CLIMATE CHANGE IN THE BRAHMAPUTRA VALLEY AND IMPACT ON RICE AND TEA PRODUCTIVITY

A thesis submitted
in partial fulfillment of the requirements for the award of the degree of

DOCTOR OF PHILOSOPHY

By

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CERTIFICATE

This is to certify that the thesis entitled "**Climate Change in the Brahmaputra Valley and Impact on Rice and Tea Productivity**" submitted by **Mr. Rajib Lochan Deka** to the Indian Institute of Technology Guwahati, for the award of the degree of Doctor of Philosophy is a record of bonafide research work carried out by him under our supervision and guidance. **Mr. Deka** has carried out research on the topic at the Centre for the Environment of IIT Guwahati over a period of three years and eight months and the thesis, in our opinion, is worthy of consideration for the degree of Doctor of Philosophy in accordance with the regulations of this Institute. The results contained in this thesis have not been submitted elsewhere in part or full for the award of any degree or diploma to the best of our knowledge and belief.

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STATEMENT

I do hereby declare that the matter embodied in the thesis is a result of research work carried out by me in the Centre for the Environment, Indian Institute of Technology Guwahati, Guwahati, Assam, India.

In keeping with the general practice and reporting scientific observations, due acknowledgements have been made wherever the work described is based on the findings of other investigators.

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ABSTRACT

Given the vulnerability of agricultural sector to variations in weather conditions, it will be one of the sectors most affected by climate change. This study assesses the state of climate change and variability in the Brahmaputra valley of India and consequent implications on productivity of two important crops – rice and tea grown extensively in the valley. The trends and fluctuations of the major climatic variables were assessed using statistical techniques. A quantitative assessment of the impact of observed as well as projected climate on rice and tea productivity was carried out in the study area through statistical and process-based simulation models. Historical rainfall data from 1901–2010, temperature data from 1951–2010 and sunshine duration data from 1971–2010 were analyzed for assessing long-term trends. A suite of climate change indices derived from daily rainfall (1955–2010) and temperature (1971–2010) data, with a primary focus on extreme events, were computed and analyzed to understand the trends. The impact of climate change and its variability on yield patterns of rice and tea were based on 26 years of district level rice yield data (1985–2010) and 20 years of estate level tea yield data (1991–2010). The CERES-Rice crop simulation model was used to predict rice yield under future climate scenarios. The likely impact of future climate changes on tea yield was based on the statistical models developed for monthly yields and climate data of 1991 to 2010.

Annual and monsoon rainfall in the study area exhibited a weak diminishing tendency during 1901–2010 due to significant decrease in rainfall in the eastern part of the valley. Significant declining trend of monsoon rainfall during the recent 30-year period was due to significant decrease of July and September rainfall and this trend was consistent at different spatial scales. The intensity of monsoon rainfall was found to diminish over the entire valley due to decrease in the extreme fractions of rainfall, marked by extremely wet, very wet and moderately wet days during the recent three decades (1981–2010). Decrease of rainfall fraction due to moderately wet days was particularly significant in the eastern and western parts of the valley. Rainfall during pre-monsoon and post monsoon season showed increasing tendency during the most recent 30-year period due rise in extreme rainfall indices over the valley. Increase of rainfall during pre-monsoon was primarily contributed by significant increase of April rainfall in the western part of the valley.

During post-monsoon, October rainfall showed a spatially coherent increasing tendency during the last three decades (1981–2010). In the eastern and central parts of the valley, winter rainfall also declined during the last three decades due to significant decrease of December rainfall. Annual mean temperature in the Brahmaputra valley increased significantly between 1951 and 2010 by 0.088°C/decade due to increase in both maximum (0.077°C/decade) and minimum (0.090°C/decade) temperature. During the recent 30-year period, the warming trend (0.313°C/decade) was particularly pronounced. During this period, minimum temperature increased at higher rate than that of maximum temperature due to significant decrease in the annual occurrence of cold nights and a significant increase in annual occurrence of warm nights. Mean bright sunshine duration in the valley significantly decreased by 0.33 hr/decade during the last 40 years. Highest decrease (0.50 hr/decade) was observed during pre-monsoon while lowest decrease (0.15 hr/decade) was observed during post-monsoon season.

Multivariate regression analysis between first differences of historical rice yield and first differences of climatic variables showed 1) number of rainy days during reproductive phase, 2) minimum temperature and 3) sunshine duration during vegetative phase of rice to be the major variables responsible for the observed positive yield trend of rice during 1986–2010. The rice yield was affected by intra-seasonal variability of climate besides the impact of changes in mean climate. Estimated impact due to increased minimum temperature during vegetative phase on observed yield trend was positive while its impact during reproductive phase was negative. Rice yield was negatively affected by intra-seasonal variability of both minimum temperature and number of rainy days during the vegetative phase. The yield response due to decrease of rainfall amount during reproductive phase was negative but decrease of number of rainy days during this phase was positive. The CERES-Rice crop simulation model was evaluated for its suitability to simulate yield under projected climate scenarios utilizing five years of secondary experimental data for the popular rice variety *Ranjit*. Sensitivity analysis showed that at prevailing ambient temperature, the CERES-Rice model was less sensitive to changes in rainfall amount, CO_2 concentration and solar radiation during the crop season. At current level of CO_2 concentration (390 ppm), with rising ambient temperature up to +3.0°C, rice yield increases linearly over the base yield. The interaction of temperature and atmospheric

CO_2 concentration indicated that for all the CO_2 levels considered, the CERES-Rice model predicted increasing yield due to an increase in air temperature up to 5°C. For all the temperature increments considered, mean relative yield increased from 6.3% at 390 ppm to 11.4% at 750 ppm of CO_2 concentration. The positive effect of 450 ppm of CO_2 on rice yield is cancelled out at a temperature +4°C over baseline, whereas the positive effect of 550 ppm to 750 ppm CO_2 concentration is wiped out at +5°C temperature. Over-all, rice yield is likely to be impacted positively under the projected climate change scenarios in the study area mainly due to the interaction of CO_2 and temperature.

Multivariate regression analysis of first differences of tea yield and first differences of climatic variables could explain 84% to 94% of yield variance during different crop seasons. Rainfall distribution (rainy days) during winter and mean temperature during both winter and pre-monsoon seasons were the potent climatic variables for the observed negative yield on early crop (March–May). The positive influence of winter warming on yield of early crop was negated by decreased number of rainy-days in winter along with increased mean temperature during pre-monsoon season, causing a net decrease in yield. The negative yield trend of main crop (June–September) was caused mainly by negative influences of decreasing trend of monsoon rainfall as well as its distribution, in spite of the positive impact of higher monsoon temperature and pre-monsoon rainfall on main crop yield. The net gain in yield of late crop (October–December) during the study period was determined by the positive impact of increased temperature and decreased sunshine duration during monsoon and decreased rainfall amount as well as sunshine duration during post-monsoon season. Empirical assessment of projected impact of climate change scenarios on tea yield is likely to be positive in the coming three decades. Tea yield during early, main and late crop seasons are likely to increase by 9%, 13% and 19% respectively. The statistical crop models derived from historical yield and climate data and their application to a range of future climate scenarios may provide a useful foundation for impact studies on tea in other agro-climatic regions. Results indicated that the yield-climate relationships can provide a foundation for forecasting tea production within a year and for projecting the impact of future climate changes.

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Chapter 1

Introduction

1.1 Background

Climate change due to anthropogenic modification of the atmosphere and its subsequent impact on food production and food security has emerged as one of the major global environmental issues (Parry et al. 2005; Beddington 2010; Berg et al. 2013). The Inter-Governmental Panel on Climate Change (IPCC 2007a) has reconfirmed that the global atmospheric stocks of greenhouse gases (GHGs) have increased markedly as a result of human activities since 1750, resulting in significant warming of the climate system by 0.74°C between 1906 and 2005 (IPCC 2007a), with most warming occurring over the recent half century. However, the warming has neither been steady nor the same spatially and temporally. Warming, particularly since the 1970s, has generally been greater over land than over oceans (Rangwala and Miller 2012). The year 2010 ranked as the warmest year on record since 1880 and all the 12 years so far in the 21st century (2001–2012) rank among the 14 warmest years in the 133 years of record (NOAA 2013). The year 2012 was the 10th warmest year since 1880. Assuming no emission control mechanism put in place, the IPCC predicted that average global surface temperatures will increase by 2.8°C during the twenty first century, with best-guess increases ranging from 1.8°C to 4.0°C (IPCC 2007a). Not only temperature increase itself is a cause for concern, other possible outcomes of climate change like increased frequency of extreme weather events, sea level rise, and changed precipitation patterns (IPCC 2007a) are formidable challenges confronting the mankind. Globally, average precipitation is projected to increase, with great deviances at regional scale (Dore 2005; Meehl et al. 2007). During 20th century, global annual mean precipitation showed an insignificant upward trend with large spatial, seasonal and inter-decadal variability (IPCC 2007a). On the other hand, solar radiation across the globe declined at a rate of 0.51 W/m^2/year during last 50 years (Stanhill and Cohen 2001), a phenomenon that is generally termed as global dimming (Wild et al. 2005).

In India, mean, maximum and minimum temperatures have significantly increased by 0.51°C, 0.71°C and 0.27°C per hundred years respectively during 1901–2007 (Kothawale

et al. 2010) with accelerated warming (0.21°C/decade) after 1970s (Attri and Tyagi 2010, Kothawale et al. 2010). In North East (NE) India, magnitude of temperature increase was higher compared to that of all-India mean. Maximum and minimum temperature in the region has increased by 1.02°C/100 years and 0.60°C/100 years during 1901–2003 (Deka et al. 2009). Though the all-India annual and monsoon rainfall during the last 100 years exhibited no significant trend, significant long-term rainfall changes were identified at different spatial and temporal scales (Dash et al. 2007; Guhathakurta et al. 2011). During this period, frequency of extreme rainfall events during southwest monsoon season had increased significantly over the country (Pattanaik and Rajeevan 2010). A trend of decreasing rainfall (–6% to –8% of normal over the last 100 years) has been observed in Northeast (NE) India (Gadgil et al. 2007). In addition, decrease of solar radiation and sunshine duration during recent past in India has also been observed (Rao et al. 2004; Kumari et al. 2007). Significant decrease of sunshine duration was observed during last four decades (Jaswal 2009; Jhajharia and Singh 2011) in the Brahmaputra valley.

Given the inextricable link of agriculture with climate variables, impact of climate change on agriculture and food security has been at the forefront of research and policy agenda in recent times. Agriculture is considered as the most weather-dependent of all human activities (Hansen 2002) since climate is a primary determinant for agricultural productivity. For most parts of the world, agricultural production is expected to face substantial productivity changes, although impacts will vary by regions and crops (Rosenzweig and Parry 1994; Sultan 2012). This may critically affect global food security by influencing crop yield (Peng et al. 2004; Schlenker and Roberts 2009) and lead to change in spatial distribution in crop productivity (Lobell et al. 2006; Lobell 2007; Fedoroff et al. 2010). An IPCC projection anticipates that a 2.0°C increase in temperature may lead to a further 20% to 40% fall in cereal yield, mostly in Asia and Africa (Lele 2010). The concern on past, present and future weather aberrations, climate trends, and their effects particularly on agriculture, has continued to stimulate deep research interests on the analysis of climate variability and consequential agricultural productivity. There is a growing mass of literature focused on quantifying and predicting the impact of climate change on crop productivity in many areas of the world (Rosenzweig and Parry 1994;

Parry et al. 1999; Parry et al. 2005; Lobell 2007; Cabas et al. 2009; Rowhani et al. 2011, Lobell et al. 2011; Knox et al. 2012).

Agriculture has been a way of life and main source of livelihoods for the vast majority of households in rural India. Shouldering the onus of providing food to teeming millions, in the past six decades of planned economic development in India, the agriculture sector has come a long way from foodgrain production level of only 51 million tonnes in 1950–51 to 252.56 million tonnes in 2011–12 (MoA 2012). Indian agriculture is facing challenges in several aspects such as increased competition for land, water and labour from non-agricultural sectors and more recently, from increasing climate variability associated with global warming (MoEF 2010). The yield of major food crops in the past few decades have stagnated in several parts of Asia, including India (Aggrawal et al. 2000; Fischer et al. 2002; Kalra et al. 2008; Milesi et al. 2010). Water stress arising partly from increasing temperatures (Singh et al. 2008), increasing frequency of El Nino events (Kripalani et al. 2003) and decrease in number of rainy days as well as annual amount of precipitation (Lal 2003; Goswami et al. 2006; Dash et al. 2007) is likely to exacerbate the influences of biotic and abiotic stresses making the task of producing enough food for the growing population a formidable one.

The NE region of India is relatively more vulnerable to climate change impacts due to its location in the Eastern Himalayan periphery, fragile geo-environmental setting and economic under-development (MoEF 2010). However, despite being viewed as a region with most climate sensitive agriculture, climate change and its impact on agricultural production in NE India has hardly been studied. Assam, constituting a major part of the Brahmaputra floodplains in tropical latitudes (24°08'N to 27°59'N) and eastern longitudes (89°42'E to 96°01'E), is the most populous state in the NE India. Agriculture and allied activities in the state have paramount importance as a source of livelihood to its people. It contributes more than one-fourth (26.09% in 2009–2010) of State's Net State Domestic Product (NSDP) at current prices (DES 2012). Almost 70% of the population is directly dependent on agriculture and another 15% is dependent on allied activities (Bujarbarua and Barua 2009). The impacts of climate variability on agriculture in Assam are already visible in terms of erratic monsoon, frequent floods, drought-like situation and warmer winter. In

three consecutive years since 2002, there were large floods in the state but the seasons of 2006, 2007 and 2009 witnessed deficient rainfall (IMD 2006, 2007; IPCC 2007a). The last decade (2001–2010) was the driest decade in the history of past 110 years in the Brahmaputra valley (Deka et al. 2012). Moreover, year-to-year variations in the onset, amount and distribution of monsoon rainfall are likely to be influenced under projected climate change scenarios in the region (Rupa Kumar et al. 2006).

Rice is the single-most dominant crop occupying about 67% of the gross cropped area and more than 90% of the total area under foodgrain crops in Assam (DES 2012). Besides rice, tea is another climate-sensitive important crop, which is most profitably cultivated in the state. It is the major agriculture-based industry of Assam, which contributes up to 55% of India's total tea output, and 15.6% of world tea production (MoEF 2010). About 88% of Assam's tea area is concentrated in the Brahmaputra valley alone. In addition, there are 70 thousand small tea growers (covering approximately 47,348 ha area) contributing about 30% of the State's total annual output (DES 2012). It has been observed that the productivity of tea in the state has either become static or shown a decline in recent past (Dutta 2010; Ramakrishna et al. 2013). The productivity level of rice has also fluctuated heavily during the last decade (2001–2010). In this context, it is of vital importance to analyze the climate change trends individually for better planning of agriculture as well as development of effective mitigation and adaptation strategies for a climate resilient agricultural production system in Assam and the Brahmaputra valley in particular. Although there is a plethora of literature on the impact of climate change on crop productivity either by process-based or empirical crop models, impact assessment studies are rather limited in this part of India. As aberrations in weather are being experienced more frequently and agriculture is the most vulnerable to climate change and variability, explicit assessment of their impact on major crops like rice and tea is urgently required to identify suitable adaptation strategies to sustain the productivity of such critical crops.

1.2 Objectives

The aim of the present study was to study the long-term trends and short-term fluctuations of major climatic elements viz., rainfall, temperature and sunshine duration in the Brahmaputra valley and subsequently to evaluate their implications to the yield variability

of two critical crops rice and tea. Changes of extremes in rainfall and temperature were assigned particular emphasis, based on the premise that the magnitude of extremes are likely to be more sensitive to climate change and their trends are an important expressions of climate variability. Sunshine duration (a proxy of solar radiation) has profound influence on surface temperature, evaporation, the hydrologic cycle and various ecosystems. Due to recent decline in solar radiation (Wild et al. 2005), trends in sunshine duration in the Brahmaputra valley were to be assessed. The past impact of climate change and variability on the recent productivity changes of rice and tea were to be examined empirically. Finally, the likely impact of different climate variables on the performance of these two crops under the projected climate change scenarios for the near future were assessed to explore possible adaptation strategies.

Based on the above scope of the research, and considering availability of data, the present study was focused on the following objectives:

1. To assess the long-term monthly, seasonal and annual rainfall trends over the Brahmaputra valley at different spatial and temporal scales for the last 110 years (1901–2010) and to evaluate the changes in daily extreme rainfall events for the last 55 years (1955–2010).
2. To assess the changes in monthly, seasonal and annual temperature trends over the Brahmaputra valley at different spatial and temporal scales for the last 60 years (1951–2010) along with changes in daily extreme temperature events for the last 40 years (1971–2010)
3. To examine the observed changes in sunshine duration over the Brahmaputra valley for the last 40 years (1971–2010)
4. To estimate the observed impact of the above climate variables on yield of rice and tea in a part of the Brahmaputra valley by empirical statistical approach
5. To evaluate the climate change impact on yield of rice by using CERES-Rice dynamic simulation model and impact on yield of tea by empirical statistical model
6. To explore adaptation options for both rice and tea crops corresponding to the findings.

1.3 Organization of the thesis

The outcome of the study on impact of climate change in the Brahmaputra valley and consequent impact on rice and tea productivity is subdivided into seven chapters. Following this introduction, ***Chapter 2*** represents a synthesis of the relevant literature on climate change and variability as well as their impact on agriculture including rice and tea productivity. ***Chapter 3*** deals with the description of the study area highlighting the location, climatic peculiarities, agricultural scenario and level of exposure to different water related hazards. ***Chapter 4*** discusses the data used, methodologies and analyses in detail relating to long-term trends and short-term fluctuations of major climatic elements in the Brahmaputra valley. ***Chapter 5*** narrates the methodologies and results of the impact of observed climate trends as well as projected climate change scenario on rice productivity in a part of the Brahmaputra valley. ***Chapter 6*** presents the materials and methods and narrates the results of impact of observed climate trends as well as projected climate change scenarios on tea productivity in a part of the Brahmaputra valley. ***Chapter 7*** summarizes the results and provides the major conclusions from the present study along with scope for future investigation. A reference section is included at the end, followed by appendices and list of publications.

Chapter 2

Review of Literature

Keeping in perspective the objective of the thesis to determine the trends and fluctuations of major climatic elements in the Brahmaputra valley and to quantify its impact on productivity of rice and tea crop, this chapter starts with an introduction to climate change and its variability and reviews the literature related to observed and projected changes in rainfall, temperature and solar radiation as well as their extremes on a global and regional perspectives. This is followed by detailed literature review on impact of CO_2, temperature and rainfall as well as extreme events on agriculture. This is followed by review of literature dealing with different methods used in assessing the climate impacts on agriculture. Finally, the literature pertaining to specific impact w.r.t. rice and tea has been reviewed elaborately.

2.1 Climate Change and Climate Variability

Climate change and climate variability has received considerable attention from the scientific community in recent decades because of several reasons – the basic reason being that climate pervades into all the spheres on which human civilization is critically poised. The tentacles of adverse climate change destabilizes the bonds between the biotic and abiotic factors of ecological balance which leads to gradual changes in the dynamics of equilibrium between man and his environment.

In the most general sense, the term 'climate change' encompasses all forms of climatic inconsistency regardless of their statistical nature or physical causes (NSIDC 2013). Climate change may result from changes in solar activity, long period changes in the earth's orbital elements (eccentricity, obliquity of the ecliptic, precession of equinoxes), natural internal processes of the climate systems or anthropogenic forcing (for example increasing atmospheric concentrations of carbon dioxide and other green house gases) (NSIDC 2013). Climate change in IPCC usage refers to "a change in the state of the climate that can be identified (e.g., using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer" (IPCC 2012) This definition differs from that in the United Nations Framework

Convention on Climate Change (UNFCCC), where climate change is defined as a change of climate, which is attributed directly or indirectly to human activities that alter the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods (IPCC 2012). The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes (IPCC 2012).

Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate at all spatial and temporal scales beyond that of individual weather events (IPCC 2012). Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

The state of the art knowledge on the observed as well predicted changes in important climatic variables are discussed in the following sections.

2.2 Changes in temperature

Since the industrial revolution, there has been a marked increase in the emission of greenhouse gases mainly CO_2 in the atmosphere, raising the atmospheric temperatures near the surface of the earth. Temperature changes, together with the changes in rainfall, are likely to exacerbate the pressure put on water resources, ecosystems and crop yields by the increasing population and increased drought years in various subcontinents (IPCC 2007a). The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC 2007a) has concluded that the global mean surface temperatures have risen by 0.74 ± 0.18°C, when estimated by a linear trend over the last 100 years (1906–2005). The rate of warming over the recent 50 years was almost double of that over the last 100 years (IPCC 2007a), which was largely attributed to anthropogenic influences. Between 1975 and 2010, land temperatures have been increasing at a rate of 0.30°C/decade, which was more than double the rate (0.12°C/decade) of ocean warming (Rangwala and Miller 2012). The largest increases in temperature have occurred over the mid– and high latitudes of northern continents, land area have warmed more than the oceans, and night temperatures have warmed more than daytime temperature (IPCC 2007a). However, the rates of change

are significantly different among regions, primarily due to varied types of land surfaces with different surface albedo, evapotranspiration and carbon cycle affecting and responding to the climate in different ways (Snyder et al. 2004; Dang et al. 2007).

Jones et al. (1999) in their analysis of the Central England temperature records found an increase in temperature that corresponded to a reduced number of days with temperature much below normal. Kadioglu et al. (2001) analyzing temperature trends in Turkey over the period 1930–1996, found significant cooling during this period. In both Australia and New Zealand, the frequency of days below freezing point decreased in association with an increase in daily minimum temperatures (Plummer et al. 1999). Kruger and Shongwe (2004) studied time series of African temperatures for temporal and spatial trends from 1960 to 2003. Trends of mean seasonal temperature showed that temperature trends are not consistent throughout the year, with the averages trend for autumn showing a maximum and spring a minimum. Chung and Yoon (2000) showed a 0.96°C increase in the annual mean temperature in Korea from 1974 to 1997.

In India, work of Hingane et al. (1985) on long-term trends of surface temperature covering the period of 1900–82 from 73 well-distributed stations showed a warming trend of 0.4°C/100yrs, providing the first quantitative indications of India sharing the large-scale aspects of global warming. Trend analysis of decadal mean temperatures by Srivastava et al. (1992) also provided a similar result and gave the first indications that the diurnal asymmetry of temperature trends over India was quite different from that over many other parts of the globe. Subsequently, Rupa Kumar et al. (1994) studied maximum and minimum temperature data from 121 stations in India during the period 1901–1987 and found that the increase in mean temperature over India was almost solely contributed by the maximum temperatures (0.6°C/100yrs), with the minimum temperatures remaining practically trendless, leading to an increase in the diurnal range of temperatures. Pant and Rupa Kumar (1997) analyzed seasonal and annual air temperature series for 1881–1997 and found that there was a significant warming trend of 0.57°C/100yrs. The magnitude of warming was higher in the pre-monsoon and winter seasons while monsoon temperature did not show any significant trend in any major parts of the country, except for a significant negative trend over northwest India. Spatial pattern of trends in the mean annual

temperature showed significant positive trend over most parts of India except over parts of Rajasthan, Gujarat and Bihar, where significant negative trends were observed (IMD 2009). In NE India, Jhajharia and Singh (2011) reported statistically significant increasing trends in mean temperature at few locations (Margherita, Nagrakata and Silchar).

Recently, Kothawale et al. (2010) reported that all-India mean, maximum, and minimum temperatures have significantly increased by 0.51, 0.71, and 0.27°C/100yrs, respectively, during the period 1901–2007. This warming was mainly due to increasing temperatures in the winter and post-monsoon seasons. During the three decades from 1971 to 2007, annual mean temperature increased by 0.22°C/decade due to unprecedented warming during the last decade (1998–2007). Attri and Tyagi (2010) also reported an increasing trend of all–India mean annual temperature by a rate of 0.56°C/100yrs during 1901–2009 with an accelerated warming after the 1970s (0.21°C/10yrs) primarily due to rise in maximum temperature. However, since 1991, minimum temperature showed a steady rising trend and was slightly higher than that of maximum temperature but was appreciably higher over northern plains due to pollution leading to frequent occurrence of fog (Attri and Tyagi 2010).

2.3 Changes in rainfall

Detection of trends in rainfall time series attracts growing attention due to widespread concerns that the human induced increase in greenhouse gases is altering the Earth's climate and ecosystems (Letcher 2009). The increased atmospheric moisture content associated with warming (Trenberth et al. 2005) might be expected to lead to increased global mean precipitation. Information on spatial and temporal variations of rainfall is important in understanding the hydrological balance on a global/regional scale. Rainfall variability and changes are predicted to have a major impact on the water and agricultural sectors in the Asia–Pacific region (Cruz et al. 2007).

Global annual land mean precipitation showed a small, but uncertain, upward trend over the 20th century of approximately 1.1 mm per decade (IPCC 2007a). Though the trend was statistically insignificant, the pattern of precipitation change was spatially and seasonally variable and characterized by large inter-decadal variability. Precipitation has very likely

been increased during the 20th century by 5% to 10% over most mid– and high latitudes of Northern Hemisphere (NH) continents, but in contrast rainfall has likely decreased by 3% on average over much of the subtropical land areas (IPCC 2007a). On the regional spatial scale, it has become significantly wetter in eastern parts of North and South America, northern Europe, and northern and central Asia, but drier in the Sahel, the Mediterranean, southern Africa, and parts of southern Asia (Dai et al. 2004). On the temporal scale, global annual land precipitation had increased overall before the 1950s, declined until the early 1990s, and has since then recovered (Peterson and Vose 1997; Mitchell and Jones 2005). As to the attribution of precipitation change, anthropogenic factors appear to have influenced the latitudinal pattern of land precipitation and heavy precipitation over the twentieth century, and volcanic forcing was also detectable as having a role in global mean land precipitation (Zhang et al. 2007).

The changes in rainfall on sub-regions can be far more dramatic than changes in global and regional averages. Available data suggest that there may be different results even on the land regions. For example, decreasing trends of annual rainfall and seasonal changes were already noticed in Indonesia (WWF 2007), Italy (Cislaghi et al. 2005), South–Eastern Australia (Murphy and Timbal 2008), Sri Lanka (Zubair et al. 2008), Turkey (Partal and Kucuk 2006) and UK (Palmer and Raisanen 2002). On the other hand, trends in European annual precipitation revealed an increase in rainfall in northern Europe by 10% to 40% in the twentieth century, but little change or drying in southern Europe (Parry 2000). Precipitation in the Great Plains of the United States of America also showed significant increase since the late 60's – the last two decades being the wettest of the 20th century (Garbrecht and Rossel 2002). The Brazilian Amazon basin precipitation records revealed a shift around 1975, a downward trend in the northern area and upward trend in the southern part (Marengo 1999). Norway (Benestad and Haugen 2007), Spain (Mosmann et al. 2004) and the United States (Groisman et al. 2001) showed increasing trends of rainfall during summer and for Canada (Groleau et al. 2007) in winter season. Vincent et al. (2011) found significant decreasing trends in annual total rainfall in the countries of Western Indian Ocean during 1961–2008. In the Tibetan plateau, rainfall has increased in the eastern and central parts, while in the western part, it exhibited a decreasing trend during 1961–2001

(Xu et al. 2008). A significant increase of annual and pre-monsoon rainfall was also observed in Bangladesh during 1958–2007 (Shahid 2012).

In India, long-term trends of southwest monsoon rainfall for the country as a whole as well as for smaller spatial regions were studied by several researchers. Most of these studies during the last four decades had pointed out that monsoon rainfall is trendless and is often random in nature over a long period of time, particularly on an all-India scale (Mooley and Parthasarthy 1984; Thapliyal and Kulshrestha 1991; Sinha Ray and De 2003; Kripalani et al. 2003; Guhathakutra and Rajeevan 2008; Attri and Tyagi 2010). Though the all-India annual and monsoon rainfall during the last 100 years exhibited no significant trend, significant long-term rainfall changes were identified at different spatial and temporal scales in some studies (Rupa Kumar et al. 2002; Sinha Ray and Srivastava 2000; Dash et al. 2007; Kumar et al. 2010; Guhathakurta et al. 2011). Analysis of rainfall data for the period 1871–2002 indicated a decreasing trend in monsoon rainfall and increasing trend in the pre-monsoon and post-monsoon seasons (Dash et al. 2007). During recent decades (1979–2006), the monsoon rainfall over India was less by 4.5% compared to the period 1949–1978 (Ranade et al. 2008). Summer monsoon rainfall showed decreasing trend over northeast India, east Madhya Pradesh and adjoining areas, and parts of Gujarat and Kerala (Rupa Kumar et al. 2002; Dash et al. 2007). Analyzing Indian summer monsoon rainfall data during 1871–2010, Kulkarni (2012) observed decreasing tendency of rainfall during the last three decades of the 20th century. During 1976–2004, the deficit (excess) monsoons have become more (less) frequent due to weakening of monsoon circulation compared to 1901–1975. In a study, Kothawale and Kulkarni (2012) showed that in the recent warming period 1971–2010, monsoon rainfall of North India (north of 20°N) showed negative trend while South India (south of 20°N) showed positive trend. The occurrence of excess years were more over intense warm area (South India) than the mild warm area (North India) indicating enhancement of monsoon rainfall in a warming environment.

Indian summer monsoon rainfall (ISMR) showed epochal variability of approximately 30 years since 1870s (Kripalani and Kulkarni 1997; Kripalani et al. 2003). Kripalani et al. (2003) examined the inter-annual and decadal variability in summer monsoon rainfall over India by using observed data for a 131-year period (1871–2001). They found random

fluctuations in annual rainfall and distinct alternate epochs (lasting approximately three decades) of above- and below-normal decadal rainfall. Earlier, Kripalani and Kulkarni (1997) characterized the ISMR series used by Kripalani et al. (2003) as below normal epochs (1901–1930 and 1961–1990) and the above normal epochs (1871–1900 and 1931–1960) of approximately 30 years each. If this epochal variability is assumed to be continued, ISMR should have entered into the above normal epoch around 1990, which did not happen. After 1990, the epochal variability of ISMR has been disturbed due to weakening of low level monsoon circulation (Kulkarni 2012).

2.4 Trends of extreme weather events

While changes in average climate condition are important, changes in extreme climatic events are likely to have greater impacts on nature and society than by changes in mean values (Trenberth et al. 2007; Peterson et al. 2008) and so have received much attention world-wide (Easterling et al. 1997; Easterling et al. 2000; New et al. 2006; Halsnaes et al. 2007; Aguilar et al. 2008; Liu et al. 2009; Sherwood and Huber 2010; You et al. 2010a, 2010b, Vincent et al. 2011). A changing climate leads to changes in the frequency, intensity, spatial extent, duration, and timing of weather and climate extremes, and can result in unprecedented extremes (IPCC 2007a; 2012). The following sub-sections provide a review of observed trends in temperature and rainfall extremes.

2.4.1 Extreme temperature events

The changing properties of temperature extremes are different from place to place, showing significant trends in some regions and not so significant changes in other regions (Bonsal et al. 2001). The study by Alexander et al. (2006) is the most recent assessment of changes in observed daily temperature and precipitation extremes, which was made world-wide. They argued that considerable changes in temperature extremes occurred for the period 1951–2003, mainly those linked to daily minimum temperatures. More than 70% of the global land areas showed a significant rise in the annual amount of warm nights and a decreasing amount of cold nights between 1951 and 2003.

Earlier, Easterling et al. (2000) reviewed briefly the observed variability and trends in extreme temperature events over Australia, China and Central Europe, Northern Europe,

New Zealand and United States, and mentioned that number of frosty days decreased over these countries and days with warm maximum temperature increased only over Australia and New Zealand. Manton et al. (2001) examined the trend in extreme daily temperature for the period 1961–1998 for Southeast Asia and South Pacific and reported that annual number of hot days and warm nights significantly increased and annual number of cool days and cold nights significantly decreased. Griffiths et al. (2005) also observed decreases in cold nights and cool days and increases in warm nights in Asia–Pacific regions, which was similar to findings by Manton et al. (2001). Klein Tank and Konnen (2003) studied trends in indices of temperature extremes on the basis of daily series of temperature observations from more than 100 meteorological stations in Europe for the period 1946–99 and reported a 'symmetric' warming of the cold and warm tails of the distributions of European daily minimum and maximum temperatures. Interestingly, an 'asymmetry' was noticed when the study period was divided into two sub-periods: episode of slight cooling during 1946–75 and an episode of pronounced warming i.e. an increase in annual number of warm extremes during 1976–99. Trends over 1960–2000 in daily temperature indices over South America indicated a significant increasing trend in the percentage of warm nights and decreasing trends in the percentage of cold nights (Vincent et al. 2005). Klein Tank et al. (2006) studied changes in indices of climate extremes on the basis of daily series of temperature observations from 116 stations in central and south Asia, and found that 70% of the stations had statistically significant increase in the percentage of warm nights/days and decrease in the percentage of cold nights/days between 1961 and 2000. IPCC (2007a) concluded that changes in temperature extremes are consisted with the observed warming of the climate.

The recent work in Hansen et al. (2012) described that future (warmer) climates will experience the emergence of a new category of extreme outliers (>3σ over the mean). During the baseline period of 1951–1980, heat wave events classified as >3σ over the mean, covered only 1% of landmass globally. However, in recent years (2006–2011) the average landmass coverage of these extreme outliers has been 10% (Hansen et al. 2012).

