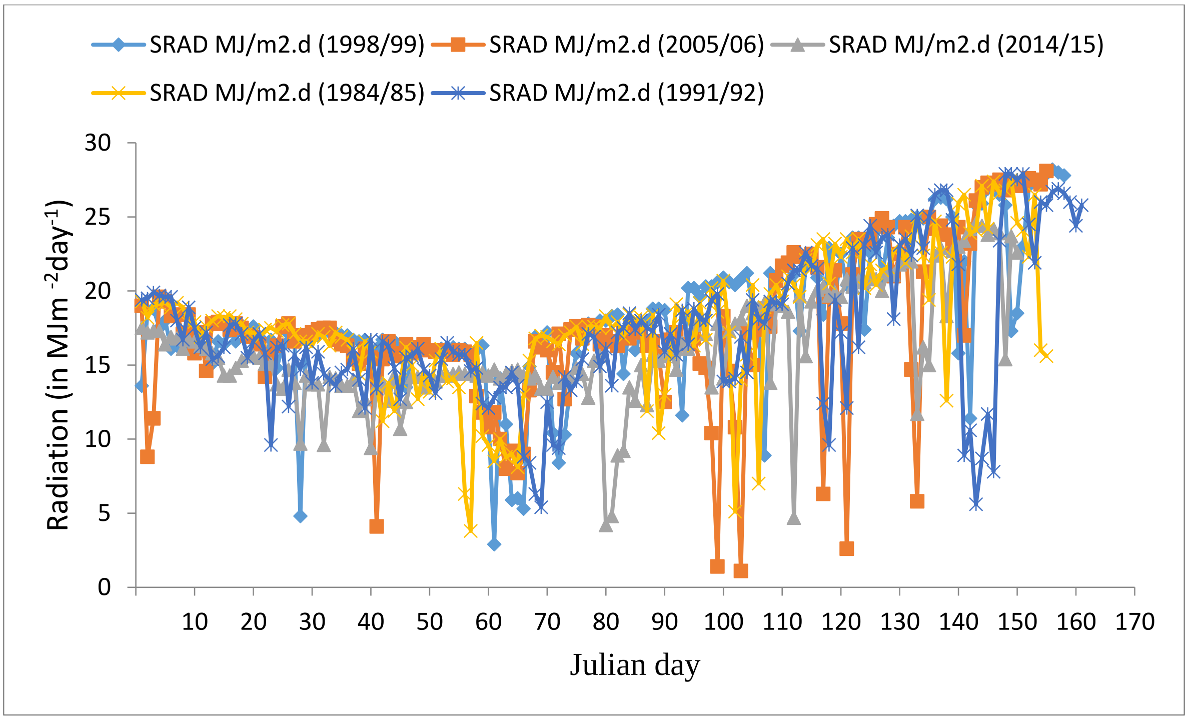


Figure 29: Daily solar radiation ($MJm^{-2}day^{-1}$) during wheat season

4.4.2 Effect of changing climatic scenarios on wheat yield

Various scenarios of temperature, carbon dioxide concentration and solar radiation were selected for running sensitivity analysis of yields simulated by CERES-Wheat for WK-1204 cultivar (Table 3). Compared to simulated yield of standard treatment, the decrease in yield was 61 for WK-1204, with the increase in both maximum and minimum temperature by 4˚C but decrease in both maximum and minimum temperature by 4˚C yield was increased by 6%. Elevated CO_2 by 20 ppm along with increased temperature had resulted in decrease in grain yield by 54%. But, in combination with decreased temperature, there was increased in yield by 9%. Simulated grain yield was found to be decreased by 62% when there was increased in 1 $MJm^{-2}day^{-1}$ solar radiation along with the increased temperature (by 4˚C) and CO_2 concentration (by 20 ppm). Decrease in yield by 57% with the decrease in solar radiation by 1 $MJm^{-2}day^{-1}$ along with increase in temperature (by 4˚C) and CO_2 concentration (by 20 ppm). Under decreased temperature (by 4˚C), increased CO_2 concentration (by 20 ppm), changes in solar radiation amount 1 $MJm^{-2}day^{-1}$had increased the simulated yield. Yield was increased by 4% for 1 $MJm^{-2}day^{-1}$ increase in solar radiation and by 12%, for 1 $MJm^{-2}day^{-1}$ decrease in solar radiation.

Table 3: Sensitivity analysis of wheat cultivar WK-1204 with changes in temperature, solar radiation and CO_2 concentration

Max Temp (˚C)	Min temp (˚C)	CO_2 conc. (ppm)	Solar radiation ($MJm^{-2}day^{-1}$)	Simulated yield (kg/ha)	% yield change
+0[a]	+0	390	+0	3673	100
+4	+4	390	+0	3261	89
-4	-4	390	+0	5641	154
+4	+4	+20	+0	3323	59
-4	-4	+20	+0	5761	102
+4	+4	+20	+1	3281	57
+4	+4	+20	-1	3358	58
-4	-4	+20	+1	5589	166
-4	-4	+20	-1	5960	177

[a] Standard year

Under increased temperature condition (along with elevated CO_2 and increased or decreased solar radiation), the yield of wheat cultivars was found decreased. Likewise, it was found to be increased in yield for decreased in maximum and minimum temperature by 4˚C (Table 3). Temperature primarily affected growth duration with lower temperature increasing the length of time that the crop could intercept radiation. Amgain *et al*. (2006)

reported that increase in minimum and maximum temperature by 4˚C over the base scenario decreased the wheat yield by 4%. Reduction of minimum and maximum temperature by 4˚C and increase in CO_2 by 20 ppm showed increase in yield (Amgain *et al*., 2006; Amgain *et al*, 2019). Decreased CO_2 concentration and increased temperature increased growth duration and yield, while increased temperature shortened growth duration and reduced leaf area, biomass and yield (Qureshi and Iglesias, 1994); Timsina *et al*, 1997). At elevated CO_2, light intensity positively affects photosynthesis and increased temperature promotes both photosynthesis and leaf area as reported by Imai and Murata (1979). The increased temperature and reduced solar radiation decreased the net photosynthetic active radiant (PAR) interception. The less interception of PAR caused lower assimilate formation in wheat and produced lower yield under increasing temperature and reduced light which was reported by Amgain *et al*. (2006). Increasing temperatures reduced growth duration, and probably decreased photosynthesis, increased water use, and reduced water use efficiency as reported by Imai (1988). Increased CO_2 concentration and decreased temperature increased growth duration and yield, while increased temperature shortened growth duration and reduced leaf area, biomass and yield (Timsina *et al*., 1997; Rao and Sinha, 1994; Qureshi and Iglesias, 1994).