In India, a significant increase in the frequency, persistency and spatial coverage of both high frequency temperature extreme events (heat and cold wave) was noticed during the

decade 1991–2000 (Pai et al. 2004). Kothawale (2005) studied the frequency of occurrence of heat and cold waves over India during 1970–2002 using a network of 40 stations and noted that heat wave conditions are relatively more frequent in May than in June, while very few heat waves occurred in the months of March and April. Rao et al. (2005) studied trends in the frequency of occurrence of extreme temperatures over India during pre-monsoon and winter seasons, using daily data of 103 stations for the period 1071–2000. They reported that, in Peninsular India during March–May, 80% of stations showed an increasing trend in the days with critical extreme maximum and minimum temperatures. In the northern part of India, 40% stations showed increasing trends in the days with critical extreme maximum temperature while about 80% of the stations showed increasing trend in the extremes in night temperatures.

Recently, Kothawale et al. (2010) analyzed daily temperature data during 1970–2005 from a network of 121 stations to study the trends in extreme temperature events during pre-monsoon season. They observed that the frequency of occurrence of hot days and hot nights showed widespread increasing trend, whereas that of cold days and cold nights showed widespread decreasing trend over India as a whole and seven homogeneous regions. Analyzing daily minimum and maximum temperature data for the period 1971–2003 over a network of 121 well-distributed stations, Revadekar et al. (2012) also observed widespread warming through an increase in intensity and frequency of hot events and also by a decrease in frequency of cold events. More than 75% of the stations showed decreasing trend in the number of cold events and about 70% stations showed an increasing trend in hot events. Semi-average changes in the annual cycles in terms of all-India monthly temperature extremes over two equal parts of the data period showed warming in all the individual months. Higher magnitude changes in temperature extremes were seen in winter months than those in the rest of the year (Revadekar et al. 2012).

2.4.2 Extreme rainfall events

The frequency of heavy rainfall events in the mid– and high latitudes of NH has increased by 2% to 4% over the latter half of the 20th century (IPCC 2007a). Alexander et al. (2006) from up-to-date and comprehensive global assessments of trends in extreme rainfall indices for the period of 1951–2003 reported widespread rainfall changes with significant

increases in the heavy precipitation indices. Their analysis showed that compared to temperature changes, changes in precipitation extremes were less spatially coherent and at lower level of statistical significance. In the Indo–Pacific region, covering the Southeast Asian and north Australian monsoon, Caesar et al. (2011) also found low spatial coherence in trends in precipitation extremes across the regions between 1971 and 2003. In the few cases where statistically significant trends in precipitation extremes were identified, there was generally a tendency towards wetter conditions, in common with the global results of Alexander et al. (2006). Increasing trend of extreme precipitation events was also observed in USA and Australia (Easterling et al. 2000, Haylock and Nicholls 2000), western New Zealand (Salinger and Griffiths 2001), Western Europe and European Russia in winter (Osborn et al. 2000; Zolina et al. 2009). On the other hand, significantly decreasing trends in extreme precipitation events were found in western Australia (Haylock and Nicholls 2000), northern Italy (Pavan et al. 2008), Poland (Lupikasza 2010), Mediterranean coastal sites (Toreti et al. 2010), parts of central Pacific (Griffiths et al. 2003), northern and eastern New Zealand (Salinger and Griffiths, 2001) and UK in summer (Osborn et al. 2000; Rodda et al. 2010). No systematic spatially coherent trends in the frequency and duration of extreme precipitation events were observed in Eastern and Southeast Asia (Choi et al. 2009), Central and South Asia (Klein Tank et al. 2006), and Western Asia (Zhang et al. 2005; Rahimzadeh et al. 2009).

Interestingly, statistically significant positive and negative trends were observed at sub-regional scales within these regions. For example, heavy precipitation increased in Japan during 1901–2004 (Fujibe et al. 2006), and in India (Rajeevan et al. 2008; Krishnamurthy et al. 2009) especially during the monsoon seasons (Sen Roy 2009; Pattanaik and Rajeevan 2010). In Peninsular Malaysia, during 1971–2005 the intensity of extreme precipitation increased and the frequency decreased, while the trend in the proportion of extreme rainfall over total precipitation was not statistically significant (Zin et al. 2009). Liu et al. (2011) reported a decline in recorded precipitation events in China over 1960–2000, which was mainly accounted for by a decrease in light precipitation events, with intensities of 0.1–0.3 mm/day. Heavy precipitation also increased over the southern and northern Tibetan Plateau but decreased in the central Tibetan Plateau during 1961–2005 (You et al. 2008). In Bangladesh, an increasing trend of heavy precipitation days and decreasing trends in

consecutive dry days in pre-monsoon season during 1958–2007 was observed (Shahid 2012).

For the Indian region, the study of Alexander et al. (2006) showed largest declining trends in the annual number of consecutive dry days. Earlier study over India (Sen Roy and Balling 2004) showed that most of the time series exhibited increasing trends in indices of precipitation extremes and that there were coherent regions with increases and decreases. Recent studies by Goswami et al. (2006), Dash et al. (2009) and Pattanaik and Rajeevan (2010) using gridded rainfall data starting from 1951 and Rajeevan et al. (2008) using gridded rainfall data starting from 1901 have examined the trend in extreme heavy and moderate rain events in India. Goswami et al. (2006) showed that there was significant rising trend in the frequency and magnitude of extreme rain events over central India during monsoon season. They also found significant decreasing trend in the frequency of moderate events during the same period, thus leading to no significant in the mean rainfall. Rajeevan et al. (2008) found that extreme rain events exhibited an increasing trend between 1901 and 2005, but the trend was much stronger after 1950. Dash et al. (2009) concluded that short, dry and prolonged dry spells were increasing while the long spells were decreasing. Pattanaik and Rajeevan (2010) observed significant increasing trend in the frequency of extreme rainfall (rainfall $\geq$ 124.4 mm) events over India during southwest monsoon season. However, this increasing trend of contribution from extreme rainfall events was balanced by decreasing trend in light to rather heavy rainfall (rainfall $\leq$ 64.4 mm) events. Sen Roy (2009) investigated changes in extreme hourly rainfall in India, and found widespread increases in heavy precipitation events across India, mostly in the high-elevation regions of the northwestern Himalayas as well as along the foothills of the Himalayas extending south into the Indo–Ganges basin, particularly in the summer monsoon season during 1980–2002.

2.5 Changes in solar radiation

Solar radiation (sunshine duration) is the primary source of energy required for sustenance of life on this planet. It has profound influence on surface temperature, evaporation, the hydrologic cycle and ecosystems. Solar radiation received on the ground surface drives photosynthesis (Baldocchi 2008) and evapotranspiration (Rocha et al. 2004) of terrestrial

ecosystems, thus affecting the global carbon and water cycles. However, changes in cloudiness and aerosol content in the atmosphere can influence solar radiation received on the ground surface, balance of direct and diffuse components of the solar radiation received on the ground surface, and even regional climate (Gu et al. 2003; Niyogi et al. 2007). As a result, cloudiness change is a factor that affects carbon and water cycle of terrestrial ecosystems. Solar radiation received at the earth's surface is conditioned by the radiation received at the top of the atmosphere and by absorption and scattering due to clouds, aerosols, and gases including carbon dioxide, ozone, water vapor, oxygen, and nitrogen dioxide (Power 2003). Aerosols also affect the radiation budget indirectly by altering the formation and precipitation efficiency of clouds.

Recent studies based on the analysis in the last 50 years have documented a decline in solar radiation across the globe at a rate of 0.51 W/m^2/year, a phenomenon that is generally termed as global dimming (Stanhill and Cohen 2001; Liepert 2002; Wild et al. 2005; Alton et al. 2007) with considerable spatial, mostly latitudinal variations (Gilgen et al. 1998). The global dimming has interfered with the hydrological cycle by reducing evaporation and may have reduced rainfall in some areas. Global dimming has also created a cooling effect that may have partially masked the effect of greenhouse gases on global warming.

On the other hand, at the regional scale, other studies have detected a decreasing trends in surface solar radiation or sunshine hours – a proxy measure of global solar radiation (Stanhill 1965) over USA (Liepert 2002), Australia (Stanhill and Kalma 1994), Germany (Weber 1990; Power 2003), and different areas of western and central Europe (Power 2003; Norris and Wild 2007). The reduction of solar radiation found in the United States during the 1960–90 periods was more than double the global average (Liepert 2002). This notable decline in surface solar radiation was also detected in China (Xu et al. 2010; Zongxing et al. 2012) and was consistent with a reduction in sunshine duration, an increase in aerosol optical thickness and deterioration in atmospheric visibility (Luo et al. 2001; Kaiser and Qian 2002; Liang and Xia 2005). Zongxing et al. (2012) reported a significant decrease of sunshine hours in Southwestern China during 1961–2009. This decline was particularly strong in summer. Spatially, statistically significant decrease of sunshine hours

was mainly occurred in lower latitude regions and in the urban stations compared to rural stations reflecting the effect of urbanization on sunshine hours (Zongxing et al. 2012).

Like other parts of the world, decrease in solar radiation and sunshine duration in India was also reported by various authors (Shende and Chivate 2000; Rao et al. 2004; Ramanathan et al. 2005, Kumari et al. 2007; Jaswal 2009; Jhajharia et al. 2011). Data on radiation measurements over several stations in India showed more than 5% reduction in global radiation during December to May (Shende and Chivate 2000). From an analysis of surface solar radiation data of 12 stations located at different cities of India, Kumari et al. (2007) reported an overall decreasing trend at a rate of 0.86 W/m^2/year for the period 1981–2004 and attributed it to increase in aerosol optical depth over the country.

In a detailed study by Biggs et al. (2007) in the Krishna River basin, India during 1952–1997 reported decadal trends in cloudiness were shown to affect incoming solar radiation. Annual average cloudiness at 14 meteorological stations across the basin was decreased by 0.09% of the sky per year. The decreased cloudiness partly balanced the effects of aerosols on incoming solar radiation, resulting in a small net increase in solar radiation in monsoon months (0.1–2.9 W/m^2/decade). During the non-monsoon, aerosol forcing dominated over trends in cloud forcing, resulting in a net decrease in solar radiation (–2.8 to –5.5 W/m^2/decade). Jhajharia and Singh (2011) reported statistically significant decreasing trends of sunshine duration during winter and pre-monsoon seasons at different locations of NE India. Significant reduction of sunshine duration at Guwahati and Dibrugarh of the Brahmaputra valley was also reported by Jaswal (2009). The maximum decrease was observed during winter at Guwahati and during summer at Dibrugarh.

2.6 Climate change projection

Projections of future climate change are typically based on assumptions about future GHGs and aerosols into the atmosphere (Nakicenovic and Swart 2000). Future emissions will be influenced by the evolution of the global population, socioeconomic development, and technological advances (Lee Quere et al. 2009). The interaction of these complex and dynamic factors results in considerable uncertainty about the future trajectory of emissions (Moss et al. 2010; Thomson et al. 2011). The present climate projections exhibit large uncertainties arising among others from assumptions on greenhouse gas emissions,

incomplete climate models and the downscaling of climate projections (IPCC 2007a). Uncertainty has for many years been recognized by IPCC as crucial (IPCC 2007b), and it will receive even more attention in the forthcoming Fifth Assessment Report (AR5) (Yohe and Oppenheimer 2011). A goal of the AR5 is to apply "a common framework with associated calibrated uncertainty language that can be used to characterize findings of the assessment process" (Mastrandrea et al. 2011). According to an AR5 uncertainty guidance note, the degree of certainty of a key finding should be characterised qualitatively in terms of the confidence in the validity of a finding and the degree of agreement as well as in quantified measures of uncertainty (Mastrandrea et al. 2011).

Increasing trends of greenhouse gases in the earth's atmosphere could accelerate in the future as a consequence of which the best estimates of increase in average global surface temperature is likely to be in the range from 1.8° to 4.0°C (IPCC 2007a). The mean annual increase in temperature by the end of this century is projected to be around 3.8°C in Tibetan plateau, 3.3°C in South Asia and 2.5°C in South East Asia (IPCC 2007a). For Indian region under south Asia, the IPCC has projected 0.5–1.2°C rise in temperature by 2020, 0.88–3.16°C by 2050, and 1.56–5.44°C by 2080 depending on the pace in future development scenario. Globally, average precipitation is projected to increase, with great deviances at regional scale (Meehl et al. 2007). Although the solar radiation received at the surface will be variable geographically, on average, it is expected to decrease by about 1% (Hume & Cattle 1990).

It is *virtually certain* that increases in the frequency and magnitude of warm daily temperature extremes and decreases in cold extremes will occur through the 21st century at the global scale (Seneviratne et al. 2012). It is *likely* that the frequency of heavy precipitation or the proportion of total rainfall from heavy rainfalls will increase in the 21st century over many areas of the globe. This is particularly the case in the high latitudes and tropical regions and in winter in the northern mid–latitudes. Heavy rainfalls associated with tropical cyclones are *likely* to increase with continued warming induced by enhanced GHGs concentrations (Seneviratne et al. 2012).

Downscaled projections using the Hadley Centre Regional Model (HadRM2) indicated future increases in extreme daily maximum and minimum temperatures throughout South

Asia due to increase in greenhouse gas concentrations (Kumar et al. 2003). For the Indian subcontinent, Lal et al. (2001) projected mean warming between 1.0°C–1.4°C and 2.23°C–2.87°C in India by 2020s and 2050s, respectively. Comparatively, increase in temperature was projected to be more in winter season than in summer. During winter, the surface mean air temperature could rise by 3.0°C in northern and central parts while it would rise by 2.0°C in southern parts by 2050. In case of rainfall, an increase of 7% to 10% in annual rainfall is projected over the sub-continent by the year 2080 (Lal et al. 2001). However, the study suggested a fall in rainfall by 5% to 25% in winter while it would be 10% to 15% increase in summer monsoon rainfall over the country by 2080s. It was also reported that the date of onset of summer monsoon over India could become more variable in future.

The study of Rupa Kumar et al. (2003) revealed marked increase in both rainfall and temperature into the 21st century, particularly conspicuous after the 2040s in India. The study also showed a general increase in minimum temperature up to 4°C all over the country, which may however exceed over the southern peninsula, northeast India and also some parts of Punjab, Haryana and Bihar. The study indicated an overall decrease in number of rainy days over major parts of the country. However, number of rainy days is likely to increase by 5–10 days in the foot hills of Himalayas and northeast India. Kumar et al. (2011) projected a decrease in dry season precipitation and an increase during the rest of the year including the monsoon season.

Results from high-resolution Regional Climate Model (PRECIS), indicate that the night temperatures increase faster than the day temperatures, with the implication that cold extremes are very likely to be less severe towards the end of 21st century (Rupa Kumar et al. 2006; Revadekar et al. 2012). A more recent PRECIS simulations under both A2 and B2 scenarios in India indicated increase in frequency of heavy precipitation events and also enhancement in their intensity towards the end of the 21st century (Revadekar et al. 2012).

In NE India, PRECIS simulations for A1B emission scenario indicates that the projected mean annual rainfall in northeast India will vary from a minimum of 940±149 to 1330±174.5 mm (MoEF 2010). This increase with respect to 1970s (1961–1990) is by 0.3% to 3% with substantial decrease in rainfall in the winter months of January and February with no additional rain projected to be available during the period from March to

May and October to December. In fact, recent data indicated the same pattern. However, monsoon rainfall during June, July and August is likely to increase by 5 mm in 2030's with reference to 1970's, a negligible rise indeed. The rise in annual mean temperature in NE region may range from 1.8°C to 2.1°C in 2030s.

Section 2.7 briefly introduces the complex subject of how climate change and variability can affect agricultural productivity.

2.7 Impact of climate change on agriculture

2.7.1 General facts

Agriculture is the most weather-dependent of all human activities (Hansen 2002). The agricultural sector can be considered to be the most vulnerable to future climate changes and climate variability, including increases in incidence of extreme climatic events (Anwar et al. 2012). The potential impact of climate change on crop productivity is an additional strain on the global food system which is already facing the difficult challenge of increasing food production to feed a projected 9 billion people by 2050 with growing scarcity of water and land (Beddington 2010). Though the impact of climate change on global food production are small (Parry et al. 2001) but geographically very unevenly distributed, with losses felt mostly in arid and sub-humid tropics in Africa and South Asia (Parry et al. 2001; Aggarwal 2007) and particularly in poor countries with low capacity for adaptation (Kurukulasuriya et al. 2006). Regarding crop yields, several uncertainties are attached to future developments. Not only how exactly climate is likely to change, but also changes in CO_2 concentration and its impacts on water use efficiency of crops and the effect of CO_2 fertilization will play a major role in future crop productivities (Tubiello et al. 2007). Moreover, potential changes in management and breeding efforts, as well as changes in cropping area will also affect the agricultural sector (Moller et al. 2009).

There are two aspects of climate change on agriculture: firstly, the potential direct effects of increased CO_2 and secondly, the potential effects of changes in temperature and precipitation (Rosenzweig and Hillel 1998). The changes in climate parameters could also have an influence on factors constraining their growth such as soil quality, pests and diseases (Zhao et al. 2005). While changes in long-term mean climate will have

significance for global food production, greater risks to food security may be posed by changes in year-to-year variability and extreme weather events (Zhao et al. 2005; Khan et al. 2009). All these will have profound effects on agricultural sectors worldwide with varying degree of consequences in different regions.

The following sub-sections briefly introduces the major physiological effects of CO_2 increase, direct impact of climate change induced changes in temperature and rainfall patterns, and indirect impacts of climate change like pest-disease incidence on agricultural productivity.

2.7.2 CO_2 fertilization effect

One of the most important parameters of climate change impact assessment on crop productivity is the atmospheric concentration of CO_2 (Lobell and Field 2008). Plants take up CO_2 via photosynthesis and use it to produce sugars and plant matter (Zavala et al. 2008). When atmospheric CO_2 concentration increases, plants produce more vegetative matter. This effect is generally referred to as the "CO_2 fertilization effect". However, rising atmospheric CO_2 will have different effects, depending on crop species. The magnitude of CO_2 fertilization effect depends on whether the plant is so-called C_3 or C_4 plant. Since C_3 plants use CO_2 less efficiently than C_4 plants, they are more sensitive to higher concentrations of CO_2 and are hence more likely to benefit from a higher atmospheric CO_2 concentration (Nelson et al. 2009). Considering world food production under climate change, this has significant implications since some of the current major staple foods, such as rice, wheat, potato, and soybean are C_3 plants. So-called C_4 plants, such as maize, sorghum, millets and sugarcane, are comparatively less responsive to increased CO_2 (Allen 1990; Lee 2011). Experiments under idealized conditions showed that doubling the atmospheric CO_2 concentration increases photosynthesis by 30% – 50% in C_3 plant species and 10% – 25% in C_4 species (Long et al. 1993; Ainsworth and Long, 2005). Based on analysis of recent data, the IPCC reports suggested that yields may increase by 10% – 25% for C_3 crops and by 0% – 10% for C_4 crops when CO_2 levels reach 550 ppm (IPCC 2007b).

The CO_2 fertilization effect hence could not only increase the capacity of plant system to absorb and temporarily store excess carbon, it could also potentially lead to significant increases in crop productivity and offset potential productivity declines resulting from

climate change such as higher temperature and altered precipitation patterns (Wolfe 2010). The extent to which CO_2 enrichment leads to positive growth effects, however, also depends on the plants availability of other important growth parameters such as light, water, and soil nutrients (Rosenzweig and Hillel 1998). Since the magnitude of the CO_2 fertilization effect is very much debated (Long et al. 2006; Tubiello et al. 2007) and one of the major sources of uncertainty when assessing the potential impacts of climate change on the agricultural sector, most climate impact studies account for the potential yield enhancing effect of increased CO_2 by comparing a "with CO_2" effect versus a "without CO_2" effect scenario. Results of impact studies on agricultural sector vary greatly. Parry et al. (2004), for example, had estimated global cereal production decline up to 400 million tons by 2080 under a "without CO_2" fertilization effect scenario. However, when the CO_2 effect was taken into account, the decrease was reduced up to 90 million tons. Similarly, according to Moeller and Grethe (2010), a 2% decline in global crop production capacity can be expected if carbon fertilization is not considered by 2050, compared to an increase by 1%, if the fertilization effect is accounted for.

2.7.3 Effect of temperature and precipitation

Most plant processes related to growth and yield are highly temperature dependent (Wolfe 2010). Yet, temperature stress is among the least well understood of all plant processes and less research has been investigated in crop responses to high temperature per se, as compared to CO_2 effects on crop growth (Rosenzweig and Hillel 1998). Whereas an increase in temperature generally accelerates metabolic activity, excessively high temperatures may cause enzymatic damage (Fitter and Hay 1987). For any crop there is an optimum temperature range for maximum yield which frequently corresponds to the optimum temperature for photosynthesis. Furthermore, higher temperatures accelerate annual crops through their developmental phases which lead to shortened life cycles of certain crops (Wolfe 2010). Up to a certain level of temperature, faster reaction rates are beneficial, but some plant processes tend to be perturbed beyond that point. The balance of the two effects determines the plant's overall response to higher temperatures and varies among different crops (Rosenzweig and Hillel 1998). Hence, a temperature increase of several degrees could reduce photosynthesis and shorten the growing period for crops which are currently grown in a climate near its optimum (seasonally arid and tropical

regions), and lead to reduced yields. As in major production areas the best adapted varieties are being cultivated, an increase of growing season temperature could necessitate shifts to new varieties (Wolfe 2010).

The modeling studies by IPCC (Easterling et al. 2007) indicated that moderate to medium increases in mean temperature (1–3°C), along with associated CO_2 increases and rainfall changes are expected to benefit crop yields in temperate regions. However, in low–latitude regions, moderate temperature increases (1–2°C) are likely to have negative yield impacts for major cereals. Warming of more than 3°C would have negative impacts in all regions. This is because, in seasonally arid and tropical regions (temperatures already close to physiological maxima for crops), higher temperatures may be more immediately detrimental, increasing heat stress on crops and water loss by evaporation. A 2°C local warming in the mid–latitudes could increase wheat production by nearly 10% whereas at low latitudes the same amount of warming may decrease yields nearly the same amount.

The historical temperature – yield relationships also indicated that warming from 1981 to 2002 is very likely to offset some of the yield gains from technological advance, rising CO_2 and other non-climatic factors (Lobell and Field 2007). In India, Lal et al. (1998) concluded that carbon fertilization effects would not be able to offset the negative impacts of high temperature on rice yields in northwestern parts. Aggarwal (2007) indicated the possibility of loss of 4–5 million tons of wheat production with every rise of 1°C temperature throughout the growing period, even after considering benefits of carbon fertilization.

Precipitation is the major determinant for soil moisture, so varying precipitation patterns have a significant impact on agriculture. Water stress during sensitive development stages will have severe impacts on crop yields (Rosenzweig and Hillel 1998). Increases in the amount of precipitation are very likely in high latitudes, while decreases are likely in most subtropical land regions (IPCC 2007a). Global Climate Models (GCM) predicts an overall increase in mean precipitation as well as changes in total seasonal precipitation, within-season pattern and between-season variability of future precipitation (IPCC 2007a). This may be even more important than an equal change in the annual total (Iglesias et al. 2009). Precipitation is not the only influence on water availability. Increasing evaporative demand

owing to rising temperature and longer growing seasons could increase crop irrigation requirements globally by between 5% and 20%, or possibly more, by the 2070s or 2080s (Doll 2002; Fisher et al. 2006), but with large regional variations (Arnell et al. 2004). Increased rainfall would increase the chance of flooding in tropical and sub-tropical regions with monsoonal climates, such as parts of the Philippines, where simulated rainfed rice yields were decreased by 10% increase in rainfall, due to flooding in areas the with already high seasonal rainfall and for similar rainfall regime in Indonesia, yields did not reduce with about 10% decrease in seasonal rainfall (Buan et al. 1996). In Japan, while increased precipitation reduce irrigation requirement, decreased precipitation did not have any adverse effect on the simulated yields of irrigated rice (Seino 1994, 1995). In the tropical area of Kerala, India there would be an exponential increase in simulated rice yields for an increase in rainfall up to 15 mm/day above the local rainfall, but a yield loss of about 50% for decrease in rainfall by 15 mm/day (Saseendran et al. 2000). Recent simulation analysis in India indicated that maize yields during monsoon are projected to be adversely affected due to rise in atmospheric temperature; but increased rainfall can partly offset those loses and the spatio-temporal variations in projected changes in temperature and rainfall are likely to lead to differential impacts in the different regions (Byjesh et al. 2010). Analysis on sorghum also indicated that the yield loss due to rise in temperature is likely to be offset by projected increase in rainfall. However, complete amelioration of yield loss beyond 2°C rise may not be attained even after doubling of rainfall (Srivastava et al. 2010).

2.7.4 Effect of climate variability and extreme weather events

While change in long-term mean climate will have significance for global food production, greater risks to food security may be posed by changes in year-to-year variability to extreme weather events. Many food crops are highly susceptible to episodes of high temperature at critical points in the growing cycle (Slingo 2005), which can result in large decreases in yield. Tian et al. (2010) for example, observed in rice that high temperatures (>35°C) coupled with high humidity and low wind speed caused panicle temperatures to be as much as 4°C higher than air temperature, causing irreversible yield loss because of floret sterility. Impacts of temperature extremes may not be limited to daytime events. Mohammed and Tarpley (2009) observed that rice yields were reduced by 90% when night

temperatures were increased from 27°C to 32°C. Challinor et al. (2006) looked at the effects of extremes of temperature on yield for wheat, groundnut and soybean and found significant decreases in yield for crops in some areas, depending on the variety. Only a few days of extreme temperature (greater than 32°C) at the flowering stage of many crops can drastically reduce yield (Wheeler et al. 2000). In 1972, extremely high summer averaged temperature in the former Soviet Union (USSR) contributed to widespread disruptions in world cereal markets and food security (Battisti and Naylor 2009). During winter season of 2002–03, summer (*boro*) rice in the Brahmaputra valley experienced a long spell of cold stress resulting in seedling mortality varying from 20.7% to 50.8% (Sarma 2003). In March 2004, temperatures were higher in the Indo-Gangetic plains of India by 3–6°C, which is equivalent to almost 1°C per day over the whole crop season. As a result, wheat crop matured earlier by 10–20 days and wheat production dropped by more than 4 million tons in the country (Samra and Singh 2004).

Historically, many of the largest falls in crop yield have been attributed to anomalously low precipitation events (Kumar et al. 2004). Lobell and Burke (2008) reported that a change in growing season precipitation by one standard deviation can be associated with as much as 10% change in production (e.g., millet in South Asia). Indian agriculture is highly dependent on the spatial and temporal distribution of summer monsoon rainfall (Selvaraju 2003; Kumar et al. 2004). Selvaraju (2003) found significant correlation between SMR and all India foodgrain production (r = 0.71) in India. Among the individual crops, rice (r = 0.66), wheat (r = 0.49) and chickpea (r = 0.49) production had significant association with summer monsoon rainfall. Asada and Matsumoto (2009), on the other hand, showed that different regions of India were sensitive to precipitation extremes in different ways. Rice yield in the upper Ganges basin was linked to total rainfall during the relatively short growing season and was thus sensitive to drought. Conversely, the lower Ganges basin was sensitive to pluvial flooding and the Brahmaputra basin demonstrated an increasing effect of rainfall variability on rice yield, in particular drought.

The balance between the potential positive and negative effects of increasing CO_2, changing temperature and precipitation will determine the net change of crop productivity (Adams et al. 1998). However, there are also indirect effects which contribute to crop

growth and development which will likely to be altered by climate change. Such indirect effects may arise from changes in the incidence and distribution of pests and pathogens (Sutherst et al. 1995; Patterson et al. 1999), augmented soil erosion and degradation, and increased tropospheric ozone levels due to rising temperatures (Adams 1986). They have been addressed to a much lesser extend in the assessment of climate change effects (Adams et al. 1998). The next sub-section describes the potential impacts of climate change on pests and plant diseases.

2.7.5 Impact on pest and diseases

Many assessments of climate change effects on crops have focused on potential yields, but factors such as pests and pathogens which have major effects in determining actual yields have mostly been neglected (Gregory et al. 1999; 2009). Elevated levels of atmospheric CO_2 can profoundly affect the interactions between crop plants and insect pests and may even promote the rapid establishment of invasive species. Although it was acknowledged that invasive species can negatively impact on agricultural productivity, most climate impact assessments on the agricultural sector did not consider them (Ziska et al. 2007). Zavala et al. (2008), for example, found that elevated CO_2 increased the susceptibility of soybean plants to the invasive Japanese beetle and to a variant of western corn root worm. According to Wolfe (2010), the geographic range of insect and disease pests will most likely change. Warmer temperatures in high latitude areas might provide more favourable conditions during winter for more insects and thus increase their ability to survive (Wolfe, 2010). Increased temperature also reduces the overwintering mortality of aphids enabling earlier and potentially more widespread dispersion (Zhou et al. 1995). These studies suggested that climate change is also likely to increase the spread of plant pathogens spread by aphid vectors in several crops which could lead to reduced yields (Harrington et al. 2007). Also fungal and bacterial diseases might have greater potential to spread in temperate regions under warmer and wetter climatic conditions (Wolfe 2010). Altered precipitation patterns can also have significant effects on insect populations. Evidence suggests that in sub-Saharan Africa migration patterns of locusts may be influenced by rainfall patterns (Cheke and Tratalos 2007) and thus potential exist for climate change to shape the impacts of this devastating pest. The impacts of pests and diseases on crop yields under nowadays conditions are well known, but the consequences of climate change on

pests and disease are complex and only imperfectly understood (Gregory et al. 2009). Including realistic impacts of pests and disease into climate impact studies would certainly lead to a more realistic prediction of future crop production under climate change (Ingram et al. 2008). Different methods utilized in assessing the climate impacts on agriculture are discussed briefly in section 2.8.

2.8 Methods for assessing climate change impact on Agriculture

Predicting the potential effects of climate change on crop yields requires a model of how crops respond to weather. To translate climate scenarios into possible agricultural outputs, two distinct approaches are usually adopted: process-based crop modeling and statistical modeling, both of which aim at estimating crop productivity as a response to climate (Roudier et al. 2011). The process-based crop models represent the physiological processes of crop growth and development as a response to climate (Rosenzweig and Iglesias 1998; Lobell et al. 2008; Iglesias and Quiroga 2007). Most previous work on climate change impacts on agriculture has used crop simulation models which predict crop responses to environmental conditions at a specific point. Such crop simulation models usually require site-specific data as inputs, such as information on weather, physical and chemical soil properties, genotype characteristics, and crop management (Whistler et al. 1986; Penning de Vries et al. 1989; Chipanshi et al. 2003). Several studies have been carried out to develop and integrated assessment of climate variability as well as climate change on regional and global supplies and demand using a dynamic model framework (Rosenzweig and Parry 1994; Adams et al. 1995). The main advantage of crop growth simulation model is the explicit formulation of physiological plant processes. A weakness though is the uncertainty about these physiological processes and often production and nutrient systems are taken as exogenous variables, which prevents the account for behavioral responses of farmers (Lobell and Field 2007).

Empirical crop models are statistical relationships derived from observations, linking crop yields in a given location to local climate. Statistical models, in which historical data on crop yields and weather are used to calibrate relatively simple regression equation, provide a common alternative to process–based models (Antle and Capalbo 2001; Parry et al. 2004; Lobell and Burke 2010; Rowhani et al. 2011). Three main types of statistical

approaches are found in literature: those based purely on time series data from a single point or area (time series methods), those based on variations both in time and space (panel methods), and those based solely on variations in space (cross-section method). The performance of statistical models differed by climate variable and spatial scale, with time–series statistical models ably reproducing site-specific yield response to precipitation change, but performing less well for temperature responses. In contrast, statistical models that relied on information from multiple sites, namely panel and cross-sectional models were better at predicting responses to temperature change than precipitation change (Lobell Burke 2010). The use of statistical yield models, developed at regional scale with regional inputs like historical weather and crop yield have advantage that they intrinsically account for a wide variety of mechanisms that can influence yields in a changing climate (Lobell 2007). Another advantage of statistical models is their limited reliance on field calibration data and their transparent assessment of model uncertainties (Lobell and Burke 2010). However, unlike process-based models, statistical models do not allow explicit consideration of management changes or other factors, such as CO_2 increases, that may alter the effect of climate on yields in the future, and in particular they are subject to problems of co-linearity between predictor variables (Lobell et al. 2006). However, where models are founded on a good knowledge of the determining processes and where there are good grounds for extrapolation, they can still be useful predictive tools in climate impact assessment (Mavi and Tupper 2004). There are already numerous large scale (Parry et al. 2004; Lobell and Field 2007; Lobell et al. 2008; Iglesias et al. 2009) and regional studies (Rosenzweig et al. 1999; Iglesias et al. 2000; Iglesias and Quiroga 2007; Almaraz et al, 2008; Reidsma et al. 2009) about multiple regression models estimating crop yields under past and future climatic conditions.

A brief review on impact of climate change and variability on rice and tea productivity is presented in the following sections.

2.9 Impact of climate change on growth and yield of rice

When temperatures exceed the optimal for biological processes, crops often respond negatively with a steep decline in net growth and yield (Rosenzweig and Hillel 1995). Extreme temperatures whether low or high, cause injury to rice plant. For delineating

specific time periods suitable for maximal production of rice at a given location, it is necessary to know the cardinal (high, low and optimal) temperature requirements of various rice growth stages. From the literature cited by Yoshida (1977), WMO (1983) and Venkataraman (1987), the low, high and optimal temperature requirements for important rice growth stages are given in Table 2.1**.**

Table 2.1 Temperature requirement for important growth stages of rice

Growth stages	Critical temperature/cardinal temperature (°C)		
	Low	High	Optimum
Germination	10	45	20 to 35
Seedling emergence	12	35	25 to 30
Transplanting	>8	–	–
Rooting	16	35	25 to 28
Leaf emergence and elongation	7	45	30 to 35
Tillering	16	33	25 to 31
Flower initiation	15	–	24 to 29
Anthesis	22	35	30 to 33
Ripening	12	>30	20 to 25

Depending on varieties, rice requires a mean temperature above 20°C throughout the growing period (Venkataraman and Krishnan 1992). The optimum air temperature range required for vegetative growth is between 25°C and 30°C. Extreme high temperatures during vegetative growth reduce tiller number and plant height and negatively affect panicle and pollen development, thereby decreasing rice yield potential (Yoshida 1981). Exposure to high temperatures (>35°C) can greatly reduce pollen viability and cause irreversible yield loss because of spikelet sterility (Matsui et al. 2001). Temperatures above the optimum (20–25°C) shorten the grain-filling period and reduce final yield (Yoshida 1981). In warm temperate/tropical regions depending on variety, local climate, growing season, soil moisture retention capacity and percolation losses, total water requirement in field from planting till harvesting varies from 800 mm to 1800 mm (Kakde 1985). Solar radiation becomes critical for a period of six weeks starting with the panicle initiation stage up to about eight days before maturity (Pal et al. 1996).