4.4.3 Multi-year prediction of wheat yield as influenced by changing climatic scenarios as given by IPCC (2007)

The model was sensitive to various scenarios of climate change parameters (temperature, solar radiation and CO_2 concentrations). Change in maximum and minimum temperatures by 1˚C (+ 1˚C) and CO_2 concentrations 370 ppm (+0 ppm) with no change in solar radiation resulted increase in yield of WK-1204 by only 2 percent (Table 4). The maximum and minimum temperature was increased by 1˚C and CO_2 concentrations added 50pmm (420ppm) with change in solar radiation (+1 $MJm^{-2}day^{-1}$) resulted increase in yield by 6 percent, which is the maximum increment in wheat due to climate change. The temperature increased further will decrease the wheat yield. The temperature increased by 2˚C the yield decreased by 8 percent, similarly increased in temperature by 3˚C and CO_2 concentration 470 (+50)ppm the yield will be minimum, declined by 15%. While the maximum increase in the maximum and minimum temperatures by 4˚ C along with 100 and 200 ppm CO_2 concentration showed the yield decline of 14 percent than the standard model treatment (without changing the weather parameters). This reflected that the wheat is more sensitive to the adverse climatic variability. The existing wheat cultivar could not sustain the yield potential of the present level in future after 2020 and hence it should be opined to adopt the climate change adaptation or mitigation strategies over the long-run. Increased CO_2 concentrations would reduce transpiration and nutrient losses and increase water, nutrient and radiation use efficiencies and that might have increased yield under decreasing temperature. Similar result was also resulted by Bhusal *et al.*, (2009), Singh and Padilla (1995). An increase of temperature of the order of 3°C or more cancels out the beneficial effects of elevated CO_2 in all the cultivars under study (Attri, S. D. and Rathore, L. S., 2003)

Table 4: Sensitivity analysis of wheat as according to the different climate change scenarios for 2020, 2050 and 2080

S. No	Max Temp (in ˚C)	Min Temp (in ˚C)	Solar radiation ($MJm^{-2}day^{-1}$)	CO_2 Conc. (ppm)	Simulated Yield (Kg/ha)	% Yield change
1.[a]	+0	+0	+0	370	4471	100
2.	+1	+1	+0	370	4582	102.5
3.	+1	+1	+1	+50 (420)	4755	106.4
4.	+2	+2	+1	+50 (420)	4107	91.9
5.	+3	+3	+1	+100 (470)	3797	84.9
6.	+3	+3	+1	+200 (570)	4114	92.0
7.	+4	+4	+1	+200 (570)	3861	86.4

Note: [1a] : Standard climatic conditions (model default), 2, 3 & 4: Climate change scenario 2020, 5 & 6:. Climate change scenario 2050 and 7: Climate change scenario 2080 as given by IPCC (2007).

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 Summary

The weather data of 33 years (1984-2016) derived from the NASA-Power was validated with the ground station data (observed data) provided by the DHM. Although the, R^2 values were less than desired, the scatter diagram show similar trends and patterns, indicating a close relationship between NASA-derived and actual ground measured data, especially for temperature. Due to lack of solar radiation data we cannot validate it and we used the data derived from (NASA Power).

To check the pattern of temperature, precipitation and solar radiation, we read the trend analysis. We used annual wheat yield data as well as the wheat growing season's weather data of temperature, total precipitation and solar radiations. The patterns were almost same for annual and seasonal data. The annual mean temperature and maximum temperature were in decreasing trend. The mean and maximum temperatures were decreased by 0.02˚C per year and 0.049˚C per year, whereas the minimum temperature was increasing and increased by 0.007˚C. Similarly the precipitation was in increasing trend and solar radiation was in decreasing. The total precipitation was increased by 28.52mm per year and solar radiation was decreased by 0.034 MJm^{-2} per year.

The impact agro climatic indices on wheat yield were observed. Both observed yield and DSSAT simulation yield were used to see the relationship. Correlation coefficient and regression analysis is done individually with the climatic indices (max, min temperature, precipitation and solar radiations). Comparatively the regression between DSSAT simulated yield and agro climatic indices were less than observed yield with agro climatic indices. Maximum temperature has negative correlation with the observed wheat yield and minimum temperature had positive correlation. The correlation coefficient of maximum and minimum temperature and wheat yield were -0.512 and 0.272 respectively, whereas with DSSAT simulated yields were -0.214 and 0.123 respectively. Similarly the correlation between wheat yield and precipitation had positive and solar radiation had negative correlation. The correlation between precipitation and observed and DSSAT simulated yield were 0.379 and 0.158 respectively. The correlation between the solar radiation and observed wheat yield and DSSAT simulated yields were -0.587 and -0.176.

We used already calibrated and validated CSM-CERES-Wheat model, DSSAT ver. 4.7. The determined genetic coefficients for WK-1204 it was 3 (P1V), 39 (P1D), 315 (P5), 40 (G1), 71 (G2), 0.9 (G3) and 64 (PHINT).

By running sensitivity analysis, the model was found sensitive to weather years and various parameters of climate change. In the 1998/99, decrease in yield was observed. In the year 1984/85 and 1991/92 increased yields was found. The maximum yield was observed in the year 2005/06 as compare to the year 2015/16.

Increase in minimum and maximum temperature by 4˚C decreased the wheat yield whereas decrease of temperature by same amount increases the yield. Change in temperature (-4˚C), CO_2 concentration (+20 ppm) with change in solar radiation (-$MJm^{-2}day^{-1}$) resulted maximum increase in yield WK-1204 by 12%. Similarly change in temperature (+4˚C), CO_2 concentration (+20 ppm) with change in solar radiation (+$MJm^{-2}day^{-1}$) resulted decrease in yield by 62%.

DSSAT model was also used to multi-year prediction of wheat yield. The wheat yield was on decreasing on the future. By increasing 1˚C maximum and minimum temperature and CO_2 concentration by 420 ppm (+50 ppm) with change in solar radiation (+$MJm^{-2}day^{-1}$) resulted maximum increase in yield of WK-1204 by 6%. After that the wheat yields was in decreasing. While, the maximum increase in the maximum and minimum temperatures by 4˚C along with 100 and 200 ppm CO_2 concentration showed the yield decline up to 16 percent.

5.2 Conclusion

It has been overlooked that the NASA (Power) weather data can be safely used for studying climate change effect on crop yields if the observed data are missing due to some technical reasons. Increasing temperature had negative effects on the wheat yield, so we have to develop new variety of wheat tolerant to heat stress. To achieve the higher productivity and increasing demand of the wheat, we should follow the climate change adaptation studies. For wider application of models and using it for better decision support system, there is a real need of further testing and verification of model in large agro-ecological areas of Nepal with multi-year seasonal, rotational and spatial analysis.

5.3 Recommendations

The following recommendations can be drawn from the results and discussion made in the previous chapters.

- ❖ It is recommended that for the validation process the proper plantation of crop in an experimental plot or field may give better results.
- ❖ For the multiyear prediction, the new and latest IPPC scenarios can be used, which gives better results. Due to unavailability of downscaled latest scenarios we simply used IPCC (2007) scenarios for our study.
- ❖ As it is the first instance of using the DSSAT model in the meteorological field; lots of queries remained that must be sorted out.

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APPENDICES

Appendix 1: Annual weather condition of Kapilvastu during 1984 to 2017 [NASA (Power) Derived weather]

Year	Mean temp (˚C)	Max. temp (˚C)	Min temp (˚C)	Rainfall (mm)	Solar Radiation (MJ/m^2)
1984	23.2	29.0	17.5	1002.6	19.4
1985	23.4	29.0	17.7	905.0	18.7
1986	23.3	29.1	17.5	708.4	19.2
1987	23.7	29.4	17.9	896.0	18.5
1988	23.7	29.2	18.1	1176.0	19.0
1989	23.3	29.3	17.4	843.4	19.2
1990	23.4	28.8	18.0	1163.2	18.7
1991	24.0	29.8	18.2	688.2	18.8
1992	23.6	29.5	17.7	756.4	19.2
1993	23.6	29.6	17.7	688.4	18.4
1994	24.1	30.1	18.2	684.8	18.7
1995	23.8	29.6	18.1	751.3	19.2
1996	23.6	29.3	17.9	774.8	18.8
1997	23.6	29.5	17.7	431.6	18.8
1998	23.7	29.1	18.2	911.1	18.2
1999	24.4	30.5	18.4	507.9	18.7
2000	23.5	29.1	17.9	903.6	18.6
2001	23.8	29.4	18.1	785.8	18.4
2002	24.5	30.4	18.6	445.3	18.6
2003	23.8	29.5	18.0	588.3	18.1
2004	23.1	28.4	17.8	1213.1	18.6
2005	23.1	28.3	17.9	1361.3	18.8
2006	23.0	28.2	17.8	1302.4	18.6
2007	22.6	27.6	17.7	1611.5	18.5
2008	22.5	27.4	17.7	1968.9	18.2
2009	23.5	28.8	18.2	1200.4	19.0
2010	23.7	29.0	18.5	1336.7	18.3
2011	22.6	27.6	17.5	1425.9	18.4
2012	22.9	28.1	17.7	1441.5	18.9
2013	22.4	27.2	17.5	1960.2	17.3
2014	23.0	28.0	17.9	1691.7	17.7
2015	23.2	28.4	18.1	1446.4	17.8
2016	23.6	28.7	18.6	1578.2	17.6
2017	23.7	28.7	18.7	1570.1	17.9

Appendix 2: Seasonal weather condition of kapilvastu during 1984/85 to 2015/16 [NASA (Power) Derived weather].

Year	Mean temp (˚C)	Max. temp (˚C)	Min temp (˚C)	Rainfall (mm)	Solar Radiation (MJ/m^2)
1984/85	20.4	27.0	13.8	73.1	18.7
1985/86	19.7	25.6	13.7	137.9	19.2
1986/87	20.5	27.0	14.0	84.3	18.5
1987/88	20.5	26.8	14.1	183.6	19.0
1988/89	20.2	26.7	13.6	78.9	19.2
1989/90	20.5	27.0	13.9	64.8	18.7
1990/91	20.8	27.2	14.4	29.8	18.8
1991/92	20.4	26.9	13.9	42.2	19.2
1992/93	20.1	26.4	13.7	141.8	18.4
1993/94	20.9	27.6	14.2	38.5	18.7
1994/95	20.5	27.1	13.9	40.4	19.2
1995/96	20.6	27.0	14.1	158.6	18.8
1996/97	19.9	26.3	13.4	95.5	18.8
1997/98	19.9	26.1	13.7	87.9	18.2
1998/99	21.6	28.2	15.0	79.1	18.7
1999/00	20.7	27.4	14.0	76.4	18.6
2000/01	20.8	27.3	14.2	20.6	18.4
2001/02	20.7	26.9	14.5	84.8	18.6
2002/03	20.7	27.2	14.3	79.9	18.1
2003/04	20.9	27.3	14.5	93.6	18.6
2004/05	20.0	26.0	14.1	133.1	18.8
2005/06	20.1	26.0	14.2	269.5	18.6
2006/07	19.7	25.5	13.8	247.7	18.5
2007/08	19.5	25.3	13.8	78.5	18.2
2008/09	20.7	26.6	14.9	61.3	19.0
2009/10	20.8	26.9	14.7	126.4	18.3
2010/11	19.5	25.2	13.9	101.6	18.4
2011/12	19.7	25.5	13.9	87.2	18.9
2012/13	19.0	24.6	13.4	166.3	17.3
2013/14	19.5	24.9	14.1	283.2	17.7
2014/15	19.4	24.7	14.1	372.8	17.8
2015/16	21.4	27.6	15.2	74.3	17.6
2016/17	20.8	26.6	14.9	212.8	17.4