The simulations by different crop models and many field experiments have shown the potential impact of climate change and the variability on rice productivity. In a major

study, Mathews et al. (1995) used the ORYZA1 and SIMRIW crop simulation models to predict changes in rice production for all the major rice producing countries in Asia under three different climate change scenarios. In general, an increase in CO_2 level was found to increase yields while increases in temperature reduce yields. From that experiment decline in rice yield were predicted under the Goddard Institute of Space Studies (GISS) and United Kingdom Meteorological Office (UKMO) scenarios for Thailand, Bangladesh, southern China and western India; while yield increases were predicted for Indonesia, Malaysia, Taiwan, parts of India and China.

Peng et al. (2004) analyzed weather data at the International Rice Research Institute (IRRI) farm from 1979 to 2003 to examine the temperature trends and the relationships between rice yields and temperature. Annual mean maximum and minimum temperatures increased by 0.35 and 1.13°C, respectively, for the above period and a close correlation between rice grain yield and mean minimum temperature was observed. They concluded that the grain yield declined by 10% for each 1°C increase in minimum temperature in the dry season whereas the effect of maximum temperature was insignificant. Subsequently, a reanalysis of the data from that study, Sheehy et al. (2006) concluded that the actual impact of minimum temperature was much smaller, because minimum temperature was negatively correlated with radiation, thus confounding the observed impact of minimum temperature with the omitted impact of radiation. Lobell (2007) also found that rising of maximum temperature was more harmful to rice yields than minimum temperature in most countries, which contradicts the major negative effect of minimum temperature inferred by Peng et al. (2004). These arguments indicated that current understanding of the impact of temperature on crop yield is still uncertain.

There have been some studies in India aimed at understanding the nature and magnitude of gains and/or losses in yield of rice crop at selected sites under climate variability and change (Sinha and Swaminathan 1991; Abrol et al. 1991; Aggarwal and Sinha 1993; Rao and Sinha 1994; Hundal and Kaur 1996; Lal et al. 1998; Rathore et al. 2001; Mall and Aggarwal 2002; Subash and Ram Mohan 2012). Sinha and Swaminathan (1991) estimated that a 2°C increase in mean temperature could decrease rice yield by about 0.75 ton/ha in the high yield areas and by about 0.06 ton/ha in low yield coastal regions of India. Hundal

and Kaur (1996) examined climate change impact on productivity of rice in Punjab using CERES–rice model. They concluded that, if all other climate variables were to remain constant, temperature increase of 1°, 2° and 3°C from present day condition would reduce grain yield of rice by 5.4%, 7.4% and 25.1%, respectively. In general, the simulation results indicated that increasing temperature and decreasing radiation levels pose a serious threat in decreasing growth and yields of cereal crops (Hundal and Kaur 1996). Lal et al. (1998) examined the vulnerability of rice crop in northwest India to climate change and found that under elevated CO_2 levels, yield of rice increased significantly by 15% for a doubling of CO_2. However, a 2°C rise in temperature cancelled out the carbon fertilization effect. Analyzing the effect of climate change (increase in monsoon season mean temperature of the order of 1.5°C, an increase rainfall of the order of 2 mm per day and CO_2 460 ppm) on rice crop over the Kerala state, Saseendran et al. (2000) showed that the rice maturity period was shortened by 8% and yield increased by 12%. They demonstrated that when temperature elevations only are taken into consideration, the crop simulations showed a decrease of 8% in crop maturity period and 6% in yield. They also showed that for every one degree rise in temperature, the decline in rice yield would be about 6% over the state.

Aggarwal and Mall (2002) studied the impact of various climate change scenarios on grain yield of rice using CERES–Rice and ORYZA1N at different levels of management in different regions of India (North, West, South and East). Increase of 1° to 2°C temperature without any increase in CO_2 resulted in a 3% – 17% decrease in grain yield in different regions. In general, as the temperatures increased, rice yields in eastern and western India were less affected, moderately affected in north whereas severely affected in southern India. Grain yields increased in all regions as the CO_2 concentration increased. A doubling of CO_2 resulted in 12% to 21% increases in yield in different regions. They also showed that the beneficial effect of 450 ppm CO_2 was nullified by an increase of 1.9° – 2.0°C in northern and eastern regions and by 0.9° – 1.0°C in southern and western regions.

Pathak et al. (2003) studied trends of climatic potential yields and on-farm yield rice in the Indo–Gangetic Plains using the DSSAT model (CERES–Rice). Negative yield trends were observed at six of the nine sites, four of which were statistically significant ($P < 0.05$). The

decrease in radiation and increase in minimum temperature were identified as the reasons for the yield decline. They showed that solar radiation decrease by 1.7 MJ/m^2/day reduced rice yield from 10.9 to 10.3 ton/ha. Increase in minimum temperature by 1.7°C decreased yield of rice from 10.9 to 10.0 ton/ha.

Krishnan et al. (2007) simulated the impact of CO_2 and temperature on rice yield (variety IR 36) at 10 different sites of eastern India using the ORYZA1 and the INFOCROP rice models. In general, for every 1°C increase in temperature, the ORYZA1 and INFOCROP rice models predicted average yield changes of –7.2% and –6.6% respectively at the current level of CO_2 (380 ppm). But considerable differences in the yield predictions under three GCM scenarios (GFDL, GISS and UKMO) were observed for individual sites, with maximum declining trend for Cuttack and Bhubneswar but an increasing trend only for Jorhat. These differences in yield predictions were mainly attributed to the sterility of rice spikelets at higher temperatures. For instance, Cuttack and Bhubaneswar had high maximum temperature of about 34°C and minimum temperature of 25°C during the flowering period. But Jorhat had the maximum temperature of about 28°C and a minimum temperature of 19°C only, which probably contributed to the benefits from the predicted effects of climate change scenarios (Krishnan et al. 2007). Recently, Kumar et al. (2011) reported the results of simulation analysis (using INFOCROP model) on various crops in NE India and inferred that climate change may bring changes in irrigated rice yields by about –10% and 5%, while in the rain-fed rice are likely to be in the range of –35% to 5% in A1B 2030 climate scenarios.

2.10 Impact of climate change on growth and yield of tea

Tea (*Camellia sinensis* (L.) O. Kuntze) is an evergreen understorey shrub from the genus *Camellia* that includes some 82 species (Banerjee 1992a). The variety *sinensis,* also called 'China tea' is more drought–tolerant and can survive short frost periods. The variety *assamica* also called 'Assam tea' is a tropical variety sensitive to dry and cold weather conditions (Banerjee 1992b). The annual yield distribution and potential yield of tea is largely influenced by seasonal fluctuations in weather variables such as rainfall, temperature and saturation deficit, soil water deficit (Squire 1979; Tandon 1982; Stephens and Carr 1990) and by photoperiod (Barua 1969). Seasonal fluctuations in tea yield within

a year is a well documented phenomenon in many environments, with both short-term variation during a growing season (Fordham 1977) and variation between seasons of the year (Barua 1969; Squire 1979). Large yield peaks often occur following a cool or dry season, with subsequent peaks that may continue throughout the remainder of the season (Tandon 1982). The timing and amplitude of those peaks depend on the prevailing weather and can vary considerably from year to year (Panda et al. 2003). Kamau (2008) found seasonal rainfall differences in years to have a marked effect on tea yields. The plucking interval is determined by temperatures or other limiting factors (Bonheure 1990, Barua 1989). Different workers reported different ranges for optimum temperatures, i.e. while Tandon (1982) has given the optimum to be from 18°C to 20°C, Carr and Stephens (1992) have used a wider range from 18°C to 30°C. Barua (1989) stated that tea grows best within a range of 13°C–30°C. The minimum or base temperature for growth (Tb) is around 13°C while the maximum ideal temperature is 30°C and within these limits, shoot growth will increase linearly (Carr and Stephens 1992). Thus in tea, there are two distinct phases to the temperature response, a base temperature effect and the linear response. It has been noted that day-time temperatures above 30°C and night-time temperatures below 10°C lead to reduction in the rate of leaf growth (Burgess 1996).

Tea is usually grown in regions with evenly distributed rainfall between 1300 to 2200 mm per year (Ng'etich and Stephens 2001). The *assamica* varieties are less hardy than the *sinensis* varieties, which can tolerate a longer dry season or lower temperature (Bonheure 1990). It has been estimated that unshaded tea transpires up to 2200 mm water per ha per year (Anandacoomaraswamy et al. 2000) depending on the area. Solar radiation (sunshine) is an important factor and the tea plant requires on average at least five sunshine hours per day. Tea yield drops significantly under cloudy conditions and with heavy and continuous rainfall, just like it does when the weather is hot, dry and sunny (Anandacoomaraswamy et al. 2000). Rainfall up to 180 mm and rise in mean temperature during cold weather period proved most beneficial to the early crop (April to June) in Assam valley (Sen et al. 1966). Rainfall and mean temperature during cold weather period along with rainfall during July to September were the most potent climatic variables influencing the main crop. However, the rate of increase in yield of late crop (October to December) with increase in mean temperature tended to decrease with an increase in rainfall (Sen et al. 1966).

Studies by Wijeratne (1996) on the likely impact of climate change on the tea industry of Sri Lanka showed that tea yield is sensitive to temperature, drought, and heavy rainfall. An increase in the frequency of droughts and extreme rainfall events could result in a decline in tea yield, which would be greatest in the low-altitude regions (< 600 m).

Wijeratne et al. (2007) found that the optimum temperature for tea cultivation is 22°C, and the optimum rainfall varies from 223 to 417 mm per month in different tea growing regions of Sri Lanka. Reduction of monthly rainfall by 100 mm could reduce productivity by 30–80 kg of made tea per hectare. Field experiments showed that the increase in ambient CO_2 concentration from 370 ppm to 600 ppm, increased tea yield by about 33% – 37% depending on elevation (Wijeratne et al. 2007). Rising temperatures were beneficial to tea grown at high elevations (>1200 m amsl) as it helps to reach optimum temperature for tea (22°C). However, it was predicted that rising temperatures and dry weather conditions in warmer regions where the present temperatures are above optimum for tea (low; <600 m amsl and mid; 600–1200 m amsl elevations) will mask the benefits of CO_2 enrichment and limit tea production (Table 2.2).

Table 2.2 Tea yields at four locations projected by the synthetic scenarios (increase in temperature by 1° and 2°C, increase in rainfall by 10%, decrease in rainfall by 10% and increase in ambient CO_2 level to 435 ppm) for the year 2050 (Wijeratne et al. 2007)

CO_2 (µmol/mol)	Rainfall change (%)	Temperature change (°C)	Yield (kg/ha/year)			
			Ratnapura	Kendy	Nuwara Eeliya	Passara
370	0	0	2489	2217	2465	2651
370	0	1	2282	2217	2651	2569
370	0	2	2070	2117	2760	2469
370	−10	0	2456	2161	2418	2591
370	+10	0	2482	2305	2480	2749
435	0	0	2710	2695	3035	3080
435	0	1	2502	2567	3035	2998

In order to minimize the adverse impacts of climate change on agriculture and attaining its sustainable development, there are needs for developing rational adaptation strategies and enhancing the capacity to adopt those strategies. The following section briefly introduces different possible adaptation-mitigation strategies for combating adverse impact of climate change on rice and tea crop.

2.11 Adaptation-mitigation strategies for rice and tea crop

Agriculture is not only sensitive to climate change but at the same time is one of the major drivers of climate change (Rosenzweig and Hillel 2000). Agriculture accounts for 13.5% of global GHG emissions or 6.6 Gt of CO_2 eqv./yr (IPCC 2007b), mainly in the form of CH_4 and N_2O from fertilized soils, enteric fermentation, biomass burning, rice production as well as manure and fertilizer production. At the same time agricultural ecosystem have a very high potential for reducing emissions and enhancing carbon sinks (IPCC 2007c). Controlling emissions and concentration can be one of the most important mitigation strategies, such as controlling emission of GHGs and/or enhancing carbon sinks, alter fertilizer application, lower use of herbicide and pesticide sprays (reduces fuel requirements) and use of conservation tillage (Voghefi et al. 2011). For instance, the rate of CH_4 emission from flooded rice soils is determined by water regime, organic matter management, temperature and soil properties as well as rice plants (Nguyen 2002). Mid-season drainage or intermittent irrigation, which prevents the development of soil reductive conditions, is considered to be an effective option for mitigating methane emissions from rice fields (Yagi et al. 1997). Improving organic matter management by promoting aerobic degradation through composting or incorporation into soil during the off-season drained period is another promising technique (Kalra et al. 2004). Improving N use efficiency can reduce N_2O emissions and indirectly reduce GHG emissions from N fertilizer manufacture (Schlesinger 1999). Adjusting application rates based on precise estimation of crop needs, using slow- or controlled- release fertilizer forms or nitrification inhibitors, applying N when least susceptible to loss, often just prior to plant uptake; placing the N more precisely into the soil to make it more accessible to crop roots (Paustian et al. 2004, Robertson 2004) are some of the practices which improve N use efficiency. Improved agronomic practices that increase yields and generate higher inputs of carbon residue can lead to increased soil carbon storage (Follett 2001). Such practices include: using improved crop varieties, extending crop rotations, notably those with perennial crops that allocate more carbon below ground and avoiding or reducing use of bare fallow (Lal 2003). Emissions per hectare can be reduced by adopting cropping systems with reduced reliance on fertilizers (rotations with legume crops), pesticides and other inputs (Paustian et al. 2004).

Adaptation measures to mitigate the potential impact of climate change on rice crop include possible changes in sowing/transplanting dates, cropping pattern and genotype selection (Attri and Rathore 2003; Rathore and Stigter 2007). Among these adaptation options, changing sowing/transplanting date can be an effective, low-cost option to take advantage of the longer growing season or to avoid crop exposure to adverse climate (Wolfe et al. 2008). As temperature varies from month to month, it is possible to select the right date for crop establishment in such a way that reproductive and grain filling period of rice fall into those months with a relatively low temperature. This would minimize the negative impact of temperature increase on rice yields as reported by Peng et al. (2004).

Adjustment of sowing dates options in rice crop was explored by Krishnan et al. (2007) under the future climate change scenarios at two sites of eastern India i.e., Cuttack and Jorhat. Average yield changes of +6.6, +4.1 and –9.8% were predicted at Cuttack during July 15 sowing for the GFDL, GISS and UKMO scenarios, respectively, considerably higher than those of –19.67, –20.32 and –30.75% observed during June 15 sowing for the corresponding scenarios. Likewise, the Jorhat site showed +27.1, +24.3 and +13.4% changes for the sowing on July 1 under the GFDL, GISS and UKMO model scenarios, respectively; these changes were considerably higher than those of +12.13, +12.64 and +8.31% for the June 15 sowing for the corresponding scenarios.

The other options like introducing late or early maturing crop varieties depending on the available growing season, developing drought/flood tolerant varieties, conserving soil and moisture through appropriate tillage practices and efficient water harvesting techniques are also important. The use of longer-maturing varieties to take advantage of longer growing seasons at higher latitudes may instead result in lower yield, due to grain formation and ripening periods being pushed to less favourable conditions later in the season (Mathews et al. 1996). Under this situation, a better strategy might be to select for shorter-maturing varieties to allow a second crop to be grown in these regions. Warmer temperatures, longer growing seasons and increased drought will lead to increase agricultural water use (Voghefi et al. 2011). Water storage facilities should be expanded and manage more efficiently.

The rice germplasm of northeast India not only endowed with genetic diversity, but also represents a wealth of valuable genotypes. The present stock of rice germplasm of NE India contains 5052 accessions out of 12256 rice collections (Paroda and Sharma 1986). Moreover, there exist a good number of traditional varieties having important traits like drought and flood tolerance, insect-pest and disease resistance. The submergence tolerant variety 'FR13A' (shows tolerance up to 14 days of flooding) has been used to develop improved rice cultivars with submergence tolerance (MacKill et al. 1993).

Unlike annual crops, perennial cropping systems which include long-lived crops like tea are generally less adaptable and thus potentially are more susceptible to damage due to changes in climate (Lobell et al. 2006). In tea growing areas of NE India, with the potential evaporation greatly exceeding rainfall in cold weather season there is likelihood of water deficits (Bhagat et al. 2009). An effort to adapt to this rainfall change can help to combat this change by judiciously and properly utilizing and conserving water resources through water harvesting and water saving techniques. Another uncertainty regarding the potential changes in temperature and rainfall on tea yields is the effect of pest and disease levels, which is likely to increase with temperature. Specific adaptation related to proliferation of pest and disesase may be required to handle such adversity. The adaptation strategies to minimize the adverse effects of climate variability and change on tea may include: use of hardy tea clones that are resistant to drought, pests, diseases; microclimate management by proper shade management; expansion of multicropping systems to reduce risk of monocropping (Wijeratne 1996).

2.12 Summary

This chapter presented a comprehensive literature review that brought forward the state of the art knowledge on observed and predicted changes in important climatic variables and their impact on agricultural productivity on a global, continental and regional perspectives. There had been significant warming globally throughout the 20th century. However the rates of warming were different among regions. During the same period, global land precipitation showed an insignificant upward trend with large spatial, temporal, seasonal and inter-decadal variations. A significant proportion of global land area has been increasingly affected by significant changes in climatic extremes during the second half of

the 20th century. There had been an overall decrease in the number of cold days and nights, and an overall increase in the number of warm days and nights at the global scale, that is for most land areas. There has been statistically significant increase in the number of heavy precipitation events in more regions than there have been statistically significant decreases, but there are strong regional and sub-regional variations in the trends. In contrast, patterns of precipitation extremes and their changes showed a large spatial variability, and therefore, the analysis of regional extreme precipitation is very important for the assessment of hydrological consequences, such as floods and droughts on various economic sectors. Although several attempts have been made to study monsoon and annual rainfall trends in India, as discussed in sections 2.3 detailed analysis of seasonal extreme rainfall and temperature changes using observed data in the Brahmaputra valley is scarce.

The major physiological effects of CO_2 increase, direct impact of climate change induced changes in temperature and rainfall patterns and indirect impacts of climate change like pest-disease outbreaks on agricultural productivity have been exclusively discussed in section 2.7. The impact of climate change on global food production is very small but geographically unevenly distributed, with losses felt mostly in poor countries with low capacity for adaptation. Though the potential impact of climate change on rice productivity had been studied by using crop simulations models at various locations of India, literature on use of process-based crop models are scarce except the works of Krishnan et al. (2007) and Kumar et al. (2011). Literature on use of CERES-Rice model in the Brahmaputra valley using experiment-based data on most popular rice varieties are not available. Though the impact of inter-annual variability of climate and extreme weather events were found to be more significant than changes in mean climate alone such studies are not available in this part of India except the work of Asada and Matsumoto (2009). The impact of observed climate trends on rice productivity by use of statistical model as well as projected climate change scenarios by using process-based CERES-Rice model are studied in a part of the Brahmaputra valley and reported in Chapter 5. In comparison to rice, climate change impact studies on tea are very limited in literature. Only few reports on such studies are available from Sri Lanka. The impact of climate change on tea productivity has been studied by empirical statistical approach and reported in Chapter 6.

Chapter 3

Study Area

The objective of this chapter is to provide relevant information on location, physiography, climatic features and seasonal weather patterns of the study area. It also includes information on the present status of agriculture including cropping patterns and soils as well as water related hazards that may have implications to crop productivity.

3.1 Location

The Brahmaputra valley is located in the tropical latitudes of 23°N to 28°N and eastern longitudes of 89°42'E to 96°01'E. The valley is bounded in the north by Himalayan mountain ranges, in the east by the Patkai hill ranges, in the south by the lower (Assam) hill ranges (Garo-Khasi-Jayantia) and in the west, it is contiguous with the plains of Bangladesh (Fig 3.1). It represents a unique landscape in the form of a 720 km long and 90 km wide valley (Goswami 1985) in Northeast (NE) India separated from the comparatively low lying Barak valley in the south by the Mikir hills and the Barail range in the central part (Fig. 3.1). The orientation of the valley is east-west in between 90°E to 92°E and along roughly about NE-SW between 90°E and 95°E (Fig 3.1).

3.2 Physiography

The valley is the dominant physiographic unit of Assam, covering 71.7 per cent of the total geographical area (78,438 km^2). The valley is an alluvial plain surrounded by hills and interspersed with small hillocks, uplands, lowlands and swampy lowlands. The river Brahmaputra constantly deposits silt in the plains and the erosional and depositional processes are intensified during heavy rainfall. Frequent seismic movements also play a dominant role in shaping the physiography of the valley. Except a few isolated hillocks, the valley is built by deposition of alluvium brought down by the Brahmaputra and its tributaries from the adjoining north and southern hill ranges. The valley as a whole slopes down towards southwest in the upper part and west in the middle and lower parts. The altitude of Kobo near the trijunction of the rivers, Dihang, Dibang and Lohit is 130 m and altitude at Dhubri is about 28 m above mean sea level. The average fall of gradient is very

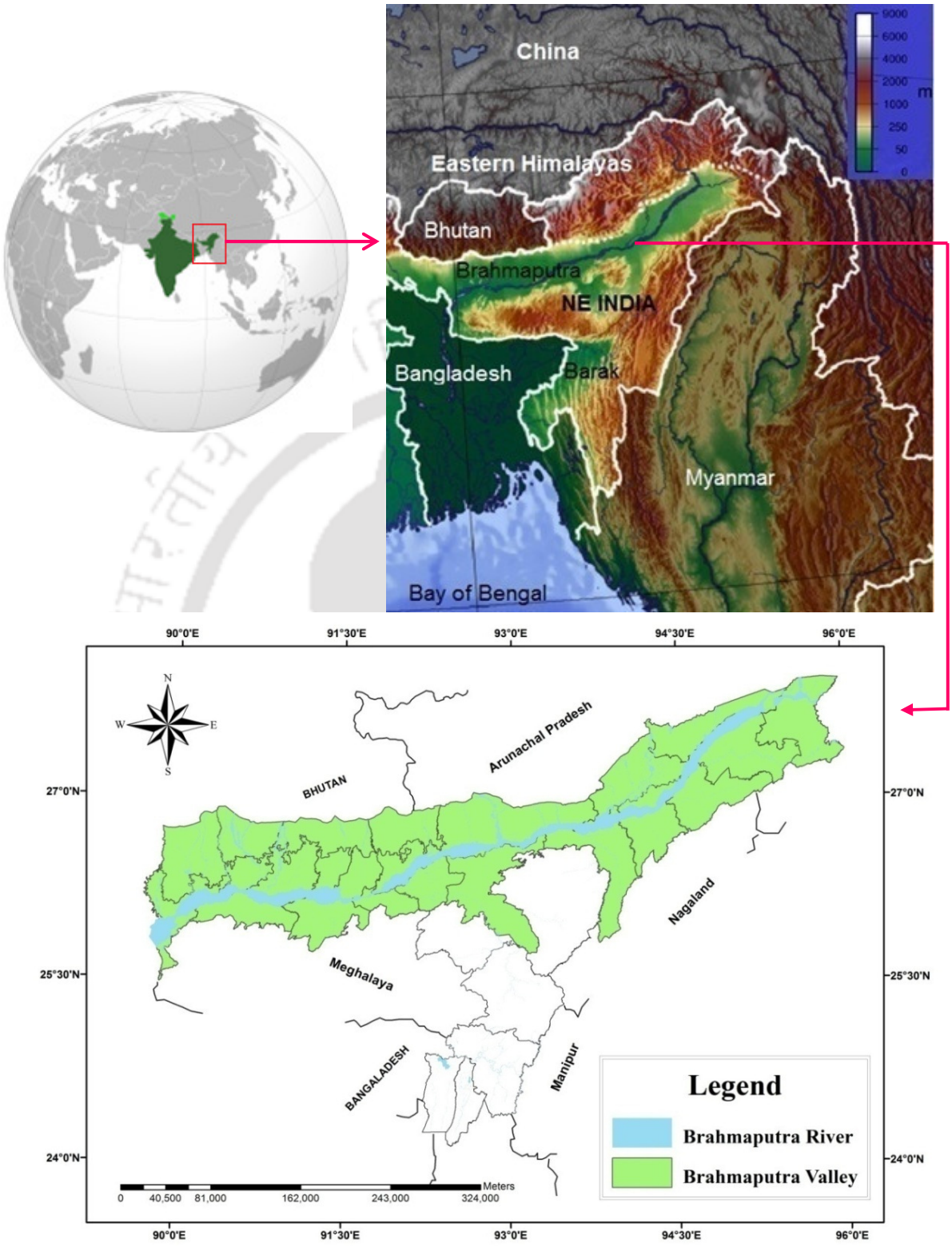

Fig 3.1 The Brahmaputra valley of Assam

low (13 cm per kilometer) and is one of the principal causes of frequent occurrence of floods in the plains following heavy rains during the southwest monsoon. As the Brahmaputra is a braiding river, its water flows through several winding channels within its bed forming many riverine islands, locally known as C*hars* or C*hapories* amongst which Majuli is reported to be the world's largest inhabited river island.

3.3 Climatic features

The climate of the Brahmaputra valley cannot perhaps be discussed separately from the climate of NE India. The climate of NE India is distinct from the rest of India due to special features such as orography, the alternating pressure cells of NE India and that of the Bay of Bengal, the predominant maritime tropical air mass from Bay of Bengal followed by south Indian ocean, the roving periodic western disturbances and the local mountain and valley winds (Borthakur 2004). The region belongs to the transition zone of tropic and extra-tropic and as a consequence experience westerly moving tropical weather systems like lows, depressions and cyclonic storms during pre-monsoon, monsoon and post-monsoon, as well as extra-tropical easterly moving weather systems like western disturbances in winter (Pathak 2000). The extensive water bodies and forest areas add to its climate individuality. The Himalayan range protects the area from cold wave from central Asia in winter and causes heavy rains as it obstructs the southwest monsoon wind from over running (Das 1992).

The climate of the Brahmaputra valley is akin to the South-East Asiatic monsoon climate, which is generally modified by local physical conditions. The interaction between the large scale circulations and the local topography plays a crucial role in determining the weather and climate over the region (Goswami et al. 2010). The Bay of Bengal, which is located south of the valley acts as a giant moisture source during summer monsoon. The periodic SW trade wind enter into the valley through two inlets, one through the eastern part of the lower Gangetic valley and other through the Barak valley and the hill gaps of the Borali ranges (Borthakur 2004). However, local severe storms or violent thunderstorms contribute rainfall, hail and gusty wind during the pre-monsoon season while western disturbances cause winter rainfall (Atri and Tyagi 2010). Normally, the monsoon sets in over the region

during the first week of June and withdraws by the second week of October (Dhar and Nandargi 2000).

Before the onset of monsoon, there is considerable thunderstorm activity in the month of April–May due to incursion of moisture in the region from the neighbouring Bay of Bengal (Dhar and Nandargi 2000). Depression, deep depression and cyclonic circulation are the potent rain bearing weather systems causing widespread rainfall in India. Their direct entry during monsoon to NE India is very rare (Pathak 2000). However, recurvature of monsoon depression after reaching Bihar plateau and adjoining area due to westerly trough is common during monsoon season (Pathak 2000). On recurvature, the rain bearing southwest sector of depression get changed to NE sector (Pathak 2000). Frequent major floods occur during monsoon season in the Brahmaputra valley caused by heavy rainfall associated with 'Break' monsoon situations or recurving monsoon depressions from the Bay of Bengal (Dhar and Nandargi 2000). The break monsoon occurs when the axis of the seasonal monsoon trough shifts northwards from its normal position and lies close to the foothills of the Himalayas (Dhar and Nandargi 2003). This particular situation results in heavy rainfall over the north eastern and central Himalayas and their adjoining plain area (Dhar et al. 1984), while the rest of the country reels under drought condition with low or no rain. Moreover, there is a link between the Indian monsoon and wide range of large scale features of the global climate such as El Nino and Southern Oscillation (ENSO) which has been related to inter-decadal variability in all-India monsoon rainfall (Krishnamurthy and Goswami 2000; Gadgil et al. 2004). However, the ENSO does not display the same degree of correlation with different homogeneous regions of India on longer time scale (Gadgil et al. 2004). Ashok and Saji (2007) reported that the NE India is least impacted by ENSO. This is also further supported by Kothawale et al. (2008) who found that all-India average rainfall during El Nino and La Nina years were 93% and 105% of normal rainfall respectively, whereas average rainfall were nearly normal in NE India during the corresponding years.

3.4 Variations of seasonal weather

The climate of the Brahmaputra valley is pre-dominantly humid subtropical with hot, humid summers, severe monsoons and mild winters. India as a whole, not to speak of

Brahmaputra valley and its neighboring areas, is a good example of monsoon climate. On the basis of precipitation received, India Meteorological Department has specified four seasons for the country. They are (a) Hot weather season (from March to May), (b) Southwest monsoon season (from June to September), (c) Retreating Southwest monsoon or post–monsoon season (from October to November) and (d) Northeast monsoon or winter season (from December to February). The divisions hold good in case of NE India too. But instead of calling the period from March to May 'Hot weather seasons' it would be appropriate to call it 'Pre-monsoon season', because in this region the hottest months are from June to August unlike in other parts of India.

3.4.1 Pre-monsoon season

The pre-monsoon starts by early March along with the gradual rise in temperature coupled with vanishing fog, pleasant mornings and hot afternoons, occasional dust storms and thunder showers. The valley gets a good amount of rain (about 25% of annual total) falling during this season due to "Nor'westers" which makes the climate cool even during spring. In contrast, there is very little rainfall from March to May in the rest of northern India (Das 1992). This occasional rain in the Brahmaputra valley is highly significant for the cultivation of jute, autumn rice and for the budding of tea plants. The Brahmaputra valley including adjacent eastern Gangetic plains gets affected by severe thunderstorms during pre-monsoon months, in particular during April–May. Thunderstorm activity over the Brahmaputra valley is highest in the country. Thunderstorm produces heavy rain showers, lightening, thunder, hail-storms, dust-storms, surface wind squalls and tornadoes (DST 2005) causing extensive damage to winter wheat, summer paddy and tea crop. Nearly 28 severe thunderstorms occur in the valley during the period of two months (DST 2005). Maximum frequency of thunderstorms is along the Brahmaputra river (Chakravarti et al. 2008) in a west to east decreasing gradient. Average number of thunderstorm events over Guwahati was 28, which was much higher than Kolkata (on an average 15) during 1998–2008 (Chaudhury and Middey 2012). On an average (1971–2000), 10 hailstorms generally occur during this season in the Brahmaputra valley. Hailstorms cause damage to tea bushes (defoliation, breakage of young stems) depending on severity of storms, its time of occurrence and stage of growth of tea bushes. Unpruned tea bushes suffer less damage from hail than young tea and bushes in the process of recovery from pruning (Barua 1989).

3.4.2 Monsoon season

The normal date of onset of monsoon in NE India is within the first week of June. Monsoon season is mainly characterized by cloudy weather, high humidity, heavy rainfall, higher temperature and weak variable surface wind. Temperature and rainfall slowly increases with advancement of the season. This is the longest season, during which the rising temperature is brought down considerably by intermittent rainfall. The undulated surface configuration deflects the monsoon winds and forces the moisture-laden air to rise along the slopes causing adiabatic cooling. This leads to heavy rainfall in the valley, except in a narrow rain-shadow belt to the east of the hills of Meghalaya. Rainfall is so frequent that about 18 to 20 days in a month are rainy. The monsoon season is the most important period for agricultural activities in the Brahmaputra valley, since the cultivation of winter rice (*sali* rice), the principal cereal crop, takes place during this period. Monsoon withdraws normally around 15th October from the region (Dhar and Nandargi 2000).

3.4.3 Post-monsoon season

With the retreat of monsoon wind, the temperature drops and morning mist and fogs appear. The post monsoon months of October and November are characterized by fair weather with fall of temperature and rainfall. The bright sunny weather with a tendency to raise atmospheric heat in the afternoon and rapid fall of temperature at night, makes the weather the most endurable and pleasant over the entire year.

3.4.4 Winter season

The winter is characterized by fall of night temperature, low rainfall with occasional cool breeze from the north and morning fog. The cool, fair and pleasant weather is interrupted by driving showers, associated with western disturbances which lower the temperature and bring cold spells. Ground fog is very common during winter on the southern bank of the Brahmaputra. The northerly or northeasterly winds drive the fog towards the southern plateaus of Karbi hills and the Meghalaya. Chilly wind from the Tibetan region is obstructed by the Himalayas and as a result, the valley is protected from unbearable cold. Winter is the driest period in the valley. Local circulations and western disturbances bring some precipitation even during the winter season (Atri and Tyagi 2010). Even a little rain during this season is of great help for tea and other *rabi* crops. Tea crop in parts of central

Brahmaputra valley is susceptible to drought than upper parts which normally gets few showers during the dry part of the year (Barua 1989).

3.5 Spatial distribution of rainfall

Rainfall distribution follows a typical monsoon pattern with peak precipitation during monsoon and scanty rainfall in winter. The annual rainfall over the Brahmaputra valley is as high as 3900 mm in the extreme northwest and extreme northeast hilly tracts (Nath and Deka 2010). A rainshadow belt comprising Karbi Anglong and Nagaon districts (southernmost portion of central part of the valley) (Fig. 3.1) extending partly to Golaghat district in the east is conspicuous in the region. The rainfall gradually increases from the rain-shadow area towards the upper and the lower Brahmaputra valley as well as towards the southern part (Barak valley) of Assam. During pre-monsoon season, the upper, central and lower part of the valley receives about 400 to 700 mm, 300 to 500 mm and 500 to 800 mm rainfall, respectively (Khanikar 2001). Monsoon contributes about 65% of total annual rainfall. The highest rainfall occurs generally during June–July. The rainshadow belt is conspicuous during this season. Rainfall generally increases from the rainshadow belt towards northeast and northwest and South (Barak valley) and reaches a maximum value of 2500 mm in the extreme northeastern part and 3100 mm in the extreme western part of the valley (Khanikar 2001). In the central part, rainfall is less than 1300 mm during the season. The varied surface configuration of different hilly tracts deflects the monsoon currents and lifts them forcefully for adiabatic cooling, thus causing heavy rainfall. During post-monsoon season, the valley receives about 160 to 200 mm of rainfall. During winter, the upper part of the valley receives 90 to 130 mm rainfall while the central and lower parts get about 40 to 60 mm of rainfall (Khanikar 2001).

3.6 Spatial distribution of temperature

The Brahmaputra valley experiences a mean annual temperature ranging between 23.0° to 24.0°C. The eastern part of the valley is slightly cooler compared to the western part. The average monthly maximum temperature ranges from 23.6°C to 32.0°C and minimum temperature varies from 10.0°C to 24.2°C (Khanikar 2001). The highest mean maximum temperature occurs in the month of August and it varies from 31.0° to 33.5°C throughout

the valley. The lowest mean minimum temperature occur in the month of January and varies from 10° to 11.5°C

3.7 Spatial distribution of sunshine hour

The average solar radiation in the Brahmaputra valley indicates that the valley intercepts only 36–38 % of the astronomically possible sunshine during June to August (FAO 1987) due to overcast sky. Though the average monthly sunshine duration increases during November to February (70–74 %), the unit of radiation intercepted is less due to foggy weather. The pre- and post-monsoon periods have intermediate duration of sunshine hours (about 50 %). Average monthly bright sunshine is the lowest (3.7–5.4 hr/day) in July and highest (6.6 to 8.0 hr/day) during November (Khanikar 2001). During July, the rain-shadow belt in central Brahmaputra valley registers the highest sunshine duration of 5.4 hr/day, whereas the rest of the Brahmaputra valley registers between 4.0 and 4.5 hr/day (Khanikar 2001). In general, sunshine duration is higher in the lower Brahmaputra valley than in the upper Brahmaputra valley, though during the rainy season, the spatial variation of sunshine duration is negligible over the valley. Short sunshine duration due to overcast sky during monsoon season is one of the major constraints for rice (*kharif*) cultivation in the valley.

3.8 Present Status of Agriculture

Agriculture is the core primary sector of the state's economy and it contributes 22.4% to State Domestic Product (DES 2012). The agricultural sector is providing employment to more than 50% of the rural population in the state. Assam has an estimated 39.99 lakh ha gross cropped area (GCA), of which net area sown is about 28.10 lakh ha and area sown more than once is 11.88 lakh ha in 2009–2010 (DES 2012). Area under irrigation is very low: 7.97 lakh ha of GCA (DES 2012). The soil, topography, rainfall and climatic condition of Assam are congenial for cultivation of rice, which covers nearly 70% of the gross cropped area and more than 90% of the total area under food grains. Being the single major source of agricultural GDP, rice plays a significant role in the state's economy. Assam also occupies advantageous place in rice production in the country by covering 6% of total rice area (41.92 mha) and 5% of the production (DES 2010). The productivity of total rice in the state was relatively lower (1,796 kg/ha) than the national average (2,125

kg/ha) in 2009–2010. Tea and rapeseed & mustard are the next most important crops, which cover 3.21 and 2.44 lakh ha respectively. Table 3.1 shows that the acreage share of Brahmaputra valley for most of the crops grown in the state of Assam is more than 80% except sugarcane (61%) and maize (38%).

Table 3.1 Area and production of different crops in the Brahmaputra valley (2010–11)

Crop	Area (lakh ha)	% of state area	Production (lakh MT)	% of state production
Autumn rice	2.76	88	2.93	82
Winter rice	15.42	83	30.08	82
Summer rice	3.79	95	9.88	96
Total rice	**21.97**	**85**	**42.89**	**85**
Wheat	0.43	97	0.54	97
Maize	0.08	38	0.05	32
Other cereals	0.05	95	0.03	96
Total cereals	**22.53**	**85**	**45.51**	**91**
Total pulses	1.15	91	0.63	90
Total foodgrains	**23.68**	**86**	**46.17**	**89**
Rapeseed & Mustard	2.20	90	1.30	91
Total oilseeds	2.43	89	1.42	90
Jute*	0.60	97	6.07	97
Sugarcane	0.18	61	6.66	62
Potato	0.75	88	5.89	89
Tea**	**2.89**	**90**	**4.61**	**90**

* Production in Bales of 180 kg, ** Year 2007 and production in lakh kg, figures in bracket denotes percentage over the state total)

Tea crop is a key sector of economy in Assam, with Brahmaputra valley playing the major role in tea production in the country. Tea industry is providing livelihood to about six lakh people (DES 2012). The Brahmaputra valley is the largest tea producing area in India with maximum concentration of cultivation in Dibrugarh, Sibsagar, Jorhat, Golaghat, Lakhimpur and Sonitpur districts located in the upper part of the valley. However, the tea production from this region is going through a difficult phase, being strongly influenced by climate change that has been adversely affecting the livelihoods in the region (Ramakrishna et al. 2013).

3.8.1 Cropping Pattern

As the rice crop has a stable share in the total cultivated area, the cropping pattern in the Brahmaputra valley is predominantly rice-based. Wide variation of physiographic features and climatic characteristics have resulted in three distinct growing seasons of rice viz., autumn or *ahu* (Feb/Mar–Jun/Jul), winter or *sali* (Jun/Jul–Nov/Dec) and summer or *boro* (Nov/Dec–May/Jun). Among the rice-based crop sequences followed by the farmers, the major ones are autumn rice followed by winter rice, winter rice followed by summer rice, jute followed by winter rice/summer rice are the primary cropping patterns in low lying areas (Borah et al. 2001). In the rainfed uplands, autumn rice/jute followed by mustard/wheat/vegetables is the common pattern, where double cropping is practiced. Diversification is taking place over the years, though the crop diversification index is heavily influenced by rice. On the positive side, the increase in area under summer (*boro*) rice has not only improved the utilization of *rabi* fallow, but also has enhanced the cropping intensity to about 142% (Borah et al. 2001). Reclamation of waste land (swamp) for summer rice cultivation and installation of shallow tube wells (STWs) in non-traditional areas (*rabi* fallow) had contributed much towards this improvement in cropping pattern. Another important reason for this diversification is to escape the crop damage due to recurring floods during monsoon season.

In the tea sector, in addition to existing large tea estates (when area under plantation is more than 10.12 ha, according to Tea Board of India) owned by both the reputed Indian and multi-national Companies, the profession of tea plantation in the Brahmaputra valley has been taken up by common people as business venture, especially by unemployed youths since late 1990s. At present, there are 68,214 small tea holdings (area under plantation less than 10.12 ha) covering approximately 47,348 ha of land in the Brahmaputra valley (DIC 2012) and contribute about 30% of the State's total annual tea production (DES 2012). About 95% of the small tea growers are concentrated in five districts (Tinsukia, Dibrugarh, Sibsagar, Golahat and Jorhat) of the upper Brahmaputra valley (DIC 2012). The increasing climate vulnerability in the last decade has resulted in a significant drop in tea productivity in spite of adoption of improved management practices by the tea estates (Ramakrishna et al. 2013). The increasing climate variability due to global warming is a grave concern to the tea Industry.

3.8.2 Soils

In the Brahmaputra valley, the alluvial deposits of the river Brahmaputra during the recent geological times predominantly form the soils. Soils are either new alluvial (Entisols) or old alluvial (Inceptisols) and are slightly acidic to strongly acidic. The soils originating directly from the river Brahmaputra are usually sandy and poor in nutrients, such as those found in parts of the north bank of the Brahmaputra. Rice is grown in upland, lowland, medium land and deep water areas while tea is grown mainly in uplands.

A greater part of tea in the valley is on soils which owe their origin more to numerous rivers and the textures of these soils vary depending on their origins; it may be loamy sand (Jorhat), clay loam (Golaghat and Nagaon) or sandy loam in upper Assam (Banerjee 1993). Barua (1989) classified the soils of the Brahmaputra valley into three groups viz. (i) the soils which owe their origin mainly to the sediments of the Brahmaputra river which are usually sandy with poor nutrients. These soils are rarely used for tea cultivation, (ii) the soils deposited from the adjacent hills by the tributaries of the Brahmaputra (generally rich loam suitable for tea), and (iii) the older red soils occurring largely in the north bank of Brahmaputra (rich in nutrients and good for tea). The tea soils of upper Assam owe their origin to Dihing river and are endowed with good plant food, apart from being deep and friable to a depth of 2 m; hence these soils are considered most ideal for tea (Banerjee 1993).

The tea soils of the Brahmaputra valley are mostly alluvial (uplands) and vary widely in texture. The pH of the soils of tea growing area is less than typical rice growing area (Tables 3.2 and 3.3). Recent estimates show that the extent of occurrence of acid soil in the Brahmaputra valley is more than 90% (Talukdar et al. 2004). The organic matter content of the Brahmaputra valley soils is low to high, which varies from 0.60% to 2.9% in surface horizon and its distribution decreases with depth (Gangopadhyay et al. 1998) and more in tea growing soils than those in case of rice soils (Tables 3.2 and 3.3) primarily due to differences in management and crop residue recycling (De Costa et al. 2005). Tea soils of the Brahmaputra valley have undergone physical, chemical and biological degradation due to heavy use of chemical inputs such as pesticides and fertilizers, causing reduced biological activity (Talukdar et al. 2004).

Table 3.2 Physical and chemical properties of typical rice soils of the Brahmaputra valley

Parameters	Soil series				
	Bharali	Tezpur	Dhubri	Nalbari	Darrang
Classification	Fine-loamy	Fine-loamy	Coarse-loamy	Fine-loamy	Fine-loamy
Physiographic position	Alluvial low land	Alluvial low land	Undulating low lands	Alluvial low land	Alluvial flood plains
Sand (%)	30	36	77	29	43
Silt (%)	35	35	10	41	29
Clay (%)	35	29	13	30	28
pH	5.9	5.4	6.7	6.4	5.6
CEC	10.2	8.7	4.6	8.9	8.1
Organic carbon (%)	1.10	1.12	1.56	1.20	1.04

Source: Vadivelu et al. (2004a)

Table 3.3 Physical and chemical properties of typical tea soils of the Brahmaputra valley

Parameters	Soil series				
	Teok	Tinsukia	Mariani	Furkating	Dibrugarh
Classification	Fine-loamy	Fine-loamy	Coarse-loamy	Fine-silty	Fine, mixed
Physiographic position	Alluvial uplands	Alluvial uplands	Piedmont plain	Uplands of old floodplains	Alluvial uplands
Sand (%)	78	44	61	2	25
Silt (%)	13	30	21	61	45
Clay (%)	9	26	18	37	30
pH	4.2	4.9	4.6	5.1	5.0
CEC	4.1	9.2	6.0	10.2	9.57
Organic carbon (%)	1.38	2.23	1.15	1.52	1.50

Source: Vadivelu et al. (2004a)

3.8.3 Natural hazards

The Brahmaputra and its tributaries and sub-tributaries cause major problems during the monsoon season every year in the form of flood, bank erosion and drainage congestion. Agriculture is vulnerable to flood effects. The total flood prone area of the Brahmaputra valley is estimated to be 32 lakh ha, which accounts for 9.6% of the country's total area (Venkatachary et al. 2001, MoEF 2010). Crop damage depends mainly on the occurrence and frequency of flood, experienced due to several numbers of flood waves, duration and

depth of inundation. The losses due to floods in the valley increased manifold over the years. Records show that catastrophic floods occurred in 1954, 1962, 1966, 1972, 1973, 1978, 1983, 1984, 1987, 1988, 1991, 1993, 1995, 1996, 1998, 2002, 2004, 2010 and 2012. During the period from 1988 to 2008, a total of 16.94 mha of crop area was damaged by floods (total area affected was 18.85 m ha area) in addition to loss of 3.32 lakhs heads of cattle (WRD 2010). The flood during 2012 affected 4.8 lakh ha of land and damaged about 2.55 lakh ha of cropped area according to the damage assessment made by the State Government. Additionally, sand deposition in fertile lands of the valley is seen to be more severe and devastating especially in the northern bank of upper Brahmaputra valley since mid 1990s (Das et al. 2009). Accumulation of dunes of sand has rendered the fertile lands to be unproductive. Though the recurrent floods were the major cause of crop loss, drought-like situations also affected the valley in recent years. For instance, the average yield of winter rice in Assam during 2006 was 1321 kg/ha – a lowest recorded yield since 1990 due to deficient monsoon rainfall.

The large scale damages associated with floods further gets exacerbated by river bank erosion in the valley due to flashy behavior of the river Brahmaputra and its tributaries. The bank erosion results in changing pattern of channel configuration, frequent shifting of river banks and breaching of embankments. Heavy bank erosion along the courses of the rivers engulfs good agricultural land and human habitation into their folds. Between 1912 and 1996, 868 km^2 of land was lost to bank erosion; averaging 10.3 km^2 of area lost per year (Sharma 2005). The intensity and frequency of major river inundation and bank erosion have gone up recently. Floods, erosion and sand casting are likely to become more frequent and intense in future due to projected increase in rainfall intensity during monsoon months, glacier retreat, deforestation (Immerzeel et al. 2010) and a ever growing population living along Assam's biggest and most flood prone river, the Brahmaputra.

Chapter 4

Trends and Fluctuations of Rainfall, Temperature and Sunshine Duration

This chapter discusses the various climate data used for the present work followed by the methodologies used to evaluate the trends and fluctuations of major climate variables in the Brahmaputra valley at different spatial and temporal scales. The second section presents, discusses and analyses in detail, the results obtained relating to trends and fluctuations of rainfall data including daily extreme rainfall events. The next section presents, discusses and analyses in detail the results obtained on trends of monthly, seasonal and annual temperature data. Changes in daily extremes temperature in the Brahmaputra valley has been also discussed here. Finally, the last section of this chapter presents, discusses and analyses in detail the trends of sunshine duration.

4.1 Materials

4.1.1 Climate data

The meteorological data used for the study were collected from a number of sources viz., National Data Centre (IMD), Pune, Regional Meteorological Centre, Guwahati, Tocklai Experimental Station, Jorhat, Assam and IMD's publication (Monthly and Annual Rainfall and Number of Rainy Days, Part-I). The time series data of monthly rainfall for 110 years (1901–2010) have been compiled for 12 stations of the Brahmaputra valley namely Dibrugarh, North Lakhimpur, Sibsagar, Jorhat, Golaghat (eastern part); Tezpur, Majbat, Lumding, Kampur, Guwahati (central part), and Goalpara and Dhubri (western part). Except Kampur, the remaining stations belong to the World Meteorological Organization's (WMO) climate data exchange network and each has a WMO number (Table 4.1).

For the purpose of the study, the entire Brahmaputra valley was divided into three parts viz., eastern, central and western (Fig. 4.1). The monthly rainfall series for three different parts of the valley was computed by arithmetic means of all the stations falling within each part. The stations considered to represent different parts of the Brahmaputra valley were based on annual rainfall pattern as well as inter-station correlation, in addition to their natural geographic features.

Table 4.1 Details of stations from where monthly rainfall data were collected

Sl No	Station name	Location in the valley	WMO Number	Period	Coordinates		
					Lat (N)	Long (E)	Altitude (m)
1	Dibrugarh	East	42314	1901–2010	27.47	94.92	106
2	Sibsagar	East	42311	1901–2010	26.98	94.63	97
3	Jorhat	East	42423	1901–2010	26.72	94.22	89
4	Golaghat	East	42419	1901–2010	26.52	93.98	96
5	Lakhimpur	East	42309	1901–2010	27.23	94.12	102
6	Tezpur	Central	42415	1901–2010	26.62	92.78	79
7	Mazbat	Central	42313	1901–2010	26.75	92.35	110
8	Lumding	Central	42523	1901–2010	25.75	93.18	149
9	Kampur	Central	–	1901–2010	26.17	92.67	61
10	Guwahati	Central	42410	1901–2010	26.10	91.58	54
11	Dhubri	West	42404	1901–2010	26.02	89.98	35
12	Goalpara	West	42407	1901–2010	26.18	90.63	38

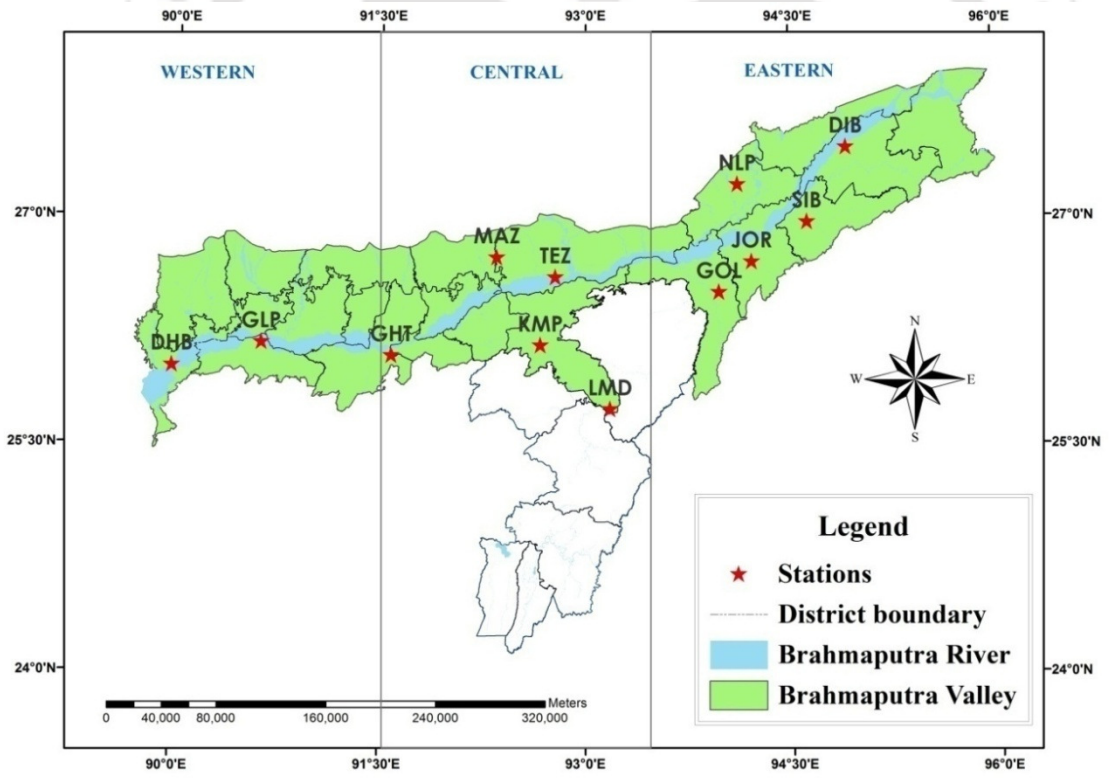

Fig. 4.1 Location of raingauge stations for monthly rainfall data

For extreme rainfall analysis, based upon availability, entire daily data for 55 years (1955–2010) for 9 stations, 4 representing the eastern part, 3 representing the central part and 2

representing the western part of the Brahmaputra valley, were compiled (Table 4.2, Fig 4.2). The stations were selected based on the criteria given by Klein Tank et al. (2002): (a) data must be available for at least 40 years, (b) missing data must not be more than 10% of the total, and (c) missing data from each year must not exceed 20%.

Table 4.2 Details of stations from where daily rainfall data were collected

Sl No	Station name	Location in the valley	Period	Coordinates		
				Lat (N)	Long (E)	Altitude (m)
1	Dibrugarh	East	1955–2010	27.47	94.92	106
2	Jorhat	East	1955–2010	26.72	94.22	89
3	Golaghat	East	1955–2010	26.52	93.98	96
4	North Lakhimpur	East	1955–2010	27.23	94.12	102
5	Tezpur	Central	1955–2010	26.62	92.78	79
6	Lumding	Central	1955–2010	25.75	93.18	149
7	Guwahati	Central	1955–2010	26.10	91.58	54
8	Dhubri	West	1955–2010	26.02	89.98	35
9	Beki Rly Bridge	West	1971–2010	26.30	91.00	-

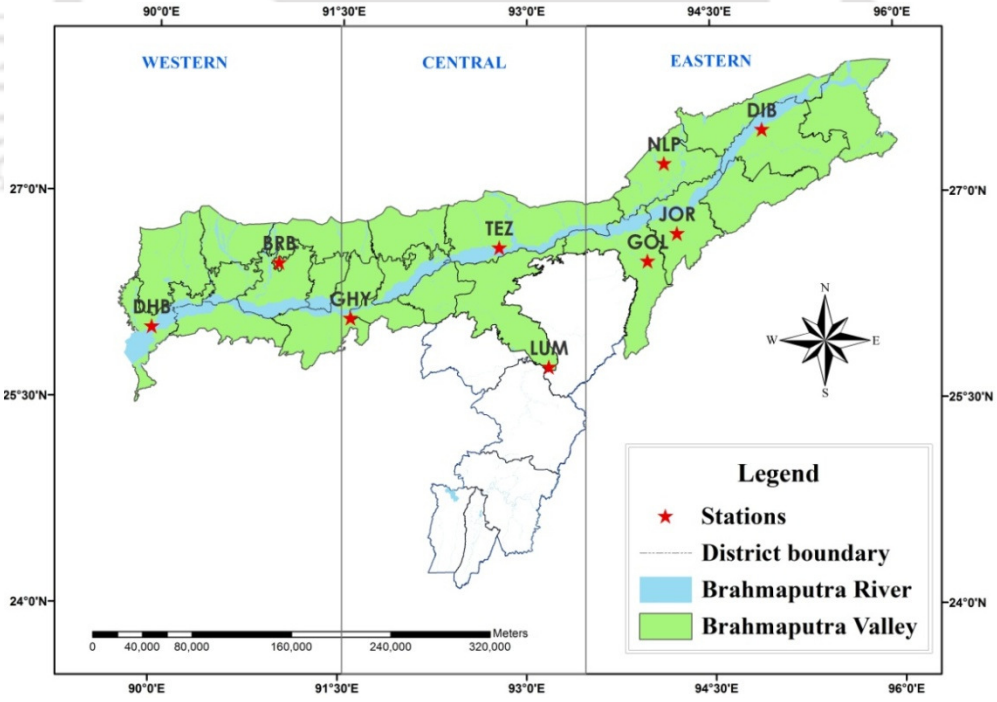

Fig.4.2 Location of raingauge stations for daily rainfall data

Maximum and minimum temperature data series for the last 60 years (1951–2010) were systematically formatted for 6 stations as well as for the entire Brahmaputra valley (Table

4.3, Fig. 4.3). Daily maximum and minimum temperature data of Dibrugarh, Jorhat, Tezpur and Guwahati have been used for extreme temperature analysis during 1971–2010 considering the same criteria as set for daily rainfall data. Monthly bright sunshine hour (BSSH) data from 1971 to 2010 of four stations (Dibrugarh, Jorhat, Thakurbari and Guwahati) as well as for the Brahmaputra valley as a whole have been utilized for trend analysis.

Table 4.3 Details of stations from where temperature data were collected

Sl No	Station name	WMO Number	Period	Coordinates		
				Lat (N)	Long (E)	Altitude (m)
1	Dibrugarh	42314	1951–2010	27.47	94.92	106
2	Jorhat	42423	1951–2010	26.72	94.22	89
3	Lakhimpur	42309	1951–2010	27.23	94.12	102
4	Tezpur	42415	1951–2010	26.62	92.78	79
5	Guwahati	42410	1951–2010	26.10	91.58	54
6	Dhubri	42404	1951–2010	26.02	89.98	35

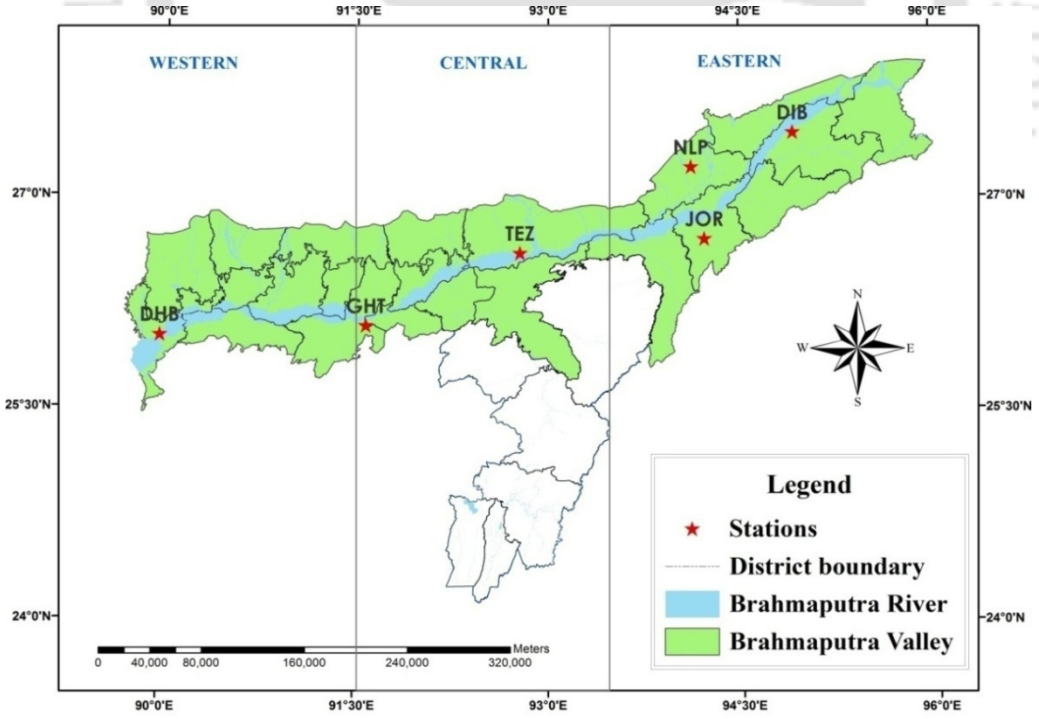

Fig.4.3 Location of stations for monthly temperature data

4.1.2 Data quality and homogeneity

Data quality control is a necessary step before the analysis, because erroneous outliers can impact trends seriously. The main objective of data quality checking was to reduce errors in data recording and processing. Inhomogeneities or discontinuities in a climate record can be caused by any change to the station or its operation, including site location, exposure, instrumentation, or observational practice (Manton 2001). These discontinuities not only affect mean climatic values, but also the extremes of the climatic distribution, and may affect the extremes differently to the mean (Trewin and Trevitt 1996). All the stations considered in this study had been located at a single site during the period of record.

The monthly rainfall, temperature and sunshine duration data were checked to identify the outliers by plotting scatter plots. The outliers were dropped or accepted by confirming from the comparison plot of the neighbouring stations. The daily time-series (for rainfall and temperature) from each station selected were first examined visually to identify any obvious outlier, trend and potential discontinuities. The daily rainfall data, where daily rainfall values have been shown as negative, were considered as missing values. Similarly, daily maximum and minimum temperature were also considered as missing values if the daily maximum temperature was lower than the daily minimum temperature. Few outliers in daily maximum and minimum temperature exceeding ±4 standard deviations were also identified and were replaced with the normal value of the concerned station.

The homogeneity of the seasonal rainfall and temperature series was tested by using short-cut Bartlett's test (Mitchell et al. 1966). Hasanean (2001) used this test to examine the homogeneity of air temperature data in the Eastern Mediterranean. The short-cut Bartlett's test of homogeneity of variance was applied by dividing the series into k equal sub-periods, where $k \geq 2$. In each of the sub-periods the sample variance was calculated as

$$S_k = \frac{1}{n}\left\{\sum x_i - \frac{1}{n}\left(\mathrm{x_i}\right)^2\right\} \tag{4.1}$$

Where, the summations range over the n values of the series in the sub-period k. Let S^2_{max} and S^2_{min} denote the maximum and the minimum of the values of S_k^2, respectively. The 95% significance point for S^2_{max} /S^2_{min} ratio can be obtained by comparing this ratio with

the values given in Biometrika Table 31 (Pearson and Hartley 1958). Here, the entire rainfall series was divided into 5 sub-periods (k) having 22 observations (n) in each sub-period. Temperature series was divided into 3 sub-periods having 20 observations in each sub-period. For $k = 5$ and $n = 22$, the 95% significance point in the Biometrika Table is 3.53. All the rainfall and temperature series considered in this study were found to be homogeneous (Table A.1 and A2).

4.2 Methods

To investigate the changes in rainfall, temperature and sunshine duration, a single year has been divided into four seasons namely, winter (previous year's December to February of current year), pre-monsoon (March to May), monsoon (June to September) and post-monsoon (October and November) of current year. The rainfall data series has been sub-divided into three periods 1921–1950 (NP1), 1951–1980 (NP2) and 1981–2010 (NP3) and temperature data series into two parts 1951–1980 (NT1) and 1981–2010 (NT2) following the criterion given by WMO (1989), NP and NT denoting normal precipitation period and normal temperature period respectively.

4.2.1 Estimation of trends

The rainfall, temperature and sunshine duration data series were subjected to statistical analysis to determine the magnitude and significance of trends. The magnitude of trend in a time series can be determined either using regression analysis (parametric test) or using Sen's estimator of slope (non-parametric method). Both these methods assume a linear trend in the time series. In this study, non-parametric methods have been utilized.

4.2.1.1 Magnitude of trends

Sen's slope model has been widely used for determining the magnitude of trend in hydro-meteorological time series (Lettenmaier et al. 1994; Partal and Kahya 2006). Since Sen's slope is insensitive to outliers or missing data, it is more rigorous than the usual regression slopes and thus provides a realistic measure of the trends in the data series (Hirch et al. 1982; Wilcox 1998). The approach involves computing slopes for all the pairs of ordinal time points using the median of these slopes as an estimate of the overall slope (Sen 1968; Gilbert 1987). The slope estimates Q_i of N pairs of data are calculated by

$$Q_i = \frac{x_j - x_k}{j - k} \text{ for } i = 1, 2, \ldots\ldots, N \tag{4.2}$$

Where x_j and x_k are data values at times j and k ($j > k$) respectively. The median of these N values of Q_i is Sen's estimator of slope. If there is only one datum in each time period, then N= n(n–1)/2, where n corresponds to the number of time periods. The N values of slopes are ranked from the smallest to largest and if N is odd, Sen's estimator of slope is calculated as

$$Q_{median} = Q_{(N+1)/2} \tag{4.3}$$

If N is even, then Sen's estimator becomes

$$Q_{median} = \left[Q_{N/2} + Q_{(N+2)/2}\right]/2 \tag{4.4}$$

A positive value of Q indicates an upward (increasing) trend and a negative value indicates a downward (decreasing) trend in the time series.

4.2.1.2 Significance of trends

To establish statistically significant trend in the series, Mann–Kendall (MK) technique (Mann 1945; Kendall 1975) has been employed. It is a non-parametric rank-based procedure, robust to the influence of extremes and suitable for application with skewed variables (Hamed 2008). More particularly, this technique can be adopted in cases with non-normally distributed data, data containing outliers and non-linear trends (Helsel and Hirsch 1992). The MK test checks the null hypothesis of no trend versus the alternative hypothesis of the existence of increasing or decreasing trend. The MK test statistic (S) is given by

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sgn}\left(x_j - x_k\right) \tag{4.5}$$

Where n is the number of data, x is the data point at times j and k ($k > j$) and the sign function is given as

$$\operatorname{sgn}\left(x_j - x_k\right) = \begin{cases} +1 & \text{if} \quad x_j - x_k > 1 \\ 0 & \text{if} \quad x_j - x_k = 0 \\ -1 & \text{if} \quad x_j - x_k < 1 \end{cases} \tag{4.6}$$

The S statistic, in cases where the sample size n is larger than 10, is assumed to be asymptotically normal, with $E(S) = 0$ and the variance of S is computed by

$$Var(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)\right] \tag{4.7}$$

Where t refers to the extent of any given tie and Σ_t states the summation over all ties. A tie is the sample data having the same value and the summation is over all ties. The standard normal deviate Z is computed by Equation 4.8 (Partal and Kahya 2006).

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\text{Var}\ (S)}} & \text{if} \quad S > 0 \\ 0 & \text{if} \quad S = 0 \\ \dfrac{S+1}{\sqrt{\text{Var}\ (S)}} & \text{if} \quad S < 1 \end{cases} \tag{4.8}$$

The presence of statistically significant trend is evaluated using the Z value. In a two-sided test for trend, the null hypothesis H_0 should be accepted if $[Z] > Z_{\alpha/2}$, at the level of significance. In this analysis, the null hypothesis was tested at 95% confidence level.