Appendix 3: Both observed and DSSAT Simulated wheat yield data from 1984/85 to 2015/16.

Year	Observed Yield (Kg/ha)	DSSAT Simulated Yield (Kg/ha)
1984/85	1200.0	3051
1985/86	1400.0	3148
1986/87	1400.0	3164
1987/88	1220.0	3244
1988/89	1390.0	2253
1989/90	1460.0	2939
1990/91	2117.0	3108
1991/92	1036.0	3359
1992/93	920.0	3245
1993/94	1566.9	3523
1994/95	1302.3	3145
1995/96	1491.3	2974
1996/97	1830.6	3288
1997/98	1186.0	2850
1998/99	1783.1	2930
1999/00	1541.3	2852
2000/01	1380.1	2742
2001/02	1900.0	3882
2002/03	2000.0	3863
2003/04	2208.0	3949
2004/05	2000.0	3207
2005/06	1910.0	3798
2006/07	2300.0	3212
2007/08	2400.0	3142
2008/09	2228.1	3287
2009/10	3096.8	3193
2010/11	3233.4	3241
2011/12	2994.3	4226
2012/13	2981.6	3583
2013/14	2900.0	3847
2014/15	3146.0	2931
2015/16	3024.0	3167
2016/17	3647.0	3606

Appendix. 4: Minimum data required for operation and evaluation of CSM-CERES-Rice Model

1. Operation

- Site -latitude, longitude, elevation, slope, aspect, water table depth.
- Weather -daily maximum and minimum temperatures, global solar radiation, rainfall, wind, dew point, temperatures or relative humidity.
- Soil -classification using the local system and (to family level) the USDA-NRCS taxonomic system, root growth factor, drainage coefficient.
- Physical properties - Depths of layers; percentages of sand, silt, and clay, and bulk density at various depths; moisture content at lower limit (LL, 15 bars), drained upper limit (DUL, 1/3 bar), and at saturation (SAT) for various depths.
- Chemical properties - pH; organic C; total N; CEC
- Initial conditions -C:N ratio and weight of root and shoot residues of previous crop incorporated or retained in field; date and depth of residue (material type, amount, and N concentration) incorporation; soil water, and KCl extractable ammonium and nitrate N by soil layer); in-crop season (ammonium and nitrate N); between phases (organic C and total N); tillage practice.

2. Management

Establishment - Dates of planting/transplanting; age of transplants; seedling (seedbed) environment temperature; plant population (number of plants for DSR; number of seedlings per hill for TPR)

- Water - Bunding (date, and depth); flood water depth (date, and depth); depth of furrows and of flood water (for beds); irrigation amount and dates; date of water removal; percolation rate (beds- from bed surface and furrows); perched water table depth (beds- from bed surface and furrows)
- Others – N fertilizer schedules, source, amount, and depth and placement of incorporation

3. Calibration and validation (data from separate experiments)

- Phenological events: Date of emergence, PI, 50% heading, 50% flowering, physiological maturity (as identified by nodes and constant weight of grain), and harvest.
- Performance at harvest -grain and straw yields, panicles or spikes per unit area, grain number per panicle, grain weight, and N concentrations of grain and straw
- Number of leaves produced in main stem; LAI, canopy dry weight (also leaf, stem, and panicle weight separately), solar radiation interception, and N concentration in above-ground biomass at key stages such as end of tillering, 50% flowering, and maturity (beds - radiation interception at edges and in centers)
- Soil water content at various depths with time (beds - in bed centers and edges, and in furrows; during rice season - depth of water in furrows measured daily and immediately after and before irrigation)
- Soil nitrate and ammonium content at various depths with time (beds - in bed centres and edges, and in furrows).

Source: Hunt and Boote (1994)

Appendix-5: Genetic coefficients of WK-1204 variety of wheat.

Run no.	Genetic Coefficients							Simulated values		
	P1V	P1D	P5	G1	G2	G3	PHINT	A	P	G
1	3	39	315	40	71	0.9	64	119	152	3556

Observed: A, Anthesis=118 days; M, Maturity=152 days; G= Grain yield=3556 kg/ha

Appendix-6 'A' file (NPKV1503.WHA) used for CERES-Wheat model.

```
*EXP.DETAILS: NPKV1503WH WHEAT AT KAPILVASTU
! File last edited on day 12/31/2019 at 3:06:30 PM
@TRNO  HWAM  HWUM  H#AM  H#UM  LAIX  CWAM  BWAM  ADAT  MDAT
    1   3146 0.040  9438    39  4.27  7296  3740 15087 15121
```

Appendix-7: 'T' file (NPKV1503.WHT) Time series file

```
*EXP.DETAILS: NPKV1503WH WHEAT AT KAPILVASTU
! File last edited on day 01/01/2020 at 11:32:26 AM
@TRNO  DATE  LAID  SWAD  GWAD  LWAD  CWAD  T#AD

    1 14334    0   -99  3566   -99  7296   307
```