4.2.2 Short-term fluctuations

To examine the short-term fluctuations in the rainfall series, the decade-wise shift in rainfall over the study area were computed to see whether the individual decadal mean differs from the mean of the entire period and the shift was tested for significance by applying Cramer's test (WMO 1966). The Cramer's test statistics (t_k) is given by:

$$t_k = \left[\sqrt{\frac{n(N-2)}{N-n-k\tau_{k^2}}}\right]\tau_k \tag{4.9}$$

Where, τ_k is the standard measure of the difference between means given as

$$\tau_k = \frac{(R_k - R)}{\sigma} \tag{4.10}$$

Where, R is the mean and σ is the standard deviation of the series for the total number of years, N, under investigation; R_k is the mean of the successive n-year.

4.2.3 Excess and deficient rainfall years

The deficient and excess rainfall years are defined for those years when rainfall is respectively less or more than one standard deviation from the mean (Pant and Rupa Kumar 1997). Mathematically, a year is classified as excess year when

$$R_i \geq R_{\mathrm{m}} + S_{\mathrm{d}} \tag{4.11}$$

and as deficient year when

$$R_i \leq R_{\mathrm{m}} + S_{\mathrm{d}} \tag{4.12}$$

Where, R_i is rainfall amount in a year i, R_{m} is long-term mean rainfall, and S_{d} is the standard deviation of rainfall.

4.2.4 Extreme rainfall and temperature indices

The analysis of rainfall and temperature extremes was based on the indices developed under the World Climate Research Programme on Climate Variability and Predictability (CLIVAR) Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) (Peterson et al. 2001; Klein Tank et al. 2006; Alexander et al. 2006). Sixteen of the 27 indices recommended by the ETCCDMI are temperature related and eleven are precipitation related (Klein Tank et al. 2006). They are derived from daily maximum and minimum temperature and daily precipitation. Exact definitions of all the indices are available from the ETCCDI website (http://cccma.seos.uvic.ca/ETCCDI).

The rainfall threshold indices R10mm and R20mm were not considered because such events are very common in this region. The user defined threshold index Rnnmm was calculated in this study for rainfall 75 mm, 100 mm and 125 mm. Simple precipitation intensity index was calculated on rainy days (rainfall ≥ 2.5 mm) instead of wet days (rainfall ≥ 1 mm) given by Klein Tank et al. (2006). Seven temperature indices not relevant

to the studied region like number of frost days (FD), ice days (ID) etc were omitted. Instead, four intensity indices with fixed threshold (Revadekar et al. 2012) were considered in this study. Selective indices used in the present study for rainfall are demonstrated in Table 4.4 and temperature in Table 4.5. Based upon availability of data, the period 1961–1990 for rainfall and 1971–2000 for temperature was chosen as the base period for the indices that represent counts of days crossing the climatological percentile thresholds.

Table 4.4 Definition of rainfall indices used in the study

Sl No	Index	Descriptive name	Definition	Units
1	R75 mm	Rainfall above 75 mm	Count of days when R ≥75 mm	d
2	R100 mm	Rainfall above 100 mm	Count of days when R ≥100 mm	d
3	R125 mm	Rainfall above 125 mm	Count of days when R ≥125 mm	d
4	Rx1-day	Maximum 1-day rainfall	Annual highest rainfall in a year	mm
5	SDII	Simple daily intensity index	Average rainfall on rainy days	mm/d
6	R99pTOT	Extremely wet day rainfall	Rainfall fraction due to R99p	mm
7	R95pTOT	Very wet day rainfall	Rainfall fraction due to R95p	mm
8	R75pTOT	Moderate wet day rainfall	Rainfall fraction due to R75p	mm

The annual as well as seasonal rainfall extreme indices were calculated for the entire 55 years (1955–2010) for the individual stations. In addition to station level analysis, trend analysis was performed for three sub-regions (eastern, central and western part) as well as for the Brahmaputra valley as a whole. The extreme rainfall indices for different parts of the Brahmaputra valley were computed by arithmetic means (Revadekar et al. 2012) of indices at all the individual stations falling in each part of the valley. Similarly, the extremes indices for the Brahmaputra valley as whole were estimated by averaging the indices of all three individual parts. As the extreme temperature indices showed broad spatial coherence (Alexander et al. 2006), the analysis was performed for the Brahmaputra valley as a whole. The extreme temperature indices for the Brahmaputra valley were also computed by arithmetic average of the indices of all the four stations considered in the study.

Table 4.5 Definition of temperature indices used in this study. TX and TN are daily maximum temperature and daily minimum temperature respectively

Sl No	Index	Descriptive name	Definition	Units
	Intensity indices			
1	TXx	Hottest day	Highest value of TX	°C
2	TXn	Coldest night	Lowest value of TX	°C
3	TNx	Hottest night	Highest value of TN	°C
4	TNn	Coldest day	Lowest value of TN	°C
	Frequency indices with percentile thresholds			
5	TX90p	Hot day frequency	Percentage of days when TX >90th percentile	d
6	TX10p	Cold day frequency	Percentage of days when TX <10th percentile	d
7	TN90p	Hot night frequency	Percentage of days when TN >90th percentile	d
8	TN10p	Cold night frequency	Percentage of days when TN <10th percentile	d
	Frequency indices with fixed thresholds			
9	TX 35	Hot days	Number of days with TX >35°C	°C
10	TX 20	Cold days	Number of days with TX <20°C	°C
11	TN 25	Hot nights	Number of days with TN >25°C	°C
12	TN 10	Cold nights	Number of days with TN <10°C	°C
	Range index			
13	DTR	Diurnal temperature range	Annual mean difference of TX and TN	°C

Non-parametric Sen's slope method (Sen 1968) was used to detect any trends in extreme indices of rainfall and temperature and the significance of all the trends was assessed based on the Mann–Kendall test (Mann 1945; Kendall 1975) as described in sections 4.2.1.1 and 4.2.1.2. Mann–Kendal test was used by various researchers around the world. For example – Kothawale et al. (2010), Ravekedar et al. (2012) in India; Klein Tank et al. (2006) in central and South Asia; Vincent et al. (2005) in South America; Plummer et al. (1999) in Australia.

To determine whether marked changes have occurred in the annual cycles of extreme temperature events in the Brahmaputra valley, semi-average method (Revadekar et al. 2012) was followed to estimate the change. For this purpose, the annual cycles in terms of mean indices for two halves of the period consisting of 20 years each has been analysed.

Changes in mean indices for two sub-periods, viz., 1971–1990 and 1991–2010 have been computed for each month with respect to data for the entire period 1971–2010.

4.3 Results and Discussion

4.3.1 Rainfall analysis

Monthly, seasonal and annual trends of rainfall during 1901–2010 over the Brahmaputra valley as a whole as well as over its three different sub-regions have been examined. The rainfall trends during the study period (1901–2010) as well as during different climate normal periods as determined using Sen's slope method, are presented in Tables 4.5 and 4.6. The trend magnitudes were examined for statistical significance at 0.05 probability levels by using Mann–Kendall rank test.

4.3.1.1 Descriptive Statistics

The long-term (1901–2010) mean annual rainfall of the Brahmaputra valley was 2219 mm with a standard deviation of 236 mm. The coefficient of variation of annual rainfall in the valley was 11%. The percentage contribution of pre-monsoon, monsoon, post-monsoon and winter rainfall to annual total was 24.8%, 66.0%, 6.8% and 2.4% respectively. The annual rainfall was lower in the central part (1660 mm) compared to eastern (2464 mm) and western (2531 mm) part of the valley (Table 4.6). The coefficient of variation of annual rainfall was highest in the western (18%) and lowest in central (10%) part of the valley. The pre-monsoon, monsoon and post-monsoon rainfall also followed similar trends as that of annual rainfall in different parts of the valley (Table 4.6). On the other hand, winter rainfall generally increased from western (29 mm) to eastern (91 mm) part of the valley. Rainfall in the valley generally increases from January onwards, attains a peak during June and then falls, reaching the lowest value in December (Fig. 4.4). Annual cycle of rainfall in three different parts of the Brahmaputra valley (Fig. 4.5) shows that rainfall in the valley is spatially variable. July is the maximum rainfall contributing month in the eastern part while contribution of June rainfall is the highest in the central and western part of the valley.

Table 4.6 Basic statistics of rainfall in the Brahmaputra valley during 1901–2010

Sl No	Region/season	Mean (mm)	SD (mm)	CV (%)	Highest	Lowest
	Winter					
1	East	90.5	37.8	42	222.9 (1992)	7.6 (1999)
2	Central	40.9	25.0	61	139.0 (1993)	2.7 (1947)
3	West	28.6	23.9	84	108.7 (1957)	0.0 (1947)
4	Valley	53.3	25.1	47	136.1 (1993)	3.6 (1999)
	Pre-monsoon					
1	East	609.8	147.8	24	982.0 (1948)	352.6 (1960)
2	Central	410.2	91.9	22	661.1 (1988)	202.8 (1917)
3	West	627.6	204.5	33	1252.4 (1948)	171.9 (1917)
4	Valley	549.2	128.6	23	932.4 (1948)	296.6 (1979)
	Monsoon					
1	East	1596.9	179.7	11	2172.2 (1935)	1183.5 (1996)
2	Central	1083.4	144.4	13	1565.9 (1918)	771.6 (2006)
3	West	1711.4	369.6	22	2962.1 (1988)	1052.8 (2001)
4	Valley	1464.2	162.5	11	1878.0 (1988)	1071.1 (2001)
	Post-monsoon					
1	East	166.4	65.6	39	366.5 (1971)	29.8 (1907)
2	Central	125.4	60.2	48	326.2 (1946)	20.7 (1981)
3	West	163.3	114.2	70	534.3 (1948)	11.2 (1918)
4	Valley	151.7	66.2	44	334.1 (1946)	33.5 (1935)
	Annual					
1	East	2463.9	250.7	10	3098.4 (1929)	1895.2 (2009)
2	Central	1660.2	192.7	12	2193.8 (1974)	1241.5 (2009)
3	West	2531.3	467.2	18	3896.7 (1988)	1733.4 (1961)
4	Valley	2218.7	235.7	11	2680.0 (1974)	1705.3 (2006)

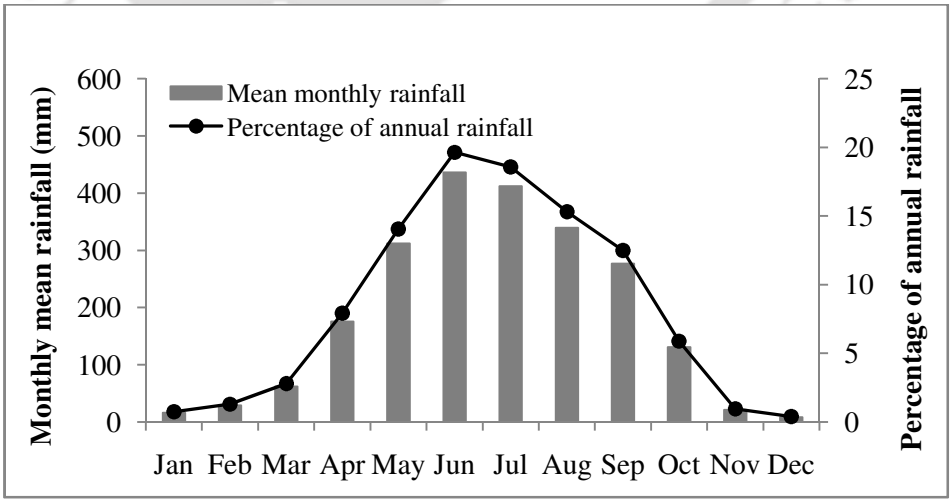

Fig. 4.4 Annual cycle of rainfall in the Brahmaputra valley during 1901–2010

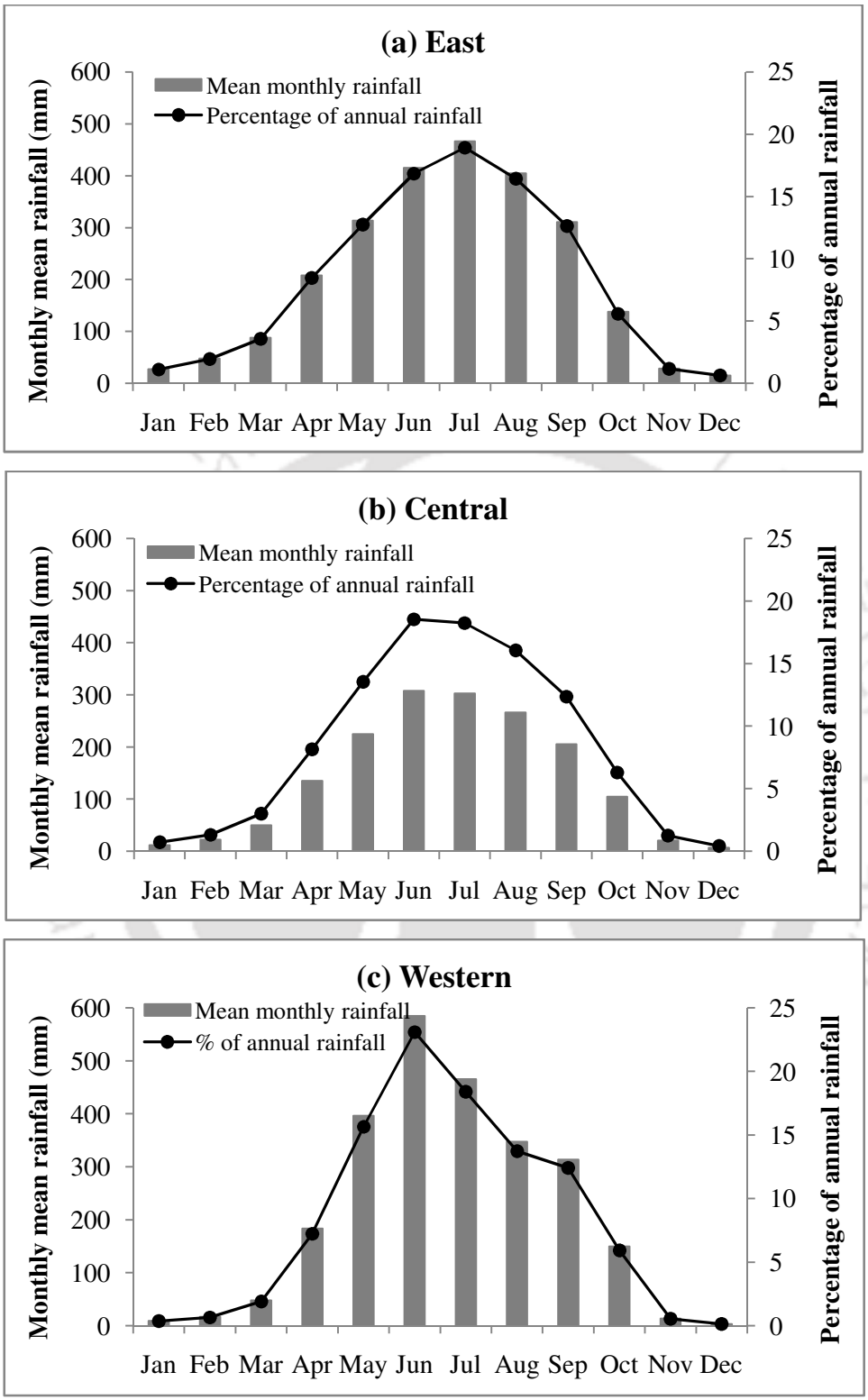

Fig. 4.5 Annual cycle of rainfall in different parts of the Brahmaputra valley during 1901–2010

4.3.1.2 Monthly rainfall trends

Monthly rainfall trends for the period 1901 to 2010 as well as different climate normal periods over the Brahmaputra valley are presented in Table 4.7. The trend magnitudes of monthly rainfall during the entire study period (1901–2010) were found to be within the range of ±3.0 mm/decade in the Brahmaputra valley (Table 4.7). Similar observations for monthly rainfall of Assam–Meghalaya sub-division of NE India, except for August, which showed significant decreasing trend (4.8 mm/decade), was reported by Kumar et al. (2010). Trend analysis of rainfall by sub-regions of the valley showed small variability in the magnitude and direction of trends from one part to another. In the case of significance of trends, only April in the western part (+5.5 mm/decade) and August in the eastern part (–6.3 mm/decade) of the valley was found to be statistically significant at 0.05 level during the study period.

Trend analysis during different climate normal periods showed increasing trend of rainfall in seven months during NP1 (1921–50) with trend magnitude of >30 mm/decade only during May and June in the Brahmaputra valley as a whole. None of the trends were found to be statistically significant during NP1. During NP2, the decreasing trend of May rainfall (57.4 mm/decade) in the Brahmaputra valley as a whole was found to be statistically significant at $p<0.001$ due to corresponding significant decrease in the eastern (53.9 mm/decade) and western (80.5 mm/decade) parts (Table 4.7). During the recent 30-year period (NP3), there was a statistically significant decreasing trend ($p<0.001$) of July (44.9 mm/decade), September (58.7 mm/decade) and December (4.1 mm/decade) rainfall over the Brahmaputra valley as a whole. Decrease of July rainfall in the eastern part and September rainfall in all three parts of the Brahmaputra valley were found to be statistically significant (Table 4.7). The pre- and post-monsoon month of October along with monsoon months of June and August showed non-significant increasing trends during NP3 (1981-2010) in the Brahmaputra valley as a whole. During this period (NP3), April rainfall increased by 12.8 mm/decade in the Brahmaputra valley due to significant increase (36.1 mm/decade) in the western part.

Table 4.7 Monthly rainfall trends (mm/decade) in the Brahmaputra valley and its three different parts during NP1 (1921–1950), NP2 (1951–1980), NP3 (1981–2010) and EP (1901–2010)

Period	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
EP (1901–2010)													
1	Eastern	−0.8	−0.2	−0.3	−3.1	−1.4	−4.1	−2.5	**−6.3**	−3.5	−1.0	−0.2	0.2
2	Central	0.0	−0.3	0.1	1.6	1.9	−0.8	1.0	−3.3	−0.2	2.3	−0.3	0.1
3	Western	0.0	−0.5	1.2	**5.5**	−3.1	−3.8	7.9	0.5	−1.1	4.1	0.0	0.0
4	Valley	−0.3	−0.3	0.3	0.9	−1.0	−3.0	2.5	−2.9	−2.2	1.9	−0.1	0.2
NP1 (1921–1950)													
1	Eastern	−2.5	0.7	13.0	−11.7	16.8	32.1	8.7	6.9	7.8	2.9	−2.7	0.8
2	Central	−3.1	1.1	10.0	−7.9	11.2	8.2	−9.7	−10.3	24.9	20.8	0.3	0.2
3	Western	−0.5	4.6	1.4	6.8	68.2	61.2	−37.5	−13.4	13.6	17.7	0.0	0.0
4	Valley	−3.0	3.2	8.7	−2.8	31.5	32.7	−11.6	−1.0	15.6	13.8	−1.3	0.3
NP2 (1951–1980)													
1	Eastern	0.8	2.0	−13.3	9.2	**−53.9**	5.3	16.6	5.6	5.2	−21.2	0.1	−2.2
2	Central	−0.2	1.2	−11.7	6.0	−23.3	5.0	19.7	−16.1	−3.7	−12.0	0.0	−1.6
3	Western	−0.8	−0.4	−6.7	−2.1	**−80.5**	−86.3	−19.7	6.2	21.1	−4.1	0.0	0.0
4	Valley	−0.8	0.4	−10.9	1.5	**−57.4**	−20.2	9.1	1.2	13.6	−9.8	15	−1.5
NP3 (1981–2010)													
1	Eastern	−1.0	−2.0	4.4	−0.8	11.9	−9.7	**−42.4**	14.6	**−48.4**	2.5	3.0	**−7.7**
2	Central	−1.9	−3.8	3.0	−10.9	9.8	9.9	−24.0	−3.4	**−32.5**	10.7	−0.2	**−2.9**
3	Western	−1.9	**−7.9**	5.4	**36.1**	−8.1	44.7	−76.2	−13.3	**−107.7**	21.5	−0.3	0.0
4	Valley	−1.2	−2.7	5.3	12.8	0.5	9.2	**−44.9**	4.1	**−58.7**	20.7	1.2	**−4.1**

Values rendered in bold indicate statistical significance at 95% confidence level according to the Mann–Kendall test.

Likewise, October rainfall increased at higher magnitude in the western part (21.5 mm/decade) followed by central (10.7 mm/decade) and eastern (2.5 mm/decade) parts during NP3. December rainfall, though small in quantity, exhibited a decreasing tendency in the Brahmaputra valley due to its significant decrease in the eastern and central parts during the recent 30-year period (Table 4.7).

4.3.1.3 Annual rainfall trends

The mean annual rainfall over the Brahmaputra valley showed a weak decreasing trend (1.6 mm/decade) during 1901–2010 (Table 4.8) with large spatial and temporal variations (Fig. 4.6). Trend analysis during different climate normal periods showed increasing tendency of annual rainfall (78.8 mm/decade) during NP1 (1921–1950) and decreasing tendency during NP2 and NP3 (Fig. 4.6). During NP2 (1951–1980), annual rainfall in the Brahmaputra valley decreased significantly by a rate of 94.9 mm/decade due to significant decrease of pre-monsoon (71.4 mm/decade) rainfall (Table 4.8). On the contrary, annual rainfall showed decreasing trend (72.0 mm/decade) during NP3 (1981-2010) and was mainly contributed by significant decrease of monsoon rainfall (103.8 mm/decade) during that period. In spite of decrease of monsoon rainfall at a higher magnitude during NP3, annual rainfall in the valley decreased at a comparatively lower rate due to increasing tendency of pre-monsoon (17.4 mm/decade) and post-monsoon (16.1 mm/decade) rainfall (Table 4.8). The eastern part of the Brahmaputra valley showed statistically significant decreasing trend (24.0 mm/decade) of annual rainfall during entire study period (1901–2010). In general, the central part of the valley exhibited least variability compared to the eastern and western parts (Fig. 4.6) particularly during the last 60 years (1981-2010).

4.3.1.4 Seasonal rainfall trends

4.3.1.4.1 Pre-monsoon

Pre-monsoon rainfall in the Brahmaputra valley showed a small increasing trend during last 110 years (Table 4.8 and Fig. 4.7). On different spatial and temporal scales, the trend magnitudes were found to be highly variable. During NP1, pre-monsoon rainfall increased by a rate of 38.0 mm/decade in the Brahmaputra valley mainly due to its increase in the

western part (Fig. 4.7). The decrease of pre-monsoon rainfall (71.4 mm/decade) during NP2 in the Brahmaputra valley was statistically significant at 0.001 level due to its significant decrease in the eastern (78.7 mm/decade) and western (90.7 mm/decade) parts (Table 4.8) due to significant decrease of May rainfall (Table 4.7) during that period. Pre-monsoon rainfall exhibited an increasing tendency (17.4 mm/decade) during NP3 over the Brahmaputra valley due to statistically significant increase of April rainfall in the western part (Table 4.7). The magnitude of trend during the recent 30-year period was highest (49.9 mm/decade) in western and lowest in the eastern (3.1 mm/decade) parts of the valley.

Table 4.8 Annual and seasonal rainfall trends (mm/decade) in the Brahmaputra valley and its three different parts during EP (1901–2010), NP1 (1921–1950), NP2 (1951–1980) and NP3 (1981–2010)

Period	Location	Annual	Pre-monsoon	Monsoon	Post-monsoon	Winter
EP (1901–2010)						
1	Eastern	**–24.0**	–5.9	**–15.1**	2.0	–0.6
2	Central	3.2	4.4	–1.8	2.3	–0.3
3	Western	12.4	4.8	–1.1	4.2	–0.1
4	Valley	–1.6	0.9	–5.1	1.6	–0.3
NP1(1921–1950)						
1	Eastern	76.8	19.8	65.9	–4.6	–2.0
2	Central	75.2	27.0	20.3	20.3	–2.1
3	Western	115.5	79.3	19.5	11.3	4.3
4	Valley	78.8	38.0	28.8	9.8	0.5
NP2(1951–1980)						
1	Eastern	–55.4	**–78.7**	31.0	–20.8	3.5
2	Central	–34.4	–28.1	3.6	–8.5	4.7
3	Western	**–199.5**	**–90.7**	–80.0	3.4	–0.4
4	Valley	**–94.9**	**–71.4**	–24.5	–9.5	2.1
NP3(1981–2010)						
1	Eastern	–91.8	3.1	**–94.3**	5.2	–6.4
2	Central	–15.8	26.0	–53.6	3.5	–9.3
3	Western	–90.7	49.9	–156.2	17.6	–8.5
4	Valley	–72.0	17.4	**–103.8**	16.1	–7.3

Values rendered in bold indicate statistical significance at 95% confidence level according to the Mann–Kendall test.

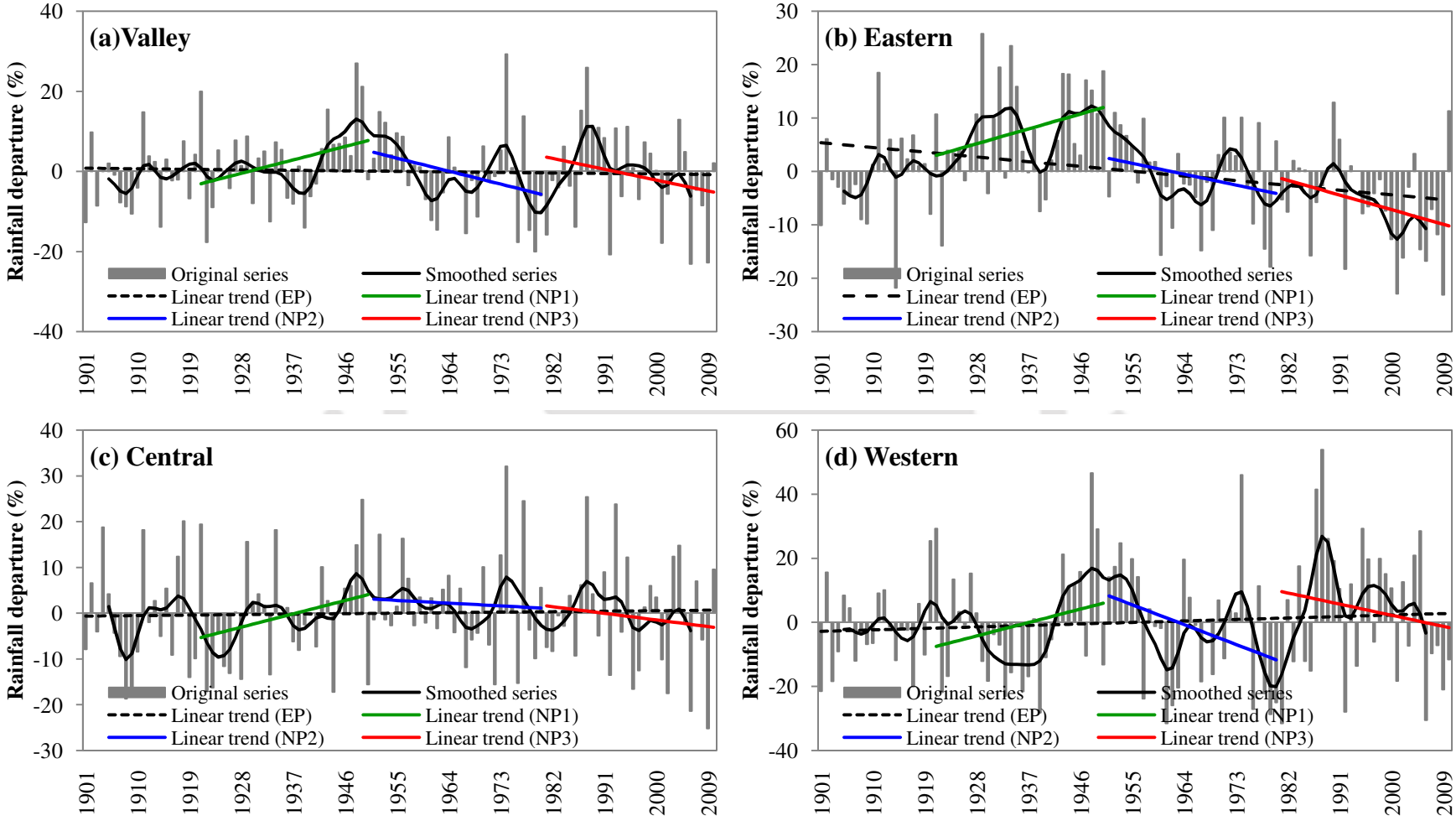

Fig. 4.6 Percentage (%) departure of annual rainfall and its 9-point Gaussian filter along with linear trend during different trend periods (EP: 1901–2010, NP1:1921–1950, NP2: 1951–1980 and NP3:1981–2010) in the Brahmaputra valley

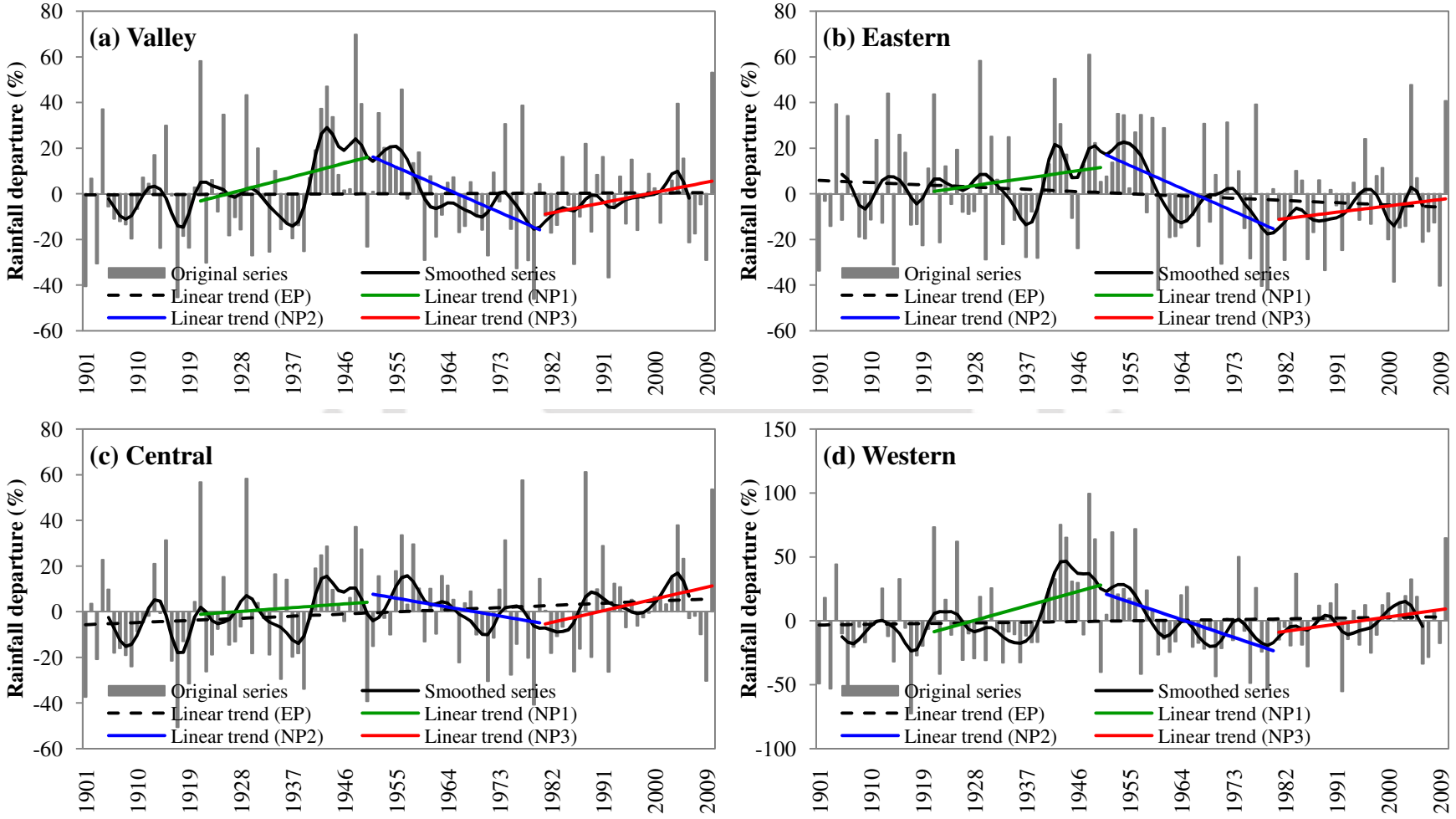

Fig. 4.7 Percentage (%) departure of pre-monsoon rainfall and its 9-point Gaussian filter along with linear trend during different trend periods (EP: 1901–2010, NP1:1921–1950, NP2: 1951–1980 and NP3:1981–2010) in the Brahmaputra valley

Shahid (2012) observed increasing trend of pre-monsoon rainfall in Bangladesh during 1958–2007 and Rangpur, which is located adjacent to western part of the valley recorded an increase by a rate of 36.4 mm/decade. The eastern and northeastern part of India gets affected by thunderstorms during pre-monsoon months, in particular during April–May. The activity of thunderstorms during pre-monsoon season depends on supply of moist air from Bay of Bengal (Shahid 2012). Stronger and more continuous winds from the Bay of Bengal during this season due to the increase of sea surface temperature may cause increased pre-monsoon rainfall in the Brahmaputra valley. The convective available potential energy (CAPE), which is considered as the measure of thunderstorm potential (Chaudhuri 2010), showed an increasing trend during March and April over the Brahmaputra valley (Chaudhuri and Middey 2012). This might be the reason for increased pre-monsoon rainfall activities over the Brahmaputra valley during recent past. Higher pre-monsoon rainfall was harmful for summer rice cultivation in the valley if it coincides with the harvesting period as observed during 2004 and 2010. In addition, excessive pre-monsoon rainfall is also associated with early flood (deluge) affecting negatively the productivity of autumn rice.

4.3.1.4.2 Monsoon season

Monsoon rainfall exhibited a decreasing trend (5.1 mm/decade) during 1901–2010 in the Brahmaputra valley as a whole due to its significant decrease (15.1 mm/decade) in the eastern part (Table 4.8). Among different climate normal periods, monsoon rainfall during NP3 (1981–2010) decreased significantly (103.8 mm/decade) due to corresponding significant decrease of July and September rainfall (Table 4.7). During this period (NP3), monsoon rainfall at all the three divisions of the Brahmaputra valley showed sharp decreasing trends (Fig. 4.8). It decreased by 94.1 mm/decade, 53.6 mm/decade and 156.2 mm/decade in the eastern, central and western parts (Table 4.8) with statistically significant value only for the eastern part. These trends, if associated with large intra-seasonal variability, indicated greater degree of likelihood of short spell drought and bound to pose a major challenge to pre-dominant rainfed rice cultivation during *kharif* season in the valley.

The results agree with the earlier analysis (Sen Roy and Balling 2004; Kumar et al. 2010; Jain et al. 2012) which reported a decline in monsoon rainfall over NE India. The amount and distribution of monsoon rainfall in NE India is controlled by activities of cyclonic disturbances including monsoon depressions and tropical storms of Bay of Bengal, strength of monsoon winds, location of monsoon trough and local orography. The increased rainfall over NE India is the result of orographic uplift of moisture laden air from the Bay of Bengal. Mandke and Bhide (2003) reported a decreasing trend of storm frequency over the Bay of Bengal since the 1980s in spite of increasing trend of sea-surface temperature of Bay of Bengal during monsoon season. Sikka (2006) reported an overall decrease in the frequency of transient monsoon rain-producing synoptic disturbances like lows and depressions in recent decades. The suppression of monsoon convection over the Indian region in association with the weakening trend of the upper tropospheric easterly winds has been reported by Ramesh Kumar et al. (2009). Jadhav and Munot (2009) also observed a significant increase in the frequency and duration of low pressure areas (LPA) and decrease in deep depressions/storms (DDS) during monsoon season since 1980. The regional warming of sea surface temperature over the Indian ocean seems to have enhanced the monsoon rainfall over the Indian ocean and reduced the rainfall over northeast India (Singh and Oh 2007). Such a decrease in the monsoon depressions over the Bay of Bengal affecting the intensity and frequency of extreme rainfall events (discussed in section 4.3.3) may be responsible for decreasing trend of monsoon rainfall in the Brahmaputra valley during last three decades (1981–2010).

4.3.1.4.3 Post-monsoon season

The direction of trends of post-monsoon rainfall was almost similar as that of pre-monsoon rainfall at different spatial and temporal scales over the Brahmaputra valley (Table 4.8 and Fig. 4.9). Trend of post-monsoon rainfall during the last 110 years over the valley was positive but statistically not significant (Table 4.8). Post-monsoon rainfall showed positive trends during NP1 and NP3 and negative trend in NP2. During the NP3 (1981–2010), post-monsoon rainfall in the Brahmaputra valley increased by a rate of 16.1 mm/decade due to increasing tendency of October rainfall in all the three divisions of the valley (Table 4.7).

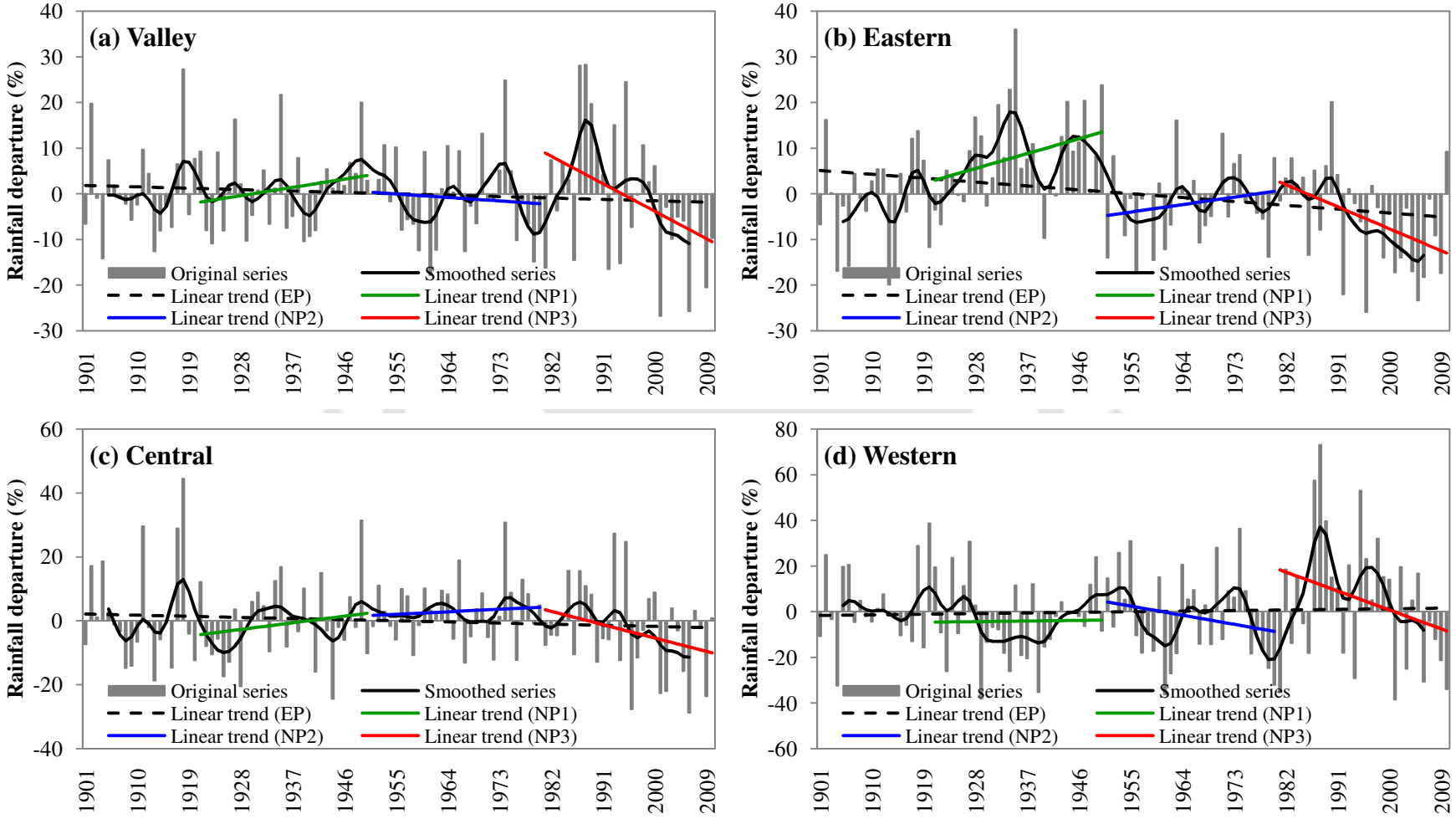

Fig. 4.8 Percentage (%) departure of monsoon rainfall and its 9-point Gaussian filter along with linear trend during different trend periods (EP: 1901–2010, NP1:1921–1950, NP2: 1951–1980 and NP3:1981–2010) in the Brahmaputra valley

The magnitude of increase was the highest in the western part (17.6 mm/decade) of the valley. Increasing tendency of post-monsoon rainfall was also observed over Assam–Meghalaya subdivision of NE India (Kumar et al. 2010) and adjacent Bangladesh (Shahid 2012). Pattanaik (2007) reported an eastward shift of rainfall belt with time over the Indian region and was very prominent during withdrawal phase of monsoon and concurrently NE India received more rainfall during 1977–2002. Increase in post-monsoon rainfall particularly during October, is generally harmful for rice crop in the Brahmaputra valley if it coincides with flowering and grain filling stages.

4.3.1.4.4 Winter season

Table 4.8 showed that the magnitude of trend of winter rainfall during NP1, NP2 and entire study period (EP) was within the range of ±5.0 mm/decade in the Brahmaputra valley as a whole as well as in its different parts. However, during the recent 30-year period, winter rainfall over the valley has decreased by 7.3 mm/decade due to statistically significant decreasing tendency of December rainfall in the eastern and central parts of the Brahmaputra valley (Table 4.7). All three parts of the valley showed a decreasing trend (Fig. 4.10). Decrease of winter rainfall in the Assam–Meghalaya subdivision of NE India during 1871–2005 was also reported by Kumar et al. (2010). Decrease of winter rainfall has negative implications on tea productivity in the Brahmaputra valley, as the relationship between tea yield and winter rainfall is significantly positive (Sen et al. 1966).

4.3.2 Short-term fluctuations of rainfall

To examine the short-term fluctuations of rainfall in the Brahmaputra valley, decade-wise percentage (%) departure of annual and seasonal rainfall from their long-term mean were computed and tested for statistical significance by using Cramer's test as described in section 4.3.2. Frequencies of excess and deficient years in each decade were identified in the rainfall series following the method described in section 4.3.3. Considering the non-significant contribution of post-monsoon and winter rainfall to annual rainfall in the valley, the analysis was confined to pre-monsoon, monsoon and annual rainfall only.

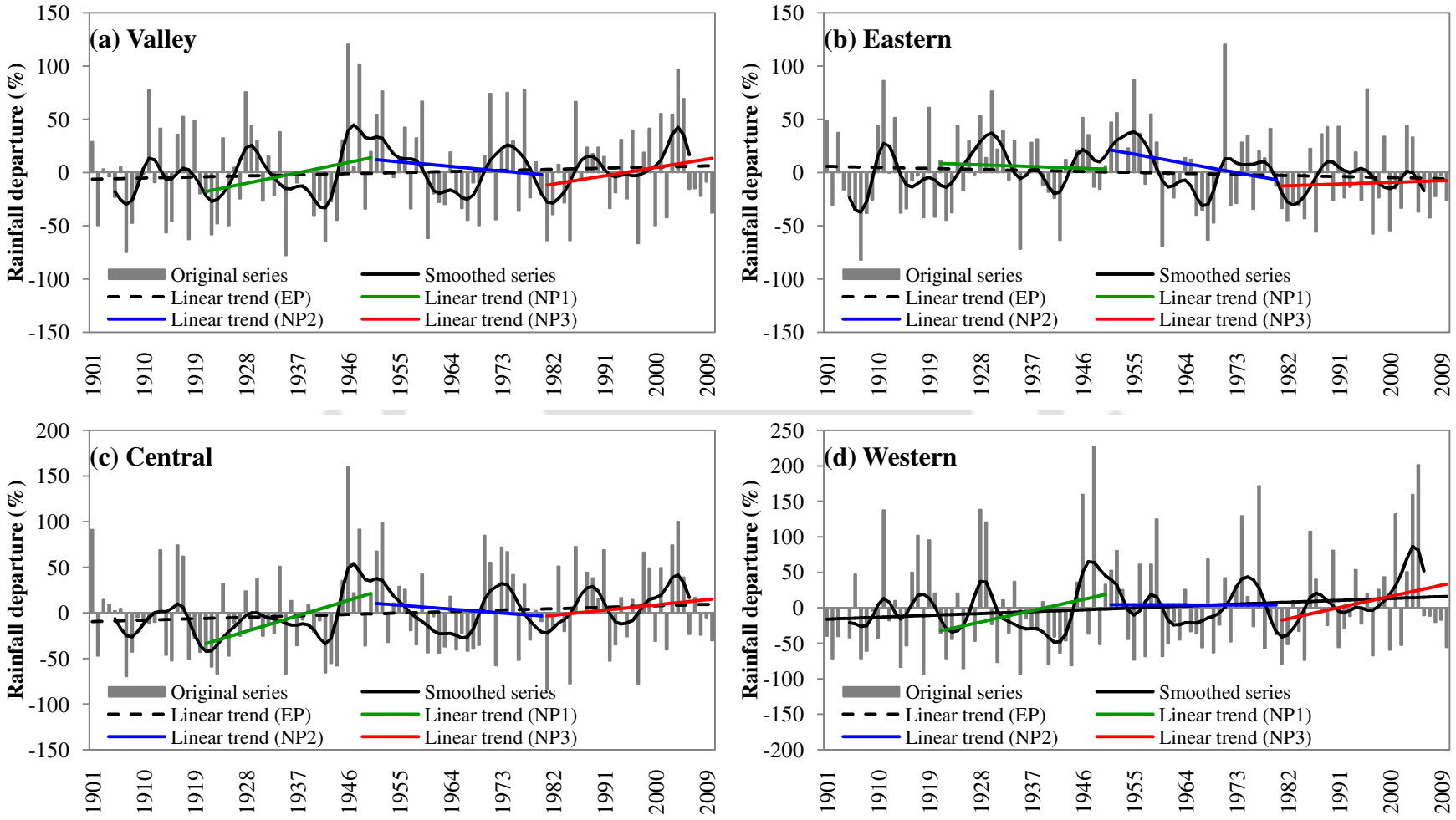

Fig. 4.9 Percentage (%) departure of post-monsoon rainfall and its 9-point Gaussian filter along with linear trend during different trend periods (EP: 1901–2010, NP1:1921–1950, NP2: 1951–1980 and NP3:1981–2010) in the Brahmaputra valley

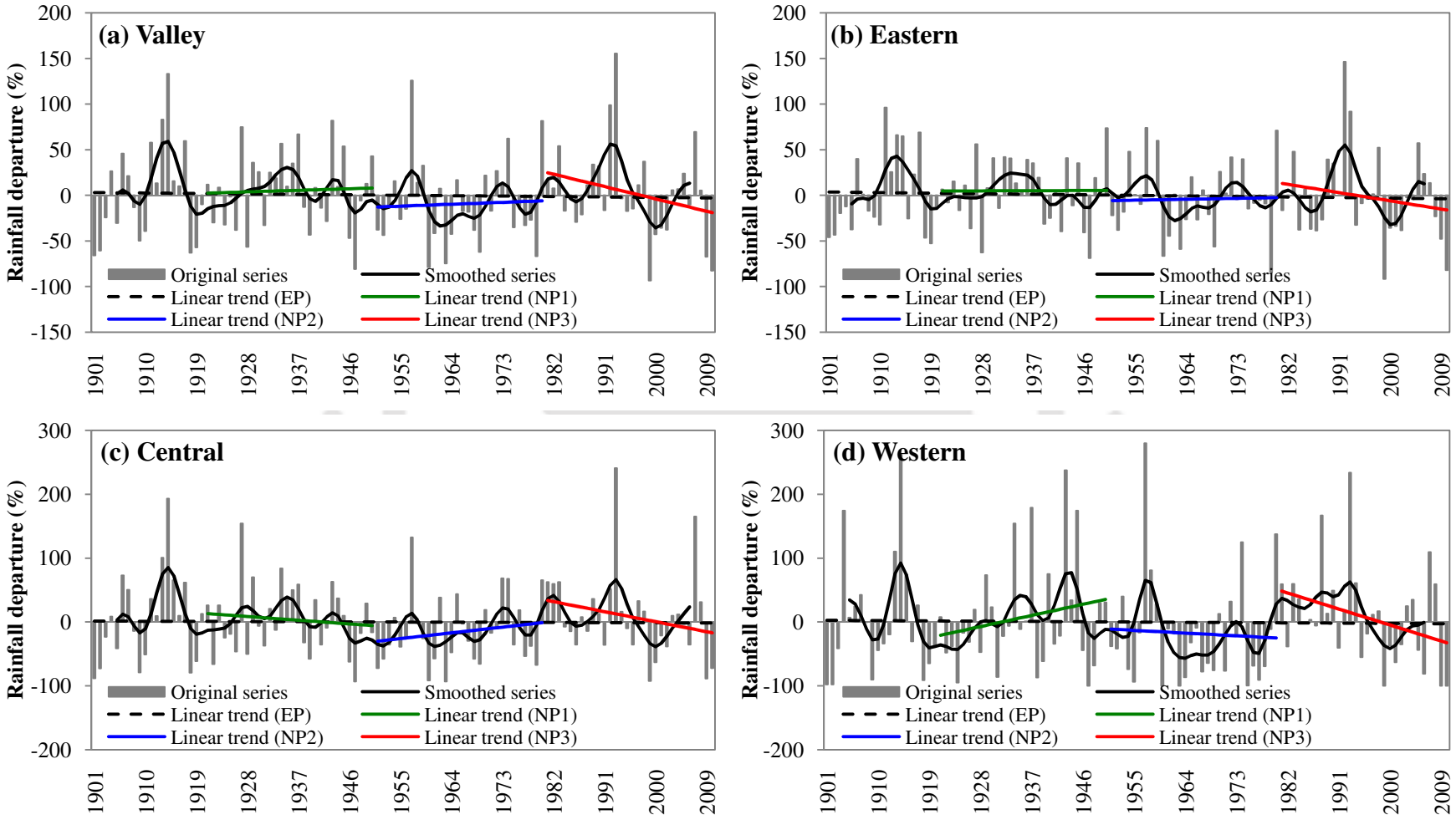

Fig. 4.10 Percentage (%) departure of winter rainfall and its 9-point Gaussian filter along with linear trend during different trend periods (EP: 1901–2010, NP1:1921–1950, NP2: 1951–1980 and NP3:1981–2010) in the Brahmaputra valley

4.3.2.1 Shift in decade-wise annual rainfall

Decade-wise percentage departure of mean annual rainfall along with frequencies of excess and deficient rainfall years in the Brahmaputra valley as well as in its different parts are shown in Figs. 4.11 and 4.12 respectively. Percentage departure of annual mean decadal rainfall was below the mean during five decades (1901–1910, 1931–1940, 1961–1980 and 2001–2010) in the valley. During 1941–1950, there were three excess rainfall years with no deficient year and the decadal mean annual rainfall was also 9.0% higher than the mean. The recent decade registered highest negative departure (–6.3%) and was statistically significant due to occurrence of three deficient years (Fig. 4.12). During this decade, the eastern part of the valley showed significant negative departure (10.1%) of annual rainfall due to six deficient years while in other two parts, the rainfall departures were less than –4.5%. Again, while annual rainfall showed significant positive departure during 1931–1940 in the eastern part (6.6%), the western part of the valley showed significant negative departure (–12.7%). Thus, rainfall departures in different parts of the valley were not similar in both direction and magnitude of change during all the decades indicating high spatial variability of rainfall. The central part of the valley showed little variability and annual rainfall departures were within ±4% of long-term mean.

4.3.2.2 Shift in decade-wise seasonal rainfall

Decade-wise shift in pre-monsoon rainfall along with frequencies of excess and deficient rainfall years over the Brahmaputra valley is shown in Figs. 4.13 and 4.14. Percentage departure of decadal mean pre-monsoon rainfall was above normal in four decades (1921–1930, 1940–1960 and 2001–2010) in the Brahmaputra valley as a whole (Fig. 4.13). Pre-monsoon rainfall was significantly higher (23.5%) during 1941–1950 due to five excess years and no deficient year (Fig. 4.14). During this decade, the rainfall departures were 17.8%, 11.2% and 37.1% in eastern, central and western parts respectively with significant values only in the eastern and western parts. During the dry seasons of 1961–2000, two excess and six deficient years were seen (Fig. 4.14). After four consecutive below-normal decades since 1961–1970, pre-monsoon rainfall in the valley showed positive departure in the recent decade 2001–2010 (Fig. 4.13) due to two excess and one deficient year (Fig. 4.14). During this decade (2001–2010), rainfall departure was below normal in eastern part

(6.3%) and above-normal in central (9.4%) and western (7.5%) parts of the valley. During the study period of 110 years, there were 16 excess and 17 deficient pre-monsoon rainfall years in the Brahmaputra valley.

Decadal mean monsoon rainfall was below normal in seven decades (1901–1910, 1921–1940, 1951–1980) in the Brahmaputra valley during 1901–2010 (Figs. 4.15). Monsoon rainfall was significantly higher (6.9%) during 1981–1990 due to three excess years (Fig. 4.16). Though the rainfall departure during 1981–1990 was above normal in all three parts of the valley, it was significantly higher (14.7%) only in the western part. During the recent decade (2001–2010), monsoon rainfall departure was significantly lower (11.6%) due to three deficient years and no excess year (Fig. 4.16). Rainfall departures were almost similar in magnitude in all three parts of the valley (Fig. 4.15) with significant value in the eastern and central parts during 2001–2010. During the study period of 110 years, there were 12 excess monsoon rainfall years and 14 deficient monsoon rainfall years (Fig. 4.16). Out of the 14 deficient years, 11 have occurred during the last five decades (1961–2010). Trend analysis of decadal excess and deficient monsoon rainfall years in the Brahmaputra valley by Sen's slope method indicated a statistically significant increasing tendency (2.5 years/decade) of occurrence of deficient years. While decadal deficient monsoon years showed increasing trends in the eastern and western part, no trend could be detected in the central part of the valley.

The findings agree with Pal and Al–Tabbaa, (2010a) who reported an increasing frequency and magnitude of monsoon rainfall deficit and decreasing frequency and magnitude of monsoon rainfall excess during 1871–2005 in India and the trend was relatively strong in the northeast, west central and central northeast India.

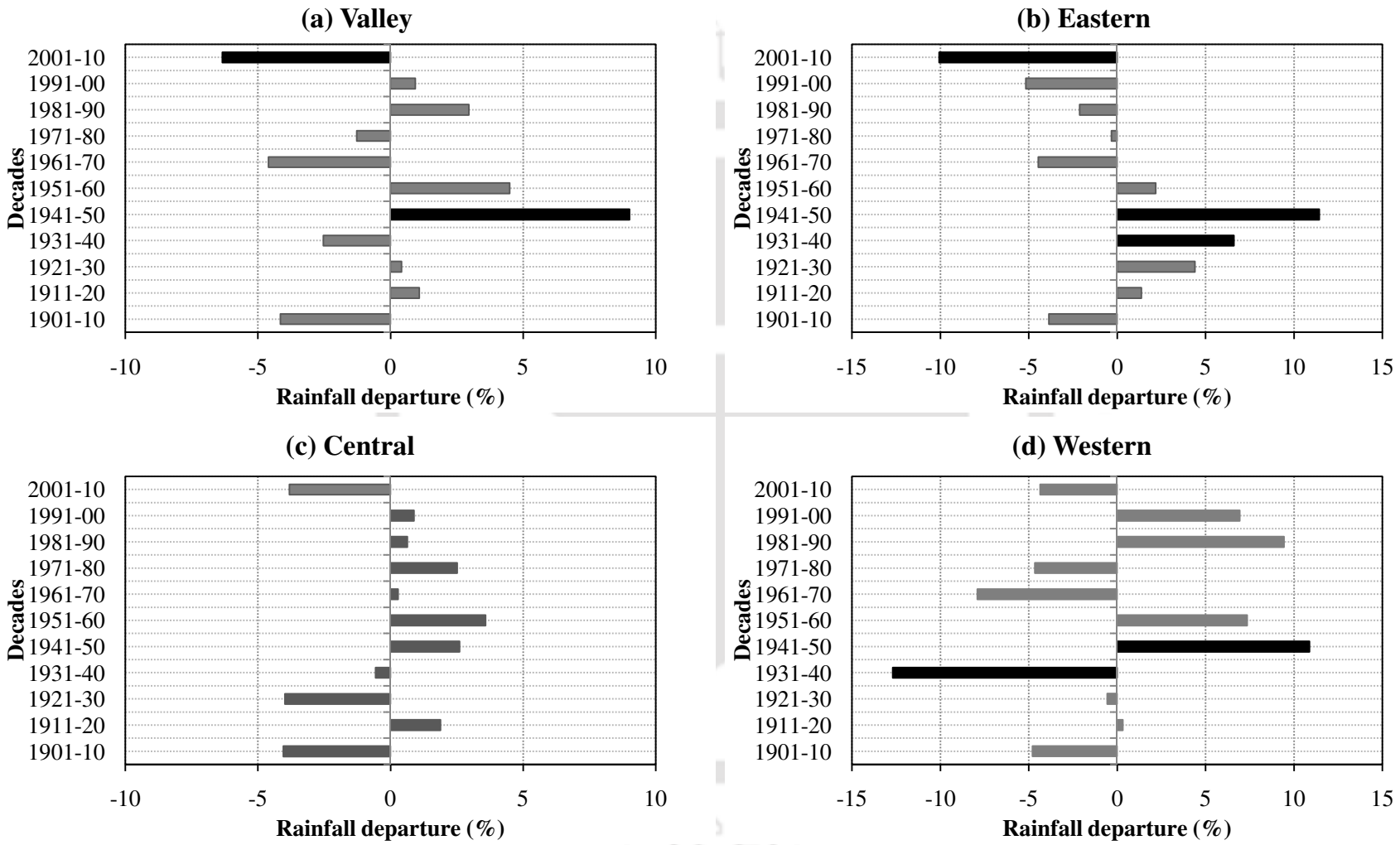

Fig. 4.11 Shift in decadal annual rainfall in the Brahmaputra valley (a) and its eastern (b), central (c) and western (d) parts during 1901–2010 (dark colour indicates statistical significance at 95 % confidence level as per Cramer's test)

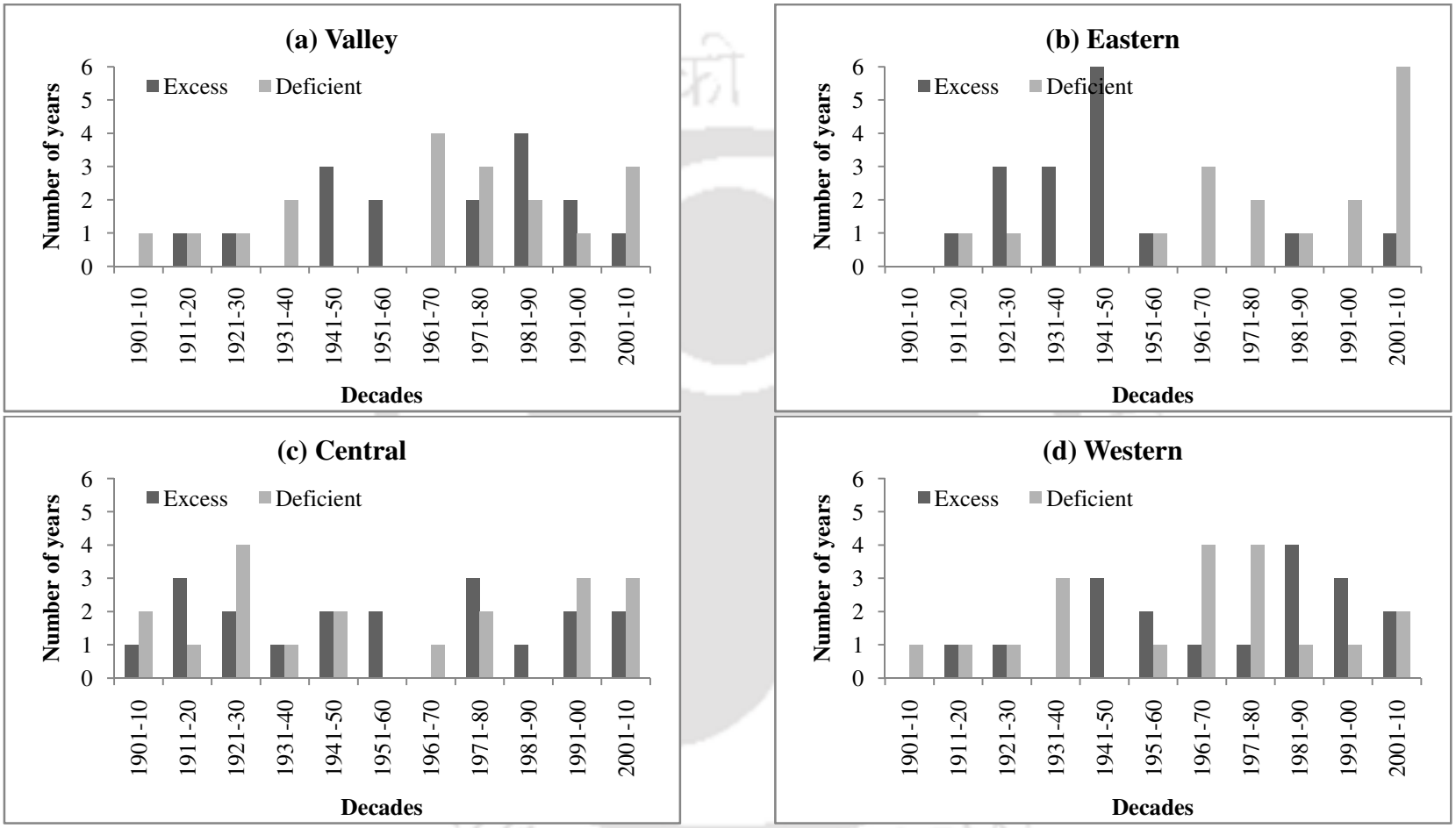

Fig. 4.12 Frequencies of excess and deficient rainfall years on annual basis in the Brahmaputra valley (a) and its eastern (b), central (c) and western (d) parts during 1901–2010

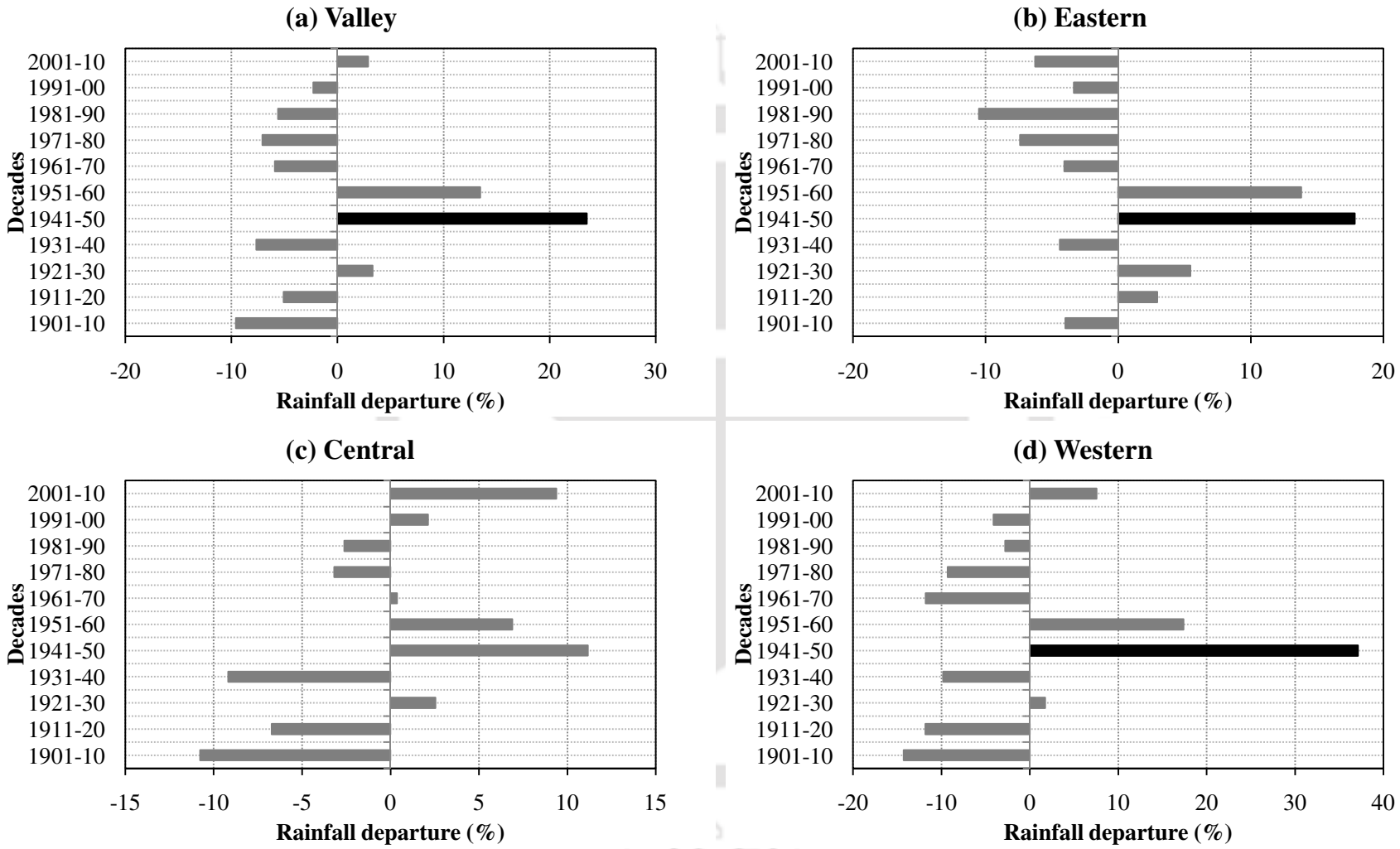

Fig. 4.13 Shift in decadal pre-monsoon rainfall in the Brahmaputra valley (a) and its eastern (b), central (c) and western (d) parts during 1901–2010 (dark colour indicates statistical significance at 95 % confidence level as per Cramer's test)