Appendix-8: 'W' file (NPKV2015.WTH) used for running experimental files in CERES-Wheat for Kapilvastu, Nepal

```
*WEATHER DATA : Kapilvastu, Nepal

@ INSI      LAT     LONG  ELEV   TAV   AMP REFHT WNDHT
  NPKV   27.550   83.067    95  23.4  15.0 -99.0 -99.0
@DATE  SRAD  TMAX  TMIN  RAIN  DEWP  WIND   PAR  EVAP  RHUM
15001   4.3  22.6  12.6   8.3
15002   2.6  19.9  13.3  11.8
15003   3.7  21.1  13.1  19.0
15004  12.0  20.7  10.5   2.0
15005   7.0  19.9   9.0   0.0
15006  10.7  18.5   8.0   0.0
15007  13.8  18.7   9.1   0.0
15008  14.0  19.3   8.2   0.2
15009   8.6  20.4   5.9   0.0
15010   6.2  18.6   7.6   0.0
15011   6.2  19.3   9.5   0.0
15012  10.4  19.2   8.5   0.0
15013  11.1  20.0   7.8   0.0
15014  14.4  19.6   9.1   0.0
15015  15.0  19.6  10.3   0.0
15016  12.1  19.5   8.4   0.0
15017   9.0  20.0   7.9   0.0
15018   8.3  19.9   7.5   0.0
15019   7.6  19.6   8.4   0.0
15020  13.0  19.3   9.0   0.0
15021  15.9  19.5   9.0   0.0
15022  14.3  21.9  10.8   0.9
15023  15.0  21.0  10.3   1.1
15024  16.3  21.6   9.8   0.0
15025   9.1  21.7  10.3   0.4
15026   5.9  19.0  10.8   0.3
15027  14.5  19.6  11.1   0.1
15028  16.3  21.7   9.8   0.0
15029  15.4  19.5   9.2   0.0
15030  11.7  19.1   7.2   0.0
15031  12.3  19.6   6.8   0.0
15032  16.2  19.9   8.2   0.0
15033  16.7  21.5   9.6   0.0
15034  16.9  23.5  11.7   3.6
15035  17.3  23.6  11.7   0.2
15036   9.2  21.9  11.0   0.1
15037  15.4  22.2  10.1   0.0
15038  16.4  23.2  10.2   0.0
```

15039	7.3	22.5	11.7	0.0
15040	17.5	23.4	11.5	0.0
15041	18.5	23.5	11.2	0.0
15042	11.2	23.2	10.9	0.0
15043	18.1	22.3	10.8	0.0
15044	17.6	22.8	11.0	0.0
15045	18.3	23.0	10.4	0.2
15046	17.5	22.5	11.6	0.9
15047	18.1	24.3	13.2	0.0
15048	18.8	22.9	13.8	0.0
15049	17.8	23.5	13.2	3.4
15050	18.0	24.5	14.1	1.3
15051	17.9	25.3	13.1	0.0
15052	17.4	27.1	14.6	0.0
15053	19.1	28.4	14.4	0.0
15054	18.1	27.3	16.1	0.0
15055	18.7	28.1	16.2	0.0
15056	14.5	26.4	17.1	0.0
15057	3.3	24.8	15.6	2.7
15058	20.2	26.9	15.0	0.1
15059	9.7	27.9	14.6	0.6
15060	1.9	19.4	13.8	13.9
15061	10.5	18.7	13.3	9.1
15062	19.0	21.4	12.4	20.8
15063	18.3	21.3	11.2	0.7
15064	21.3	23.4	9.5	0.0
15065	21.4	24.8	10.9	0.0
15066	21.6	25.8	11.6	0.0
15067	21.4	27.0	13.4	0.1
15068	21.8	28.8	14.0	0.1
15069	22.7	27.8	11.7	0.0
15070	22.6	28.6	12.8	0.0
15071	21.4	29.6	14.9	0.0
15072	19.7	29.8	15.7	0.1
15073	15.6	27.4	15.4	6.0
15074	4.6	27.5	15.1	4.9
15075	21.6	24.6	13.6	1.6
15076	22.7	27.5	15.0	0.0
15077	21.1	26.4	14.8	1.4
15078	22.9	27.4	12.9	0.1
15079	22.8	29.2	16.1	0.0
15080	23.0	29.8	16.3	0.0
15081	23.1	31.4	17.3	0.0
15082	23.0	31.8	18.3	0.0
15083	23.2	32.0	18.8	0.0
15084	23.2	31.5	20.0	0.0
15085	23.2	31.7	21.1	0.7

15086	20.2	29.0	20.6	20.1
15087	22.2	30.1	19.1	4.7
15088	19.8	31.1	19.0	0.5
15089	2.1	23.1	17.4	25.0
15090	23.9	27.7	16.1	0.0
15091	23.1	29.7	17.7	0.0
15092	23.7	31.6	18.0	0.2
15093	22.1	32.6	19.0	1.1
15094	11.8	29.3	18.1	2.5
15095	23.8	29.5	17.6	0.1
15096	24.7	30.3	16.4	0.0
15097	12.0	30.7	17.0	0.1
15098	25.1	30.8	17.7	0.0
15099	25.3	31.3	17.1	0.0
15100	25.4	32.8	18.3	0.0
15101	25.5	33.6	18.9	0.0
15102	10.0	32.3	18.7	0.9
15103	14.4	28.2	20.4	11.1
15104	18.4	26.2	19.6	1.1
15105	14.8	28.1	19.4	0.9
15106	24.5	30.9	19.4	0.2
15107	19.6	30.2	20.3	0.7
15108	25.0	32.2	18.6	0.4
15109	24.7	35.3	20.9	0.0
15110	23.9	34.4	21.4	0.2
15111	25.0	36.1	21.2	3.3
15112	26.5	35.6	20.7	3.5
15113	27.0	35.3	18.9	0.2
15114	21.3	34.4	20.4	1.4
15115	9.1	24.3	19.4	0.3
15116	24.9	28.1	17.0	0.1
15117	24.1	30.6	18.2	5.2
15118	8.0	28.9	19.7	18.1
15119	23.5	27.8	19.4	4.1
15120	23.5	30.6	18.8	5.8
15121	25.8	34.1	19.5	1.3
15122	26.2	33.6	21.0	9.8
15123	26.8	34.0	20.4	0.5
15124	27.3	35.7	18.9	0.0
15125	26.8	36.6	20.4	0.0
15126	26.6	36.8	21.1	0.0
15127	25.3	36.0	22.1	0.4
15128	24.2	36.5	22.8	0.0
15129	24.3	35.0	24.0	0.1
15130	23.6	36.6	22.1	1.8
15131	25.8	37.0	22.7	8.2
15132	21.3	34.4	21.8	3.1