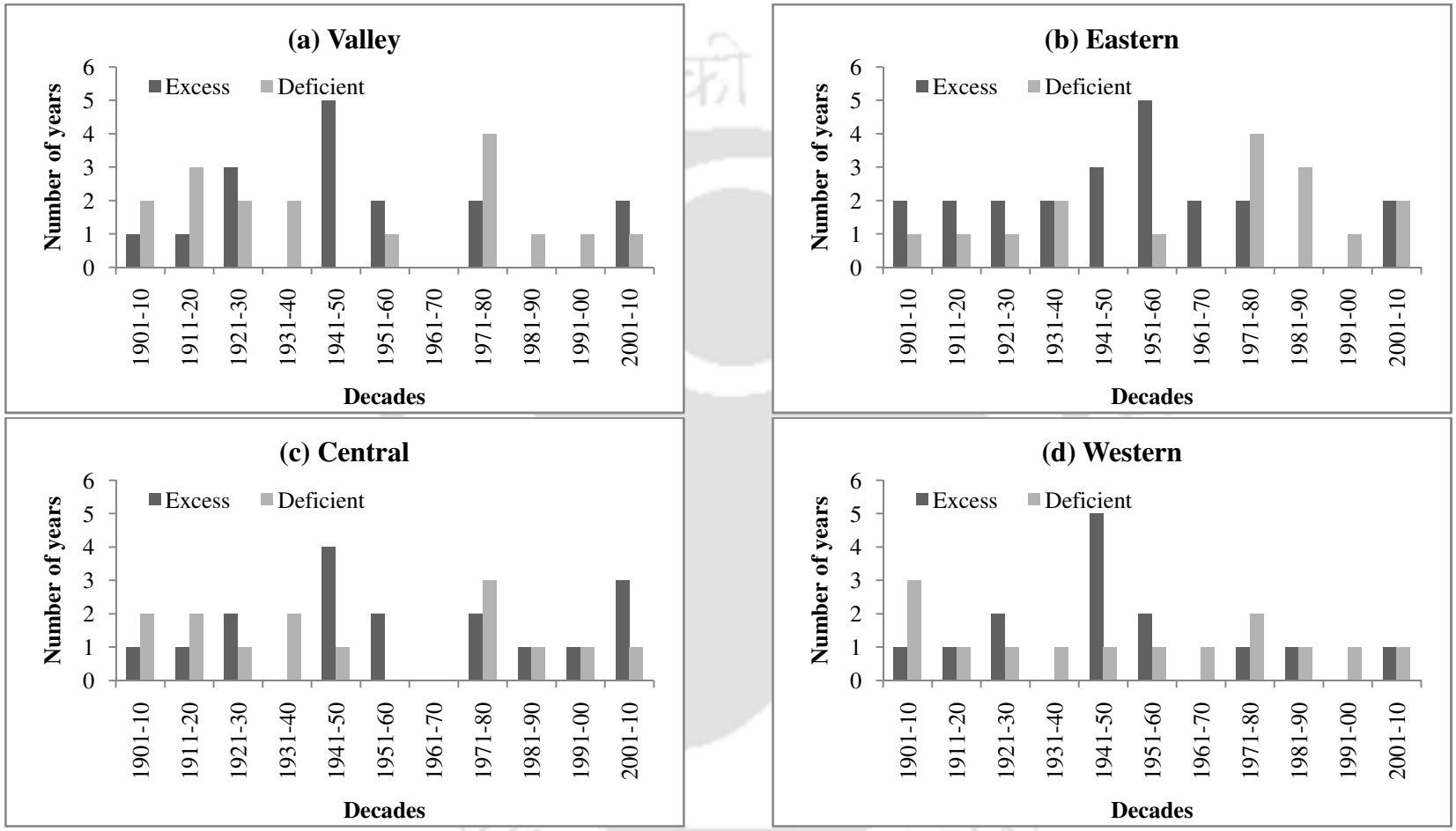

Fig. 4.14 Frequencies of excess and deficient rainfall years during pre-monsoon season in the Brahmaputra valley (a) and its eastern (b), central (c) and western (d) parts during 1901–2010

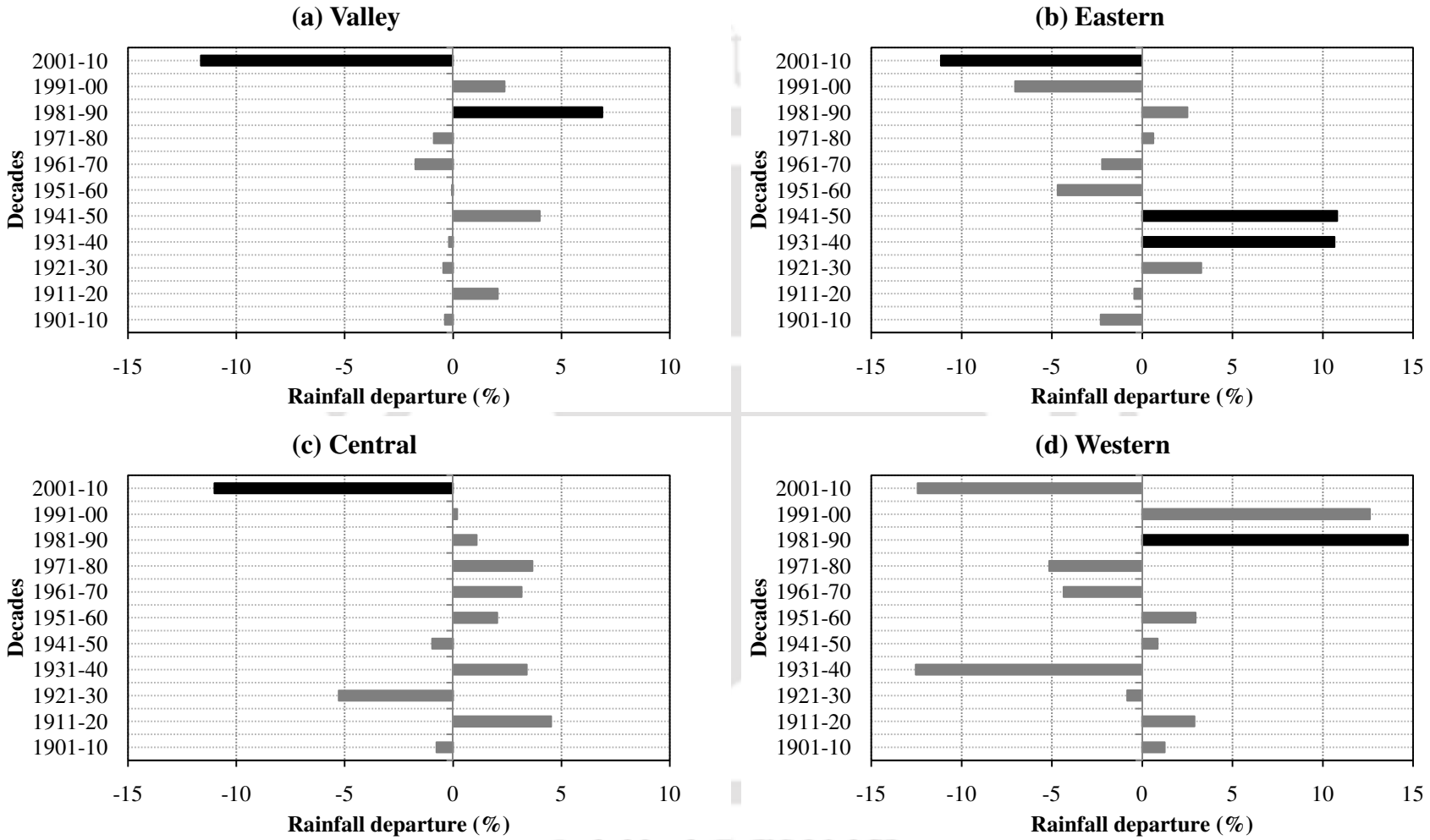

Fig. 4.15 Shift in decadal monsoon rainfall in the Brahmaputra valley (a) and its eastern (b), central (c) and western (d) parts during 1901–2010 (dark colour indicates statistical significance at 95 % confidence level as per Cramer's test)

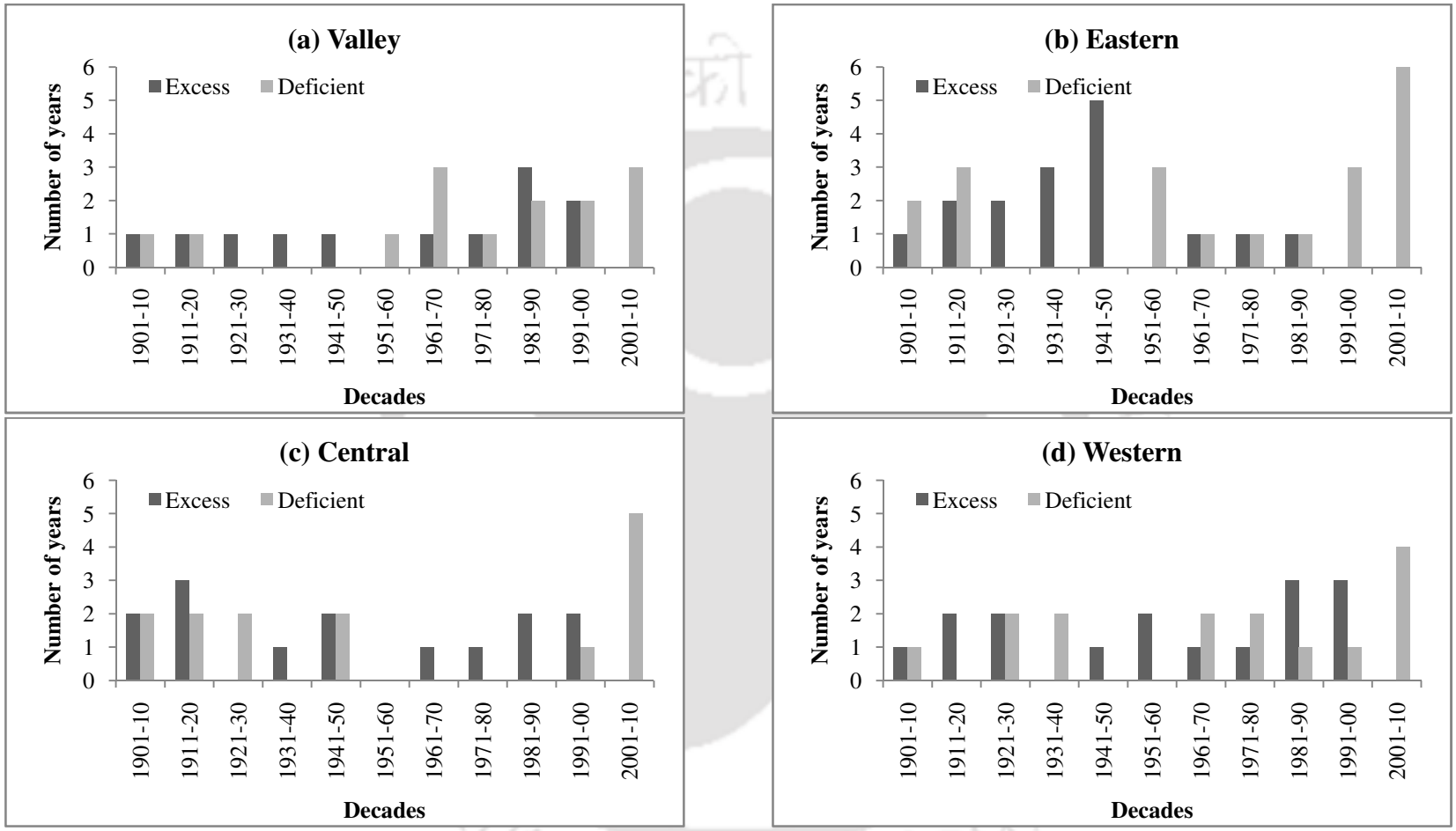

Fig. 4.16 Frequencies of excess and deficient rainfall years during monsoon season in the Brahmaputra valley (a) and its eastern (b), central (c) and western (d) parts during 1901–2010

4.3.3 Trends of extreme rainfall indices

Trends of annual and seasonal rainfall extreme indices, which can be considered as an indicator of climate change at local scale and were assessed using daily rainfall data of 55 years (1955–2010) from nine stations representing different parts of the Brahmaputra valley, have been discussed in this section. The analysis of extreme rainfall events would also provide an idea whether the observed rainfall changes in the valley is affected by the extremes. Trend analysis was performed at two temporal scales i.e., entire study period (1955–2010) and the recent 30-year period (1981–2010), using the methods described in section 4.3.1.

4.3.3.1 Threshold based indices

Different threshold based indices (R75mm, R100mm and R125mm) during the last 55 years (1955–2010) over the Brahmaputra valley were free from any trend. However, during the last three decades (1981–2010), the negative trends of R75 mm and R125mm during monsoon and positive trend of R75mm during pre-monsoon was observed over the Brahmaputra valley as a whole, although their magnitudes were very small.

Figs. 4.17, 4.18 and 4.19 showed large spatial variability of these threshold based indices over the Brahmaputra valley. R75mm, R100mm and R125mm during monsoon season were observed to be more frequent in the western part (2.5 days/year, 1.5 days/year and 1.4 days/year respectively) compared to the central and eastern parts of the valley due to orographic effect. The height of Garo hills in Meghalaya is low compared to the Khasi-Jayantia hills (Fig. 3.1) and it is located in the southern side of the valley bordering the western most part. As a result, rain bearing winds from the Bay of Bengal cross Garo hills without much rain in the Garo hills and eventually strikes Bhutan hills (northern side) causing heavy rainfall in the western part of the Brahmaputra valley. However, during last two decades (1991–2010) of monsoon season, R125mm showed a sharp decreasing trend in the western part (Fig. 4.17d) and also became less frequent in other two parts (Fig. 4.17b and 4.17c), which indicated decrease of rainfall strength of single rainfall events.

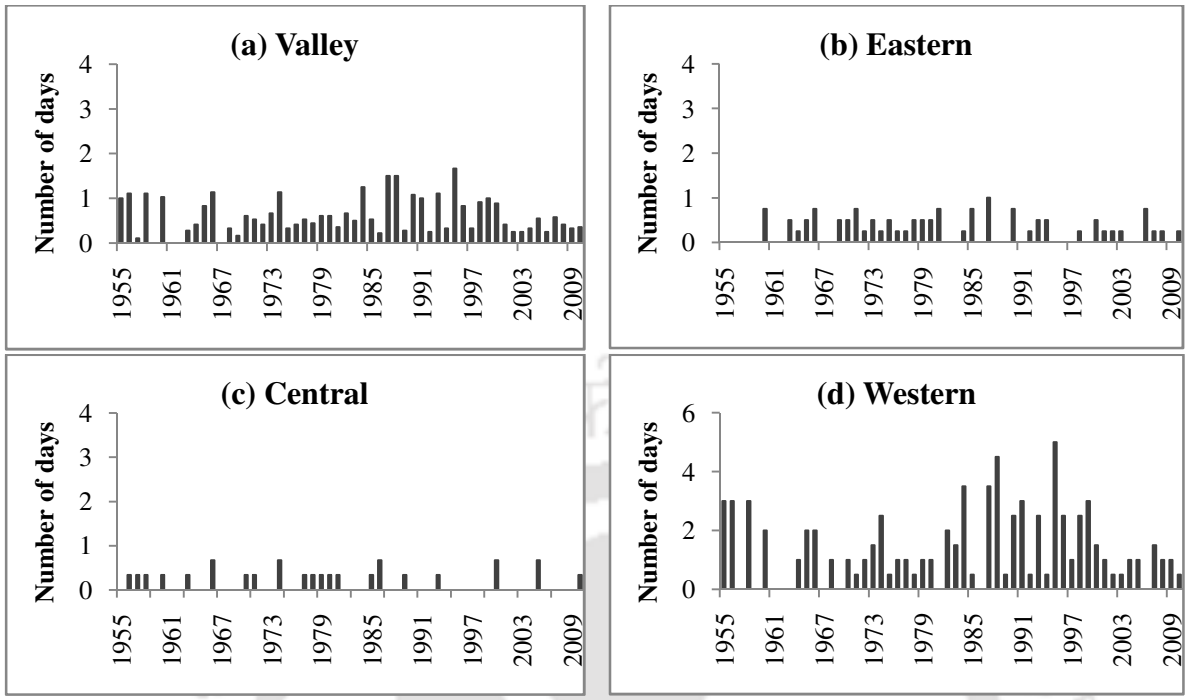

Fig. 4.17 Variations of R125 mm in the Brahmaputra valley during 1955–2010

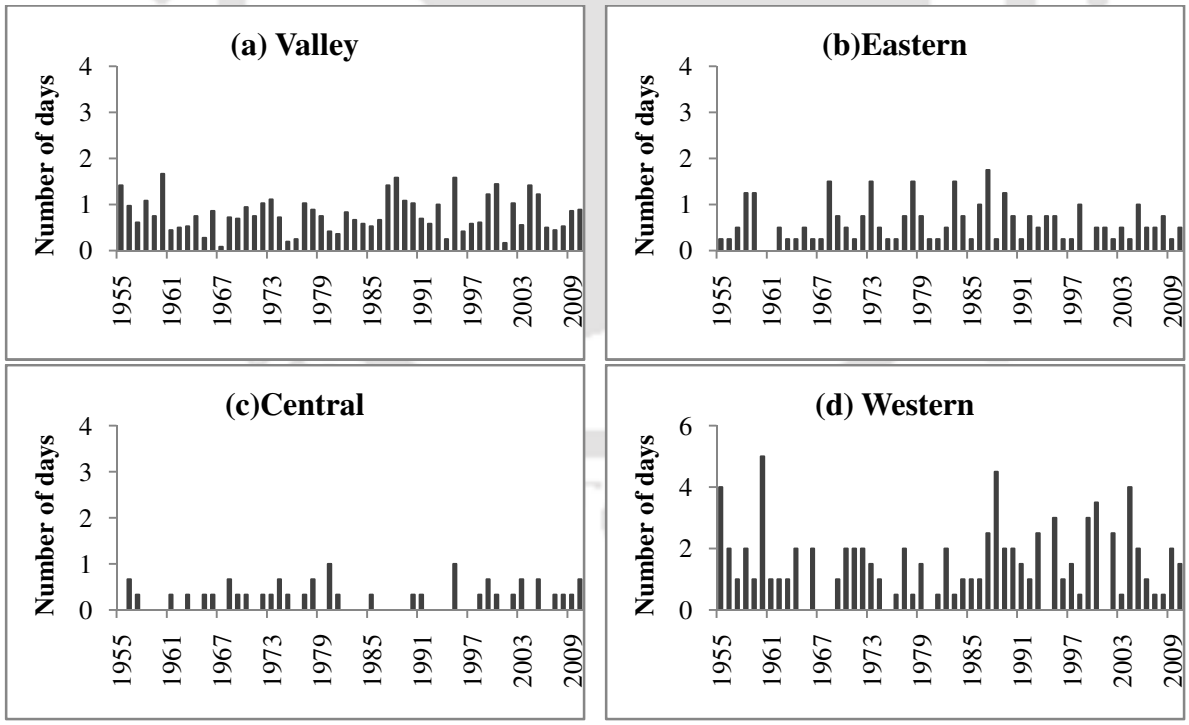

Fig. 4.18 Variations of R100mm (i.e., 99.9<R<124.9) in the Brahmaputra valley during 1955–2010

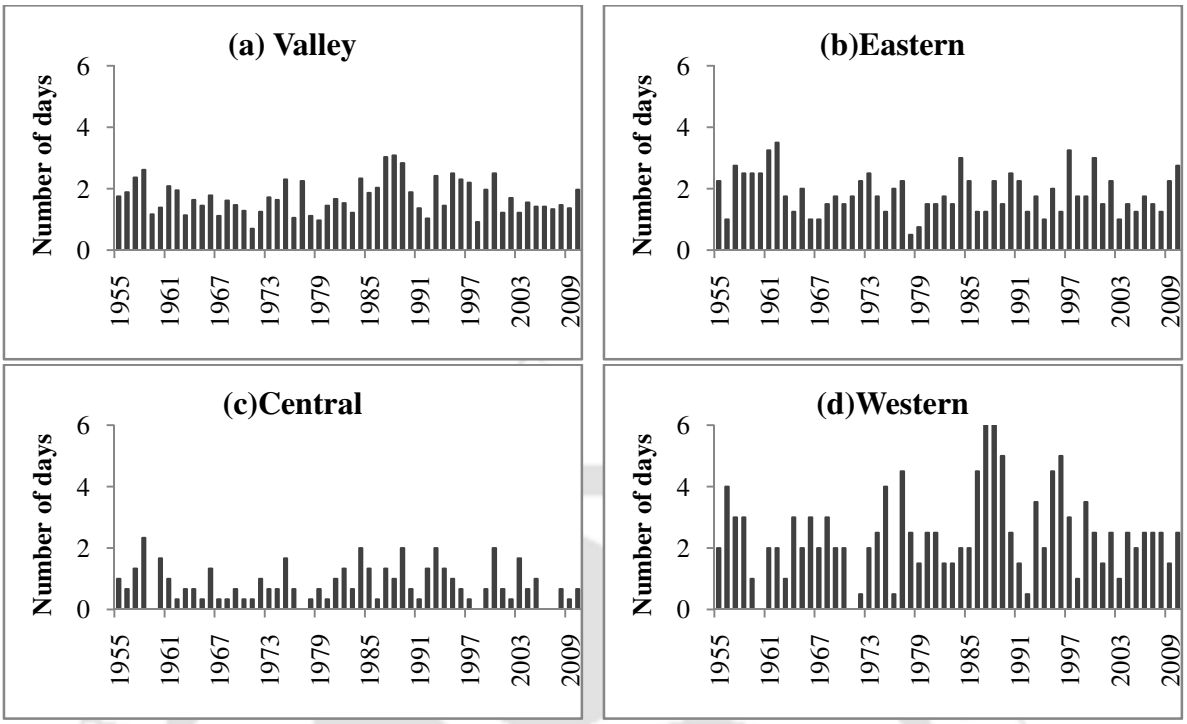

Fig. 4.19 Variations of R75mm (i.e., 74.9<R<99.9) in the Brahmaputra valley during 1955–2010

4.3.3.2 Absolute index (Rx1-day)

Rx1-day gives an indication of the trend in rainfall amount usually coming from extreme weather occurrences. Fig. 4.20 shows the Rx1-day over the Brahmaputra valley and its different parts during 1955–2010. It has been observed that, on annual basis, mean Rx1-day was highest in the western part of the valley followed by eastern and central parts during 1955–2010 due to orographic effect.

Annual Rx1-day showed positive trend during last 55 years in the Brahmaputra valley (Table 4.9). Maximum increase in Rx1-day was observed in the western part (2.67 mm/decade) while in the central part the trend was negative. Though the trend of Rx1-day during pre-monsoon was negative in the Brahmaputra valley as a whole and in its eastern and central parts during the last 55 years (1955–2010), it showed increasing trend during recent 30-year period (1981–2010) in all parts of the valley. The magnitude of increase of rainfall varied between 2.4 mm/decade and 2.8 m/decade in different parts of the valley (Table 4.9). During monsoon season, Rx1-day decreased by a rate of 2.67 mm/decade during last three decades (1981-2010) in the Brahmaputra valley a whole (Table 4.9).

Table 4.9 Trend of Rx1-day (mm/decade) in the Brahmaputra valley during 1955–2010 and 1981–2010

Indices	Entire valley		Eastern part		Central part		Western part	
	1955-2010	1981-2010	1955-2010	1981-2010	1955-2010	1981-2010	1955-2010	1981-2010
Annual	0.83	0.70	0.42	0.50	−0.31	−0.52	2.68	2.50
MAM	−0.30	2.63	−1.04	2.83	−0.88	2.74	1.45	2.40
JJAS	−0.37	−2.67	0.06	−2.93	−1.52	−1.80	1.77	−0.25
ON	−2.09	5.89	1.36	3.61	**4.03**	6.31	**−10.15**	6.80

Values rendered in bold indicate statistical significance at 95% confidence level according to the Mann–Kendall test. (MAM: pre-monsoon, JJAS: monsoon and ON: post-monsoon months)

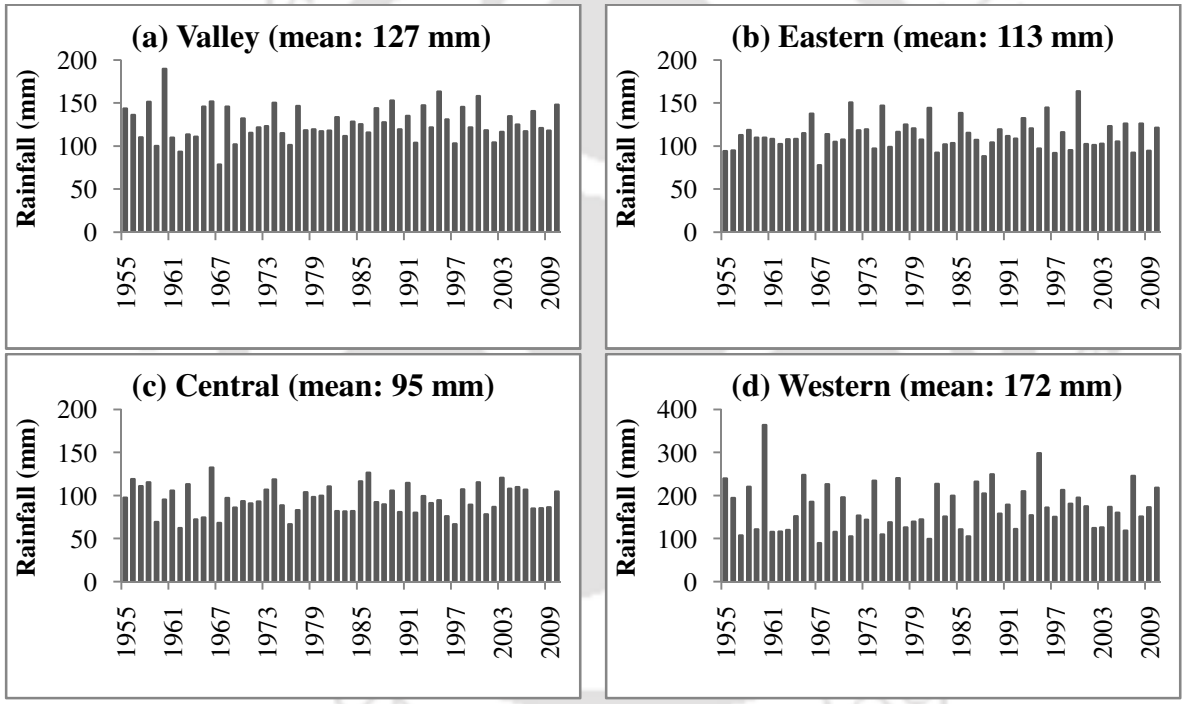

Fig. 4.20 Annual variations and trends of maximum 1-day rainfall (Rx1-day) in the Brahmaputra valley during 1955–2010

Maximum decrease was observed in the eastern part (2.93 mm/decade) followed by central and western parts. Trend of post-monsoon Rx1-day rainfall was negative in the Brahmaputra valley as a whole during last 55 years due to its significant decrease (10.15 mm/decade) in the western part (Table 4.9). On the other hand, the direction of trend of Rx1-day during recent 30-year period (1981–2010) was similar as that observed during

pre-monsoon season. However, the magnitude of increase was slightly higher during post-monsoon season and varied between 3.61 mm/decade and 6.80 mm/decade (Table 4.9). The results indicated that while contribution of maximum 1-day rainfall to monsoon rainfall total was decreased, its contribution to pre-monsoon and post-monsoon rainfall totals was increased during the recent 30-year period in the Brahmaputra valley.

4.3.3.3 Simple Daily Intensity Index (SDII)

Average rainfall on rainy days (SDII) showed a non-significant decreasing trend during pre-monsoon, monsoon and annually based upon data for the last 55 years (1955–2010) in the Brahmaputra valley as a whole (Table 4.10). The trend during post-monsoon season was positive. However, in the recent 30-year period (1981–2010), SDII increased during pre-monsoon and post-monsoon and decreased during monsoon season in all parts of the Brahmaputra valley (Table 4.10). The magnitude of increase of SDII during pre-monsoon and decrease during monsoon season was spatially coherent over the Brahmaputra valley during the recent 30-year period (1981–2010). But during post-monsoon season, the strongest positive trend was detected in the western part (2.74 mm/decade) and the weakest in the eastern part (0.56 mm/decade) of the valley (Table 4.10). This indicated the increase of intensity of pre-monsoon rainfall as the number of rainy days remained constant during the last 30-year period.

Table 4.10 Trend of SDII in the Brahmaputra valley during 1955–2010 and 1981–2010

Indices	Entire valley		Eastern part		Central part		Western part	
	1955-2010	1981-2010	1955-2010	1981-2010	1955-2010	1981-2010	1955-2010	1981-2010
Annual	–0.11	0.72	–0.17	–0.15	–0.13	–0.33	0.09	0.00
MAM	–0.27	0.27	–0.30	0.44	–0.09	0.46	–0.13	0.40
JJAS	–0.13	–0.38	–0.23	–0.50	–0.37	–0.54	0.35	–0.56
ON	0.35	1.60	0.25	0.56	0.99	1.63	0.06	2.74

(MAM: pre-monsoon, JJAS: monsoon and ON: post-monsoon months)

4.3.3.4 Percentile-based indices

Trends corresponding to the rainfall fraction above 99th, 95th and 75th percentile in the Brahmaputra valley are shown in Table 4.11. The percentile rainfall values were averaged

over 1961–1990 (the base line set by WMO) to separate 24-hr daily rainfall extremes in every year of the 55 years under study. All extreme rainfall amounts in a year were then summed up to get R99p, R95p and R75p totals. In the valley as a whole, rainfall due to the trends of percentile based indices (R99pTOT, R95pTOT and R75pTOT) were less prominent during 1955–2010 compared to the last three decades (1981–2010) in most cases.

Table 4.11 Trends of percentile based indices in the Brahmaputra valley during 1955–2010 and 1981–2010

Indices	Entire valley		Eastern part		Central part		Western part	
	1955-2010	1981-2010	1955-2010	1981-2010	1955-2010	1981-2010	1955-2010	1981-2010
R99pTOT								
Annual	0.69	–17.73	3.56	–8.46	0.97	–20.80	8.12	–38.75
MAM	–0.98	5.81	–4.43	9.25	–0.87	8.00	6.69	2.67
JJAS	–0.29	–25.48	–0.61	–30.85	–4.88	–20.42	3.68	–38.50
ON	0.80	12.31	0.89	5.40	**7.36**	9.05	–5.98	14.65
R95pTOT								
Annual	2.88	–17.83	**–22.44**	–18.94	–11.48	–12.86	34.40	–39.68
MAM	0.73	9.75	–2.92	13.73	4.00	15.50	1.20	7.88
JJAS	0.67	–21.50	–7.28	–0.43	–14.07	–23.23	18.17	–37.14
ON	**–6.65**	0.61	–3.19	1.43	–2.10	1.09	**–13.26**	1.05
R75pTOT								
Annual	13.35	–25.25	–9.57	–28.80	12.98	11.36	**36.98**	**–82.83**
MAM	7.60	4.25	–0.73	–5.30	1.20	1.80	**19.40**	5.20
JJAS	6.61	**–44.33**	–8.11	**–50.51**	5.43	–3.21	20.05	**–92.44**
ON	**–2.35**	1.73	–1.78	0.11	0.76	3.58	**–6.26**	1.04

Trends estimated by Sen‘s slope method, values rendered in bold indicate statistical significance at 95% confidence level according to the Mann–Kendall test.

Annual rainfall fraction due to extremely wet days (R99p) showed an increasing trend during 1955–2010 and decreasing trend during the recent 30-year (1981–2010) over the Brahmaputra valley as a whole as well as in its different parts with large seasonal variations (Table 4.11). During the recent 30-year period, the contribution of extreme fraction of rainfall due to R99p to pre-monsoon and post-monsoon rainfall totals was observed to increase, while during monsoon season its contribution decreased. During monsoon season, R99pTOT decreased by 30.9 mm/decade, 20.4 mm/decade and 33.5

mm/decade in eastern, central and western part respectively causing a net decrease of 25.5 mm/decade in the valley (Table 4.11).

The contribution of number of very wet days (R95p) to annual rainfall total decreased in the eastern (22.44 mm/decade) and central part (11.48 mm/decade) and increased (34.40 mm/decade) in the western part of the valley. Decrease of R95pTOT in the eastern part was statistically significant. R95pTOT followed similar pattern during monsoon season in different parts of the valley. During the recent 30-year period, the contribution of extreme fraction of rainfall due to R95p to pre-monsoon and post-monsoon rainfall total was increased while during monsoon season, its contribution decreased as observed in R99pTOT.

R75pTOT increased by 13.35 mm/decade during the entire study period of 55 years in the Brahmaputra valley as a whole due to its corresponding increase in pre-monsoon and monsoon season. On the contrary, R75pTOT showed statistically significant decreasing trend during post-monsoon season in the Brahmaputra valley as a whole due to its significant decrease (6.26 mm/decade) in the western part (Table 4.11). On the other hand, in the recent three decades (1981–2010), rainfall fraction due to moderate wet days (R75p) decreased significantly in the Brahmaputra valley due to its significant decrease in the eastern and western parts of the valley. R75pTOT decreased by 92.44 mm/decade in the western part and by 50.5 mm/decade in the eastern part of the valley. The decrease in the central part was only 3.2 mm/decade (Table 4.11).

These results agree well with the report (Das et al. 2009) that the frequencies of moderate and low rain days have significantly decreased during the last century due to weakening of the summer monsoon circulation over India. Goswami et al. (2010) found significant decreasing trend of aggregate of extreme rain events in NE India during 1975–2006. They observed that this decreasing trend of extreme events is consistent with observed decreasing trend in convective available potential energy (CAPE) and increasing convective inhibition energy (CINE) over the region in contrast to reverse trends observed by Goswami et al. (2006) over central India.

Similarly, the increasing trend of CAPE during March and April in the Brahmaputra valley (Chaudhuri and Middey, 2012) might be responsible for increasing tendency of extreme rainfall events during pre-monsoon, especially in last 30-year period. Similar observations for pre-monsoon rainfall extremes from the adjacent Bangladesh were also reported by Shahid (2012). In a recent study, Pathak and Bhuyan (2012) observed increasing trend in aerosol optical depth (AOD) measured by Moderate-Resolution Imaging Spectro-radiometer (MODIS) during pre-monsoon seasons of 2001–2010 at two locations (Guwahati and Dibrugarh) of the Brahmaputra valley. They concluded that the increased pre-monsoon rainfall activities during that period were due to the impact of aerosols on formation of cloud drops and resultant precipitation.