15133	25.1	35.2	22.0	0.8
15134	25.6	33.9	22.7	0.0
15135	23.0	36.1	22.4	0.4
15136	17.5	35.6	23.5	0.6
15137	26.4	35.3	24.3	0.0
15138	19.1	35.0	24.2	0.9
15139	23.1	36.4	24.1	3.7
15140	23.2	38.1	23.6	2.9
15141	26.2	38.0	23.1	2.1
15142	27.8	40.0	22.8	0.0
15143	27.9	39.7	23.2	1.7
15144	27.2	39.9	24.0	0.4
15145	27.1	38.8	23.1	0.1
15146	26.9	38.9	23.6	1.3
15147	26.9	38.3	23.4	1.1
15148	26.3	37.7	23.3	0.4
15149	24.3	39.8	22.8	0.1
15150	25.0	38.4	22.7	8.3
15151	26.1	38.4	23.1	2.5
15152	26.3	39.2	23.9	0.7
15153	-99m	39.1	24.2	0.5
15154	26.2	39.6	23.7	1.1
15155	16.8	38.2	27.1	1.0
15156	26.7	38.7	26.1	0.0
15157	27.2	40.0	25.2	0.0
15158	26.6	40.2a	25.8	0.0
15159	27.1	40.9a	26.1	0.6
15160	26.4	41.3a	25.6	6.5
15161	21.7	41.6a	27.2	1.3
15162	17.6	36.6	26.7	16.6
15163	20.8	37.8	25.6	15.2
15164	21.8	36.3	25.7	7.5
15165	25.9	34.8	23.8	6.2
15166	22.5	32.7	24.9	19.9
15167	22.1	34.3	24.1	2.0
15168	24.4	35.5	25.2	1.0
15169	25.2	36.5	25.8	0.4
15170	22.8	34.8	25.9	5.4
15171	24.5	35.6	25.6	3.5
15172	24.4	34.0	25.6	9.2
15173	22.5	32.1	25.0	2.1
15174	20.6	36.6	24.2	5.7
15175	22.5	34.5	25.5	32.0
15176	13.8	31.9	24.3	45.0
15177	6.3	31.3	24.5	33.0
15178	14.3	33.7	23.1	8.0
15179	5.6	26.4	23.2	34.2

15180	17.2	29.7	22.1	6.0
15181	22.9	31.7	23.5	1.8
15182	16.8	32.0	24.8	1.6
15183	21.6	31.9	23.9	4.9
15184	19.3	34.1	24.7	2.0
15185	18.9	34.2	24.2	3.1
15186	6.3	34.0	25.2	44.2
15187	9.8	31.4	24.9	18.8
15188	13.2	30.4	24.0	4.0
15189	19.9	29.3	23.7	2.9
15190	18.3	32.1	24.1	6.9
15191	15.4	30.9	23.9	12.5
15192	6.7	27.0	23.0	13.3
15193	20.6	30.9	23.1	1.6
15194	19.1	31.2	23.1	1.4
15195	17.5	30.7	24.3	4.1
15196	7.6	29.5	24.3	50.2
15197	6.8	30.2	24.0	35.4
15198	21.8	30.4	23.4	4.3
15199	18.8	28.1	22.4	0.7
15200	21.6	30.9	21.9	6.3
15201	17.5	29.7	23.5	6.2
15202	21.9	29.9	22.8	3.4
15203	16.0	29.7	22.3	8.5
15204	15.4	28.4	22.8	7.1
15205	21.3	28.9	22.6	8.1
15206	17.2	28.3	22.9	6.4
15207	22.8	30.6	23.0	5.0
15208	23.4	30.1	22.8	3.1
15209	21.6	30.9	22.3	2.7
15210	20.2	30.9	22.1	4.1
15211	23.0	29.4	22.3	34.1
15212	13.1	29.6	22.6	42.5
15213	9.0	29.9	22.1	13.5
15214	20.5	30.7	23.7	3.4
15215	22.6	28.8	23.8	0.5
15216	19.7	29.1	22.8	0.5
15217	15.9	29.8	23.5	1.0
15218	13.6	28.0	22.9	17.1
15219	11.6	29.8	22.1	15.3
15220	20.2	30.2	22.5	25.5
15221	19.5	29.8	23.6	21.6
15222	22.0	30.8	24.1	20.0
15223	17.9	28.9	24.0	31.3
15224	20.8	29.5	23.9	2.8
15225	18.3	28.5	23.4	4.2
15226	15.8	28.7	23.9	4.3

15227	21.0	28.4	24.0	15.1
15228	15.4	28.9	23.9	34.6
15229	9.3	29.2	23.8	31.2
15230	9.9	29.4	23.8	15.9
15231	17.5	28.8	22.8	8.7
15232	16.1	28.8	22.9	20.7
15233	8.3	28.5	22.2	40.7
15234	14.8	28.7	22.2	15.9
15235	18.9	29.1	22.3	0.6
15236	20.2	29.5	22.4	0.3
15237	19.1	28.7	23.0	1.4
15238	16.7	29.0	23.1	5.5
15239	7.0	27.9	23.7	10.0
15240	17.8	28.8	23.0	12.7
15241	19.0	29.2	23.1	34.2
15242	19.1	29.3	22.9	17.5
15243	17.7	29.3	22.8	12.2
15244	17.6	28.8	21.9	5.5
15245	22.3	29.3	21.1	1.3
15246	21.1	29.5	21.7	0.8
15247	22.4	29.3	21.8	0.9
15248	21.9	28.9	21.5	0.4
15249	16.7	28.7	21.2	0.2
15250	21.4	28.9	21.6	0.9
15251	21.7	29.1	21.3	1.4
15252	20.9	29.8	21.7	0.0
15253	18.5	29.5	22.6	0.2
15254	19.7	29.0	22.9	2.3
15255	14.3	25.1	22.7	11.3
15256	20.7	28.9	21.5	4.7
15257	19.2	29.8	23.3	15.2
15258	20.1	29.9	22.9	0.3
15259	20.6	28.9	21.7	0.1
15260	16.3	29.0	22.8	0.5
15261	20.5	30.0	23.9	0.0
15262	21.5	30.9	23.3	1.3
15263	15.8	28.1	23.0	8.1
15264	17.3	26.3	22.3	2.8
15265	14.5	27.9	21.8	12.4
15266	17.7	29.1	21.4	5.0
15267	16.0	28.5	19.9	0.7
15268	19.4	28.1	18.6	0.0
15269	18.7	28.2	19.4	0.1
15270	19.8	28.9	20.9	0.0
15271	19.7	29.2	21.3	0.0
15272	20.2	30.3	21.3	0.0
15273	19.8	30.5	20.9	0.0

15274	20.5	30.4	21.7	0.1
15275	20.5	30.4	21.6	11.4
15276	21.5	29.9	20.4	0.6
15277	21.0	30.6	19.7	0.0
15278	21.2	29.7	19.6	0.0
15279	21.2	30.3	20.0	0.0
15280	21.0	30.8	20.0	0.0
15281	20.6	31.4	20.2	0.0
15282	20.4	30.6	20.0	0.0
15283	19.7	30.3	20.1	3.5
15284	17.0	28.8	19.5	0.7
15285	11.3	26.3	19.5	0.1
15286	19.3	28.2	19.3	1.4
15287	18.7	28.2	19.7	0.9
15288	18.0	27.7	19.6	6.7
15289	18.5	27.1	18.7	2.5
15290	15.0	27.9	18.7	0.0
15291	17.0	28.2	18.5	0.0
15292	17.5	28.4	19.4	0.0
15293	17.2	29.1	17.8	0.0
15294	17.6	29.0	18.8	0.0
15295	18.1	29.0	16.8	0.1
15296	18.5	28.3	15.4	0.8
15297	18.1	27.8	15.6	0.0
15298	18.3	27.7	17.3	0.0
15299	15.8	28.1	17.3	0.0
15300	18.2	27.8	15.9	0.0
15301	12.3	26.7	15.8	1.4
15302	3.7	25.0	16.1	4.4
15303	16.4	24.8	16.1	0.3
15304	17.5	27.6	15.9	0.0
15305	17.5	27.4	15.8	0.0
15306	17.2	27.6	17.3	0.0
15307	17.3	27.1	17.1	0.0
15308	17.3	26.4	15.7	0.1
15309	16.4	26.8	15.9	0.2
15310	16.9	27.0	15.4	0.0
15311	16.8	26.9	15.5	0.0
15312	16.1	26.3	15.0	0.0
15313	16.7	26.8	15.4	0.0
15314	16.6	27.1	15.6	0.0
15315	16.3	27.3	15.6	0.0
15316	16.1	26.8	15.3	0.0
15317	15.8	26.4	15.3	0.0
15318	15.5	26.1	15.2	0.0
15319	14.3	26.9	15.5	0.0
15320	14.3	26.2	15.1	0.0

15321	14.8	26.5	15.1	0.0
15322	15.3	25.8	14.8	0.0
15323	15.6	25.4	14.1	0.0
15324	15.6	26.5	16.5	0.0
15325	15.5	26.1	16.1	0.0
15326	15.1	25.5	15.9	0.0
15327	15.1	25.0	16.3	0.0
15328	13.7	25.1	16.1	0.0
15329	13.4	24.9	14.3	0.0
15330	14.7	24.0	14.7	0.0
15331	13.8	24.4	14.5	0.0
15332	9.7	21.3	15.6	0.0
15333	14.3	25.6	15.3	0.0
15334	13.7	26.8	16.5	0.0
15335	13.7	27.0	15.2	0.2
15336	9.6	26.9	14.4	0.0
15337	14.2	24.7	14.4	0.0
15338	14.1	23.0	13.2	0.0
15339	13.6	22.4	12.1	0.0
15340	13.6	22.6	12.3	0.0
15341	14.0	23.1	13.6	0.0
15342	11.9	22.7	12.3	0.0
15343	12.7	22.4	11.2	0.0
15344	9.4	22.9	12.8	0.0
15345	13.7	23.8	12.5	0.0
15346	13.8	23.4	13.6	0.0
15347	12.6	21.6	11.8	0.0
15348	14.3	20.6	10.6	0.0
15349	10.7	20.5	10.2	0.0
15350	12.5	20.4	8.9	0.0
15351	14.2	20.0	9.8	0.0
15352	14.2	19.1	8.8	0.0
15353	13.5	20.1	9.2	0.0
15354	13.7	19.4	8.7	0.0
15355	13.9	18.7	8.0	0.0
15356	14.3	19.4	8.2	0.0
15357	14.3	20.1	8.7	0.0
15358	14.4	19.6	9.2	0.0
15359	14.5	19.7	8.0	0.0
15360	14.4	20.1	7.9	0.0
15361	14.4	22.1	10.1	0.0
15362	14.3	22.6	9.9	0.0
15363	14.5	22.5	9.5	0.0
15364	14.3	22.8	11.1	0.0
15365	14.7	22.8	11.2	0.0

Appendix 9: X file (NPKV1506.WHX) used CERES-Wheat Model.

```
*EXP.DETAILS: NPKV1506WH WHEAT AT KAPILVASTU

*GENERAL
@PEOPLE
DEVID DHAKAL
@ADDRESS
NUWAKOT, NEPAL
@SITE
KAPILVASTU, NEPAL

*TREATMENTS                    -------------FACTOR LEVELS------------
@N R O C TNAME.................... CU FL SA IC MP MI MF MR MC MT ME MH SM
 1 1 1 0 2014/15               1  1  0  0  1  1  1  0  0  0  0  0  1
 2 1 1 0 2014/15               1  1  0  0  1  1  1  0  0  0  1  0  1
 3 1 1 0 2014/15               1  1  0  0  1  1  1  0  0  0  2  0  1
 4 1 1 0 2014/15               1  1  0  0  1  1  1  0  0  0  3  0  1
 5 1 1 0 2014/15               1  1  0  0  1  1  1  0  0  0  4  0  1
 6 1 1 0 2014/15               1  1  0  0  1  1  1  0  0  0  5  0  1
 7 1 1 0 2014/15               1  1  0  0  1  1  1  0  0  0  6  0  1
 8 1 1 0 2014/15               1  1  0  0  1  1  1  0  0  0  7  0  1

*CULTIVARS
@C CR INGENO CNAME
 1 WH IB0488 WK-1204

*FIELDS
@L ID_FIELD WSTA....  FLSA  FLOB  FLDT  FLDD  FLDS  FLST SLTX  SLDP  ID_SOIL
FLNAME
 1 NPKV2015 NPKV       -99   -99   -99   -99   -99   -99 -99    -99  WI_CMNP007 -99
@L ...........XCRD ...........YCRD .....ELEV .............AREA .SLEN .FLWR .SLAS FLHST FHDUR
 1            -99            -99       -99               -99   -99   -99   -99   -99   -99

*PLANTING DETAILS
@P PDATE EDATE  PPOP  PPOE  PLME  PLDS  PLRS  PLRD  PLDP  PLWT  PAGE  PENV
PLPH  SPRL                   PLNAME
 1 15324   -99   270   250     S     U    20     0     4   -99   -99   -99   -99   -99                     3rd 20

*IRRIGATION AND WATER MANAGEMENT
@I  EFIR  IDEP  ITHR  IEPT  IOFF  IAME  IAMT IRNAME
 1     1    30    50   100 GS000 IR001    10 3rd
@I IDATE  IROP IRVAL
 1 15340 IR003    70
 1 16005 IR003    70
 1 16052 IR003    70

*FERTILIZERS (INORGANIC)
@F FDATE  FMCD  FACD  FDEP  FAMN  FAMP  FAMK  FAMC  FAMO  FOCD FERNAME
 1 15324 FE016 AP002     5     0     0    40   -99   -99   -99 1st 20
 1 15324 FE006 AP002     5     0    60     0   -99   -99   -99 1st 20
 1 15324 FE005 AP002     5    50     0     0   -99   -99   -99 1st 20
 1 15354 FE005 AP002     5    50     0     0   -99   -99   -99 1st 20

*ENVIRONMENT MODIFICATIONS
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```
@E ODATE EDAY  ERAD  EMAX  EMIN  ERAIN ECO2  EDEW  EWIND ENVNAME
 1 15305 A   0 A   0 A   0 A   0 A 0.0 A  20 A   0 A   0 initial
 2 15305 A   0 A   1 A   1 A   0 A 0.0 A  20 A   0 A   0 tem +1
 3 15305 A   0 A   1 A   1 A   1 A 0.0 A  20 A   0 A   0 tem +1, 420
 4 15305 A   0 A   1 A   2 A   2 A 0.0 A  30 A   0 A   0 tem +2, 420
 5 15305 A   0 A   1 A   3 A   3 A 0.0 A  40 A   0 A   0 tem +3, 470
 6 15305 A   0 A   1 A   3 A   3 A 0.0 A  50 A   0 A   0 tem +3, 570
 7 15305 A   0 A   1 A   4 A   4 A 0.0 A  60 A   0 A   0 tem +4, 570

*SIMULATION CONTROLS
@N GENERAL     NYERS NREPS START SDATE RSEED SNAME.................... SMODEL
 1 GE              5     1     S 15305  2150 DEFAULT SIMULATION CONTR
@N OPTIONS     WATER NITRO SYMBI PHOSP POTAS DISES  CHEM  TILL   CO2
 1 OP              Y     Y     Y     N     N     N     N     Y     M
@N METHODS     WTHER INCON LIGHT EVAPO INFIL PHOTO HYDRO NSWIT MESOM
MESEV MESOL
 1 ME              M     M     E     R     S     L     R     1     G     S     2
@N MANAGEMENT  PLANT IRRIG FERTI RESID HARVS
 1 MA              R     R     R     R     M
@N OUTPUTS     FNAME OVVEW SUMRY FROPT GROUT CAOUT WAOUT NIOUT
MIOUT DIOUT VBOSE CHOUT OPOUT FMOPT
 1 OU              N     Y     Y     1     Y     Y     Y     Y     Y     N     Y     N     Y     A

@  AUTOMATIC MANAGEMENT
@N PLANTING    PFRST PLAST PH2OL PH2OU PH2OD PSTMX PSTMN
 1 PL          11001 11001    40   100    30    40    10
@N IRRIGATION  IMDEP ITHRL ITHRU IROFF IMETH IRAMT IREFF
 1 IR             30    50   100 GS000 IR001    10     1
@N NITROGEN    NMDEP NMTHR NAMNT NCODE NAOFF
 1 NI             30    50    25 FE001 GS000
@N RESIDUES    RIPCN RTIME RIDEP
 1 RE            100     1    20
@N HARVEST     HFRST HLAST HPCNP HPCNR
 1 HA              0 01001   100     0
```