It can be inferred that the reduction of extreme rainfall frequencies played one of the most important roles in the observed reduction of monsoon rainfall in the Brahmaputra valley during the last three decades. In fact, the recent Super High Resolution Global models study by Rajendran and Kitoh (2008) has also concluded that the Indian summer monsoon rainfall may increase over the interior regions of India but there could be significant decrease in orographic rainfall over the northeast and west coast hilly regions.

4.3.4 Temperature analysis

4.3.4.1 Descriptive statistics

The valley-averaged characteristics of air temperature over the past 60-years (1951–2010) are listed in Table 4.12. The annual mean air temperature over the Brahmaputra valley was 23.9°C with a standard deviation of 0.35°C. The highest temperature record occurred in 2009 (24.93°C), and the second highest in 1999 (24.74°C). The eastern part of the Brahmaputra valley was slightly cooler (23.4°C) compared to the central (24.4°C) and western (24.5°C) parts. Mean air temperature during monsoon was the highest (28.2°C), followed by pre-monsoon (24.4°C) and post-monsoon (23.7°C), and it was the lowest in winter (17.9°C). January was the coldest (16.7°C) and August (28.6°C) was the hottest month in the Brahmaputra valley (Fig 4.21). The annual mean maximum and mean minimum air temperature in the Brahmaputra valley during 1951–2010 was 28.7°C and 19.1°C respectively (Table 4.12). During the pre-monsoon season the western part of the Brahmaputra valley has higher mean maximum and minimum temperature (30.9°C and

20.4°C respectively) than those in the eastern part (28.3°C and 19.0°C respectively) of the valley. During monsoon and post-monsoon seasons, the entire valley experiences almost uniform maximum temperature ranging between 31.1°C–32.0°C and 28.2°C–29.0°C respectively. During winter season, the mean maximum temperature was slightly higher in the central and western part compared to the eastern part. The mean minimum temperature was also found to be lower during post-monsoon and winter seasons in the eastern part compared to the central and western parts.

Table 4.12 Features of annual and seasonal temperature of the Brahmaputra valley during 1951–2010

Season	Maximum (°C)		Minimum (°C)		Mean (°C)	
	Mean	CV (%)	Mean	CV (%)	Mean	CV (%)
Winter	24.3 ± 0.10	1.4	11.5 ± 0.08	1.2	17.9 ± 0.07	1.2
Pre-monsoon	29.4 ± 0.10	1.4	19.5 ± 0.06	2.0	24.4 ± 0.06	1.4
Monsoon	31.5 ± 0.06	3.1	24.8 ± 0.04	5.4	28.2 ± 0.04	3.1
Post-monsoon	28.7 ± 0.08	2.6	18.7 ± 0.10	2.4	23.7 ± 0.08	2.1
Annual	28.7 ± 0.05	2.1	19.1 ± 0.05	4.2	23.9 ± 0.04	2.5

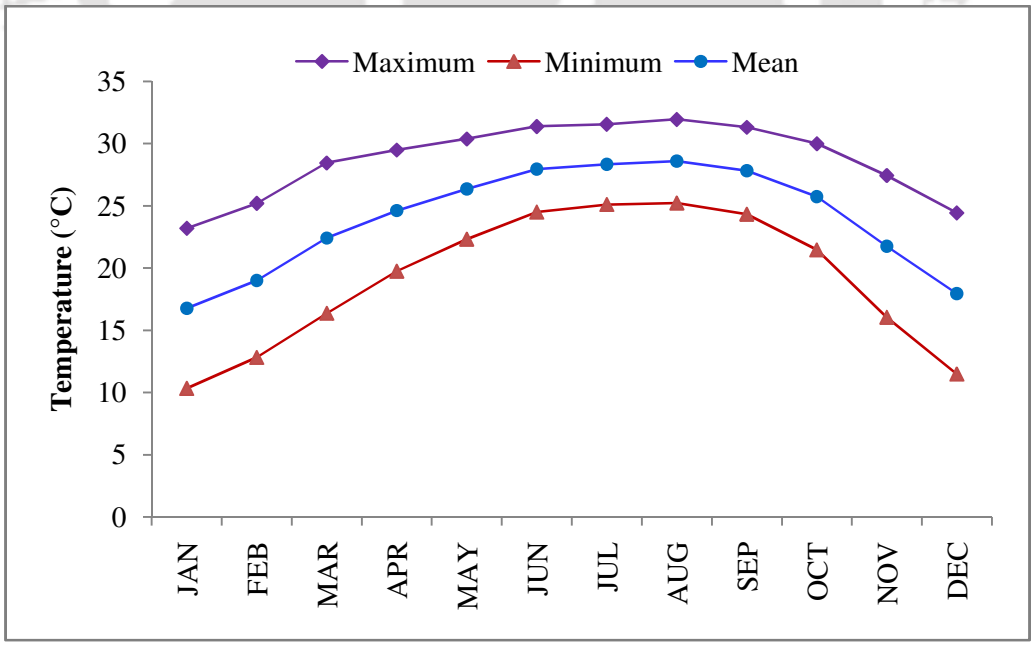

Fig. 4.21 Annual cycle of temperature in the Brahmaputra valley during 1951–2010

4.3.4.2 Monthly temperature trends

The trend test results of monthly temperature (mean, maximum and minimum) time series over the Brahmaputra valley are shown in Table 5.13. Mean air temperature showed increasing trends in all the months except during April with significant values in May to August and October to December during the entire study period (1955–2010) over the valley (Table 4.13). During NT1, the magnitude of trends was lower compared to the recent 30-year period (NT2). Mean temperature during NT2 (1981–2010) showed an increasing tendency in all the months except during June which showed negative trend, with significant values during five months (May and September to December). Increasing tendency of June rainfall (Table 4.7) during 1981–2010 might have rendered the mean temperature to be negative. The magnitude of trend was found to be highest in the month of September (0.522°C/decade) followed by February (0.488°C/decade).

Table 4.13 Trends (°C/decade) of monthly temperature in the Brahmaputra valley during trend periods of 1951–2010 (EP), 1951–1980 (NT1) and 1981–2010 (NT2)

Months/ seasons	Temperature trend (°C/decade)								
	Mean			Maximum			Minimum		
	EP	NT1	NT2	EP	NT1	NT2	EP	NT1	NT2
Jan	0.067	–0.125	0.178	0.037	0.000	0.053	0.114	–0.190	0.259
Feb	0.095	–0.214	0.488	0.010	–0.285	0.573	0.119	–0.250	0.364
Mar	0.020	0.104	0.308	–0.079	0.415	0.311	0.086	–0.143	0.250
Apr	–0.092	0.000	0.269	**–0.186**	0.116	0.147	0.000	–0.063	**0.444**
May	**0.147**	0.108	**0.322**	**0.210**	0.280	0.300	**0.087**	0.000	**0.300**
Jun	**0.132**	0.150	–0.006	**0.168**	0.337	–0.128	**0.081**	–0.045	0.000
Jul	**0.100**	0.042	0.368	0.109	0.143	**0.467**	**0.078**	0.000	**0.250**
Aug	**0.105**	0.057	0.054	**0.132**	0.200	0.020	**0.089**	–0.100	**0.167**
Sep	0.047	–0.140	**0.522**	0.067	–0.060	**0.660**	0.027	**–0.167**	**0.417**
Oct	**0.125**	–0.080	**0.305**	**0.167**	0.100	0.228	0.093	–0.250	**0.346**
Nov	**0.201**	–0.011	**0.437**	**0.212**	0.141	0.217	**0.185**	0.000	**0.714**
Dec	**0.159**	–0.164	**0.432**	**0.173**	0.000	**0.500**	0.125	–0.278	**0.533**

Trends estimated by Sen‘s slope method, values rendered in bold indicate statistical significance at 95% confidence level according to the Mann–Kendall test.

Maximum temperatures in all the months were increased in the Brahmaputra valley except a decreasing tendency in March and April (Table 4.13) during the entire study period (1951–2010). Generally, the magnitude of changes in monthly maximum temperatures was higher during NT2 compared to NT1 in all the months, except during March, June and August. During NT2, maximum temperature showed increasing trends in all the months except the decreasing trend in the month of June (–0.128°C/decade). Maximum increase was noticed in the month of September (0.600°C/decade) followed by February (0.573°C/decade), December (0.500°C/decade) and July (0.467°C/decade).

Monthly minimum temperature in the Brahmaputra valley showed increasing trends in all the months during the entire study period (Table 4.13) due to its accelerated warming during the last three decades (1981–2010). Monthly minimum temperature increased in 11 months with significant values during May to August and November during the entire study period (Table 4.13). Except during May, July, and November which showed no trend, trends in the remaining months were negative during NT1 (1951–1980) with significant value only in the month of September (–0.167°C/decade). In contrast, during the recent 30-year period, except in June, which showed no trend, the remaining months showed increasing trends (Table 4.13). The trend magnitudes were significant for eight months (April, May and July to December). The rate of increase was maximum in the month of November (0.714°C/decade) followed by December (0.533°C/decade).

4.3.4.3 Seasonal and annual temperature trends

4.3.4.3.1 Maximum temperature

Annual mean maximum temperature increased significantly by a rate of 0.077°C/decade during 1951–2010 in the Brahmaputra valley (Table 4.14). Figure 4.22a exhibits an above normal epoch from 1966 to 1981 followed by a below normal epoch from 1982 to 1992 and again an above normal epoch since 1993. The rate of increase in maximum temperature was 3 times higher during the recent 30-year normal period (NT2) compared to the period 1951–1980 (NT1) (Fig 4.22b and Table 4.13). On seasonal basis, statistically significant increasing trends were observed during monsoon (0.113°C/decade) and post-monsoon (0.188°C/decade) seasons. On the other hand, maximum temperature during pre-monsoon season showed negative trend (–0.030°C/decade) due to its significant decrease

in the month of April (Table 4.14). The magnitude of changes in annual as well as seasonal maximum temperature was significantly higher during NT2 compared to NT1 (Table 4.14). The trend rate of maximum temperature during NT2 in different seasons was almost identical and the rate varied between 0.23°C to 0.28°C/decade with statistically significant value only during monsoon season.

Table 4.14 Trends (°C/decade) of annual and seasonal temperature in the Brahmaputra valley during trend periods of 1951–2010 (EP), 1951–1980 (NT1) and 1981–2010 (NT2)

Sl No	Variable	Annual	Pre-monsoon	Monsoon	Post-monsoon	Winter
1951–2010 (EP)						
1	Tmax	**0.077**	–0.030	**0.113**	**0.188**	0.052
2	Tmin	**0.090**	0.063	**0.080**	**0.124**	**0.131**
3	Tmean	**0.088**	0.005	**0.094**	**0.159**	**0.106**
1951–1980 (NT1)						
1	Tmax	0.084	0.133	0.133	0.091	–0.136
2	Tmin	**–0.119**	–0.090	–0.096	–0.082	–0.240
3	Tmean	–0.033	–0.033	0.012	–0.033	–0.167
1981–2010 (NT2)						
1	Tmax	**0.250**	0.262	**0.233**	0.244	0.282
2	Tmin	**0.363**	**0.333**	**0.226**	**0.526**	**0.373**
3	Tmean	**0.313**	**0.285**	**0.219**	**0.353**	**0.300**

Trends estimated by Sen‘s slope method, values rendered in bold indicate statistical significance at 95% confidence level according to the Mann–Kendall test.

4.3.4.3.2 Minimum temperature

The annual mean minimum temperature increased significantly by a rate of 0.090°C per decade during 1951–2010. Two distinct phases of temperature change was observed during the study period: a falling trend (–0.119°C/decade) during NT1 followed by an abrupt rising trend (0.363°C/decade) during NT2 (Fig 4.22b). During NT1, seasonal and annual minimum temperature exhibited decreasing trends with significant values only for the annual trend (Table 4.14) On the other hand, annual and seasonal minimum temperature during NT2 showed sharp increasing trends and all trends were statistically significant. Among different seasons, the magnitude of trend was highest in post-monsoon (0.536°C/decade) followed by winter (0.375°C/decade) and lowest in monsoon season

during NT2. Station level trends showed annual as well as seasonal mean minimum temperature to increase significantly at four locations of the valley during 1951–2010.

4.3.4.3.3 Mean temperature

A statistically significant positive trend (0.088°C/decade) in the mean air temperature during 1951–2010 was observed with an accelerated warming (0.313°C/decade) during 1981–2010 (Table 4.14). Figure 4.22c, which displays the mean air temperature anomaly relative to the 1961–90 average along with its 9-point binomial filtered series, showed consisted warming tendencies of mean temperature in the Brahmaputra valley since 1993. The air temperature in all the seasons tended to increase with a wide range of slope values. Increasing tendency of post-monsoon (0.159°C/decade), (0.106°C/decade) and winter was statistically significant. The recent 30-year period (NT2) showed statistically significant increasing trend of mean temperature during all the seasons in contrast to the previous 30-year period (1951–1980) which exhibited negative trends during all the seasons except monsoon (Table 4.14) The magnitude of increase was the highest in post-monsoon (0.353°C/decade) followed by winter (0.300°C/decade) and the lowest in monsoon (0.219°C/decade) season.

The increase in annual minimum temperature was 1.5 times higher than that of the maximum temperature during 1981–2010 in the Brahmaputra valley. A lower change in increase in maximum temperature than that minimum temperature may be a sign of presence of solar dimming (Wild et al. 2007). Moreover, less amount of precipitation coupled with enhanced green house gas (GHG) contents in the atmosphere have rendered the post-monsoon and winter significantly warmer particularly in the last three decades (1981–2010). During post-monsoon and winter, maximum temperature increased by 0.244°C/decade and 0.282°C/decade respectively (Table 4.14) whereas increase in minimum temperature in the two seasons was much higher (0.536°C/decade and 0.375°C/decade). Kothawale and Rupa Kumar (2005) found that the all India mean annual surface temperature had increased by 0.05°C/decade for the period 1901–2003 and the rise was steeper during the last three decades (0.22°C/decade). This indicates that the rate of increase in mean annual temperature in the Brahmaputra valley was 1.6 times higher than the all-India average during the last three decades (1981–2010).

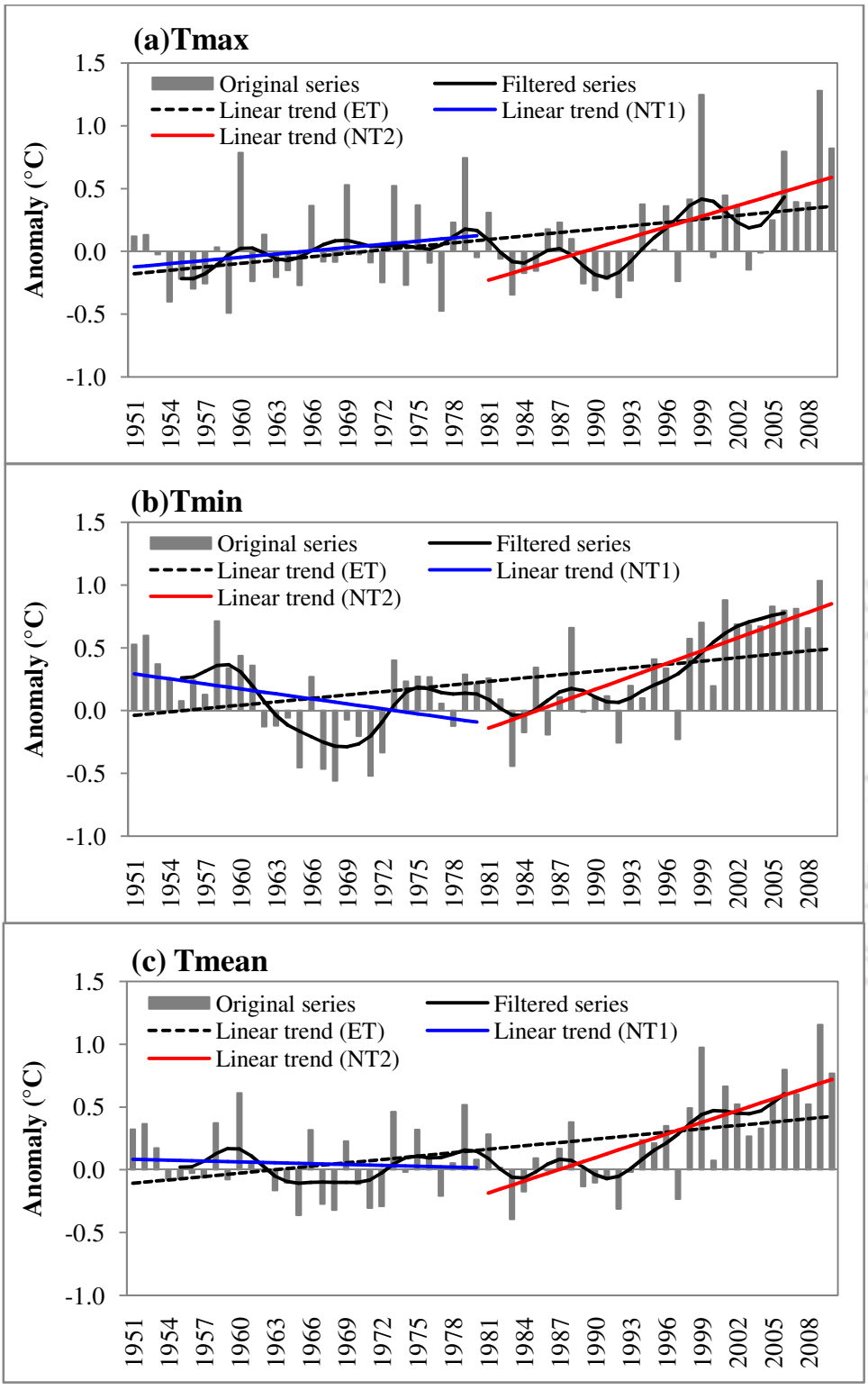

Fig. 4.22 Annual maximum (a), minimum (b) and mean (c) temperature anomaly relative to 1961-1990 mean along with its 9-point binomial filtered series during trend periods 1951–2010 (ET), 1951–1980 (NT1) and 1981–2010 (NT2)

Changes in monthly minimum temperature during 1951–1980 (NT1) were highly different from that of maximum temperature changes. During this period, minimum temperature showed negative trend in nine months in contrast to only two months in case of maximum temperature. During NT2 (1981–2010), on the contrary, the direction of changes in monthly minimum temperatures were similar with that of maximum temperature. However, changes in monthly maximum temperatures were less significant compared to that of minimum temperature. This result disagrees with Pal and Al-Tabbaa (2010b) who reported that the changes in monthly minimum temperatures were less significant than maximum temperature changes in NE India during 1901–2003. They also reported statistically significant decreasing trends in minimum temperature during the months from May to August in NE India, which contradicts with the positive and statistically significant trends observed for said months during 1951–2010 in this study. This may be due to the length of data period considered in trend analysis.

4.3.5 Trends of extreme temperature indices

4.3.5.1 Intensity Indices

The annual hottest day (TXx), hottest night (TNx) and coldest night (TNn) temperature showed increasing trends, while the coldest day (TXn) temperature showed decreasing trend (Fig. 4.23). The increase in hottest night (0.19°C/decade) and coldest night (0.32°C/decade) in the Brahmaputra valley was found to be statistically significant at 95% level of confidence according to the Mann–Kendall test. Seasonally, significant rise in TXx was observed during post-monsoon season and significant fall in TXn was observed during pre-monsoon season (Table 4.15). Except during winter season, significant increase in TNx was observed in all the other three seasons. On the other hand, significant increasing trend of TNn was observed during post-monsoon (0.39°C/decade) and winter (0.23°C/decade) seasons. Station-level trend showed both TNx and TNn increased at all the four locations of the Brahmaputra valley. On the other hand, coldest day (TXn) showed decreasing trend at all the locations. The trends observed for various intensity indices of temperature in the Brahmaputra valley are in accordance with the findings of Revadekar et al. (2012) except coldest day temperature (TXn). In contrast to the widespread increasing

trend of all-India TXn, it showed a decreasing trend in the Brahmaputra valley due to its significant decrease (–0.41°C/decade) during pre-monsoon season.

Table 4.15 Annual and seasonal trends (per decade) of extreme temperature indices in the Brahmaputra valley during 1971–2010

Indices	Unit	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
TXx	°C	–0.03	0.14	0.18	**0.24**	0.11
TNx	°C	0.21	**0.24**	**0.18**	**0.25**	**0.19**
TXn	°C	–0.17	**–0.41**	–0.11	–0.28	–0.27
TNn	°C	**0.23**	0.25	0.14	**0.39**	**0.32**
TX90p	%	**5.12**	0.89	1.81	**4.10**	0.86
TN90p	%	**3.97**	**2.41**	**7.74**	**2.29**	**2.72**
TX10p	%	–0.63	0.75	–1.02	–1.88	–0.78
TN10p	%	**–4.74**	**–1.94**	**–4.54**	**–2.10**	**–1.31**
DTR	°C	–0.12	**–0.27**	**–0.14**	–0.08	**–0.15**

Trends estimated by Sen's slope method, values rendered in bold indicate statistical significance at 95% confidence level according to the Mann–Kendall test.

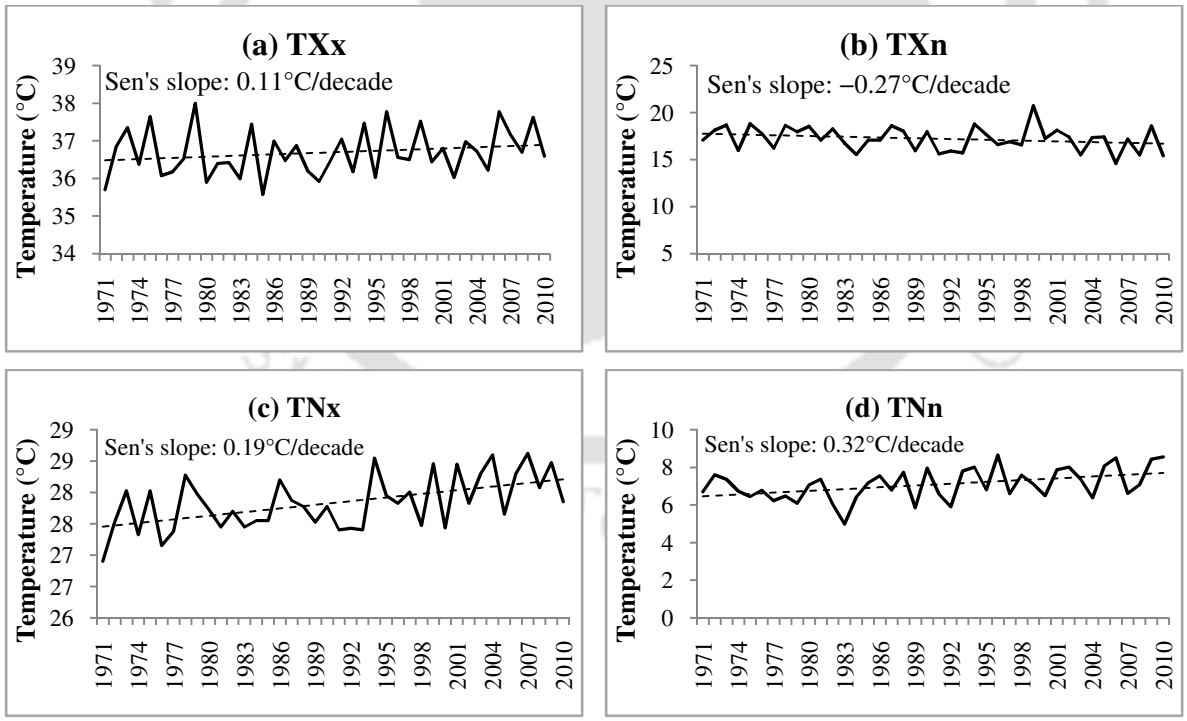

Fig. 4.23 Annual trends of hottest day (a), coldest day (b), hottest night (c) and coldest night (d) temperature in the Brahmaputra valley during 1971–2010

The pre-monsoon thunderstorm activity in the Brahmaputra valley is vigorous unlike other parts of India and contributed 25% to the annual rainfall total. During the recent 30-year period (1981–2010), rainfall during this season exhibited an increasing tendency over the Brahmaputra valley (Fig 4.7). Moreover, during good monsoon years, substantial decrease in incoming solar radiation due to dense cloud cover and evaporative cooling of rainwater are responsible for lowering the surface temperature during the day (Kothawalwe et al. 2012).

4.3.5.2 Frequency indices with percentile thresholds

All the frequency indices of hot events (above 90th percentile of 1971–2000 average) showed increasing trends while that of the cold events (below 10th percentile of 1971–2000 average) showed decreasing trends in the Brahmaputra valley (Fig. 4.24).

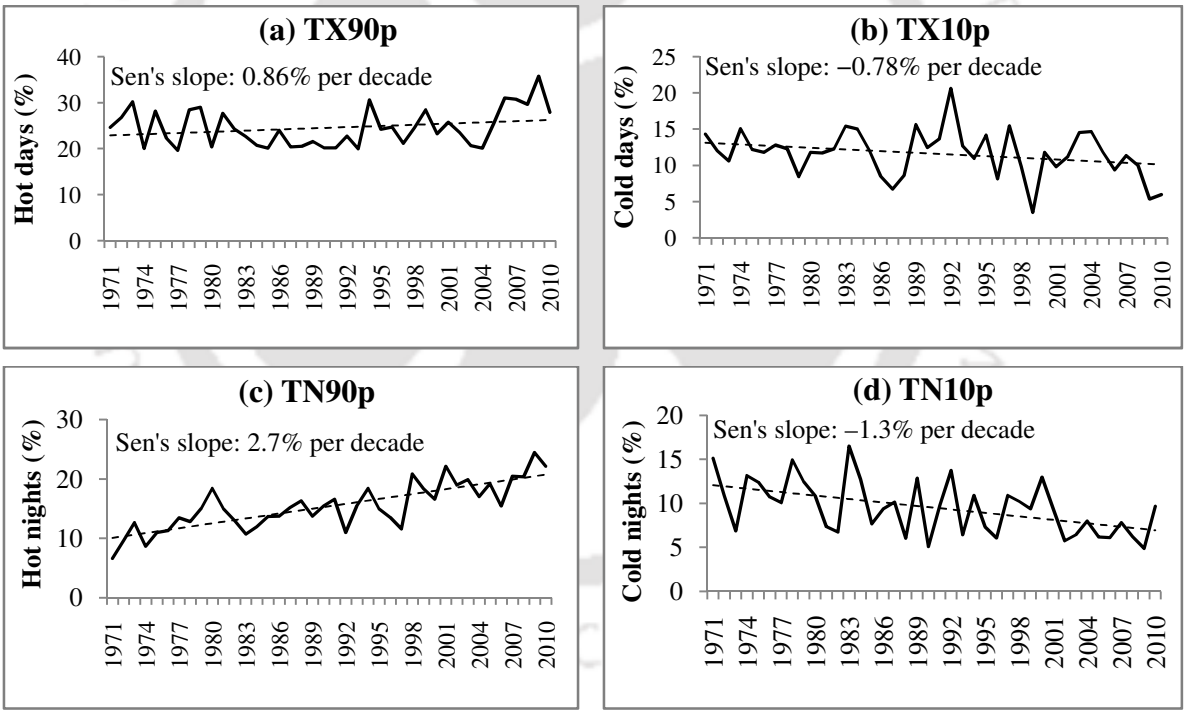

Fig. 4.24 Annual trends of frequency indices of hot days (a), cold days (b), hot nights (c) and cold nights (d) in the Brahmaputra valley during 1971–2010

Though the magnitude of increase in the frequency of hot days was significantly higher during winter (5.12% per decade) and post-monsoon (4.10% per decade) seasons, their increase on annual basis was only 0.86% per decade due to lower frequency of hot days

during pre-monsoon and monsoon seasons (Table 4.15). On annual basis, increase in the frequency of hot nights (2.7% per decade) and decrease in the frequency of cold nights (1.3% per decade) were statistically significant (Table 4.15). Increase in the frequency of hot nights was highest (7.74% per decade) during monsoon and lowest (2.29% per decade) during post-monsoon seasons. On the other hand, decrease in the frequency of cold nights was highest (4.74% per decade) during winter and lowest (1.94% per decade) during pre-monsoon seasons.

The above results indicated significant changes in temperature extremes associated with observed warming in the Brahmaputra valley during last three decades (Table 4.15), especially daily minimum temperature indices i.e., the warming trend was higher for nighttime indices than for those of daytime. Similar observations in the frequency indices of annual hot and cold events were observed by Kothawale et al. (2010) and Ravekedar et al. (2012) in India; Klein Tank et al. (2006) in central and south Asia; Vincent et al. (2005) in South America; Plummer et al. (1999) in Australia to mention a few. Manton et al. (2001) reported significant increase in the annual number of hot days and warm nights and decrease in cool days and cold nights in Southeast Asia and South Pacific during the period 1961–1998. Dash et al. (2011) also observed decreasing trend in the cold nights in northeast India.

4.3.5.3 Frequency indices with fixed thresholds

Annually, number of days above maximum temperature 35°C (hot days) increased significantly by a rate of 1.4% per decade during 1971–2010 (Table 4.15 and Fig. 4.25). On the other hand, number of nights above 25°C (hot nights) showed significant increasing trend (10.0% per decade) while the number of nights below 10°C (cold nights) showed significant decreasing trend (4.2% per decade). Spatially, cold nights decreased at all the locations except at one station located in the central part (Tezpur) where the trend was positive. On seasonal basis, cold nights showed decreasing trends in all the four seasons, except post-monsoon and winter seasons at Tezpur.

4.3.5.4 Range index (DTR)

Annual diurnal temperature range (DTR) decreased significantly by a rate of 0.15°C/decade (Table 4.15). The lowering of DTR in the Brahmaputra valley was due to

the higher magnitudes of nighttime indices compared to their daytime counterparts. DTR decreased during all the four seasons in the valley with significant value only in the pre-monsoon and monsoon seasons. In the pre-monsoon and monsoon months, due to cloudy and humid weather, there is lowering of maximum temperatures and increase in minimum temperatures (Kothawale, 2005) narrowing down the DTR. The observed trends in DTR may be affected by large scale effects of increased GHGs and aerosols (Zhou et al. 2008). The nighttime temperature over land had increased by about twice of the rate of daytime temperature during the past 50 years (Folland et al. 2001) and the DTR decreases was due to the evident increase of nighttime temperature.

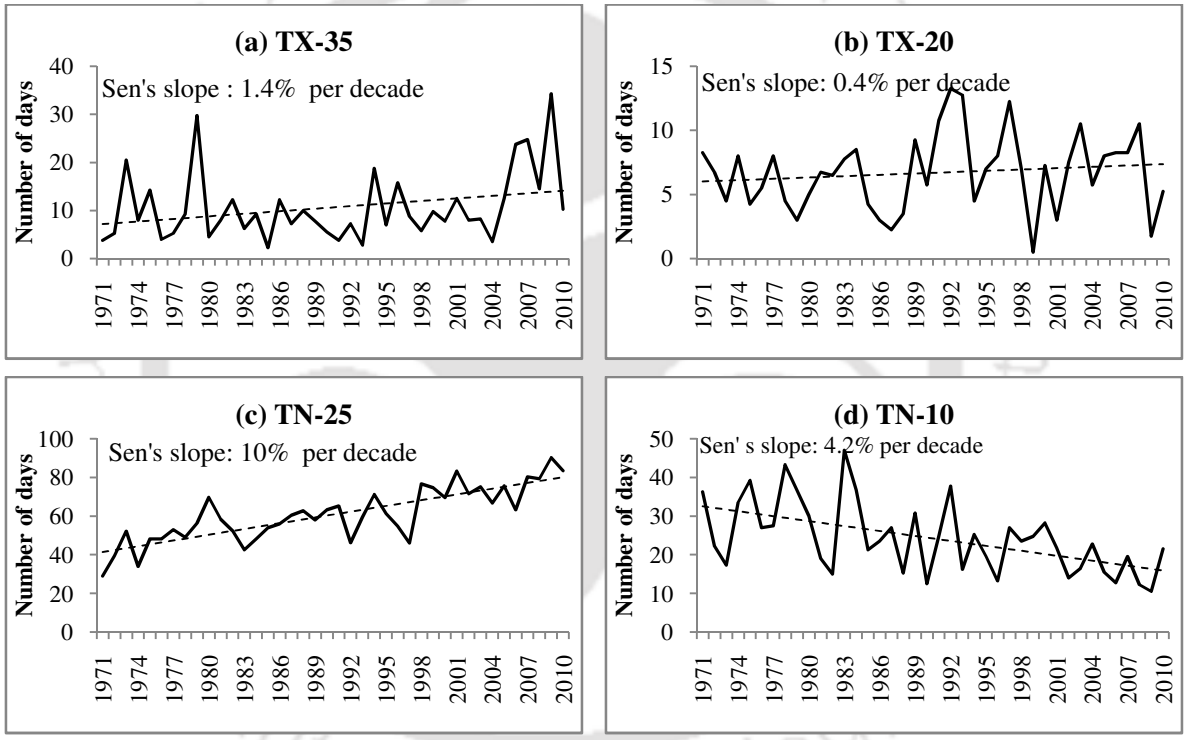

Fig. 4.25 Annual trends of number of days with TX > 35°C (a), TX < 20°C (b), TN > 25°C (c) and TN < 10°C (d) in the Brahmaputra valley during 1971–2010

4.3.6 Changes in annual cycles of extreme temperature events

Monthly intensity and frequency indices of hot and cold events during two sub-periods of 1971–1990 and 1991–2010 relative to the mean of the entire period (1971–2010) showed that the hottest day temperature was lower in the months of March, April and June during 1991–2010 while in other months it was higher than the 1971–1990 sub-period (Fig. 4.26).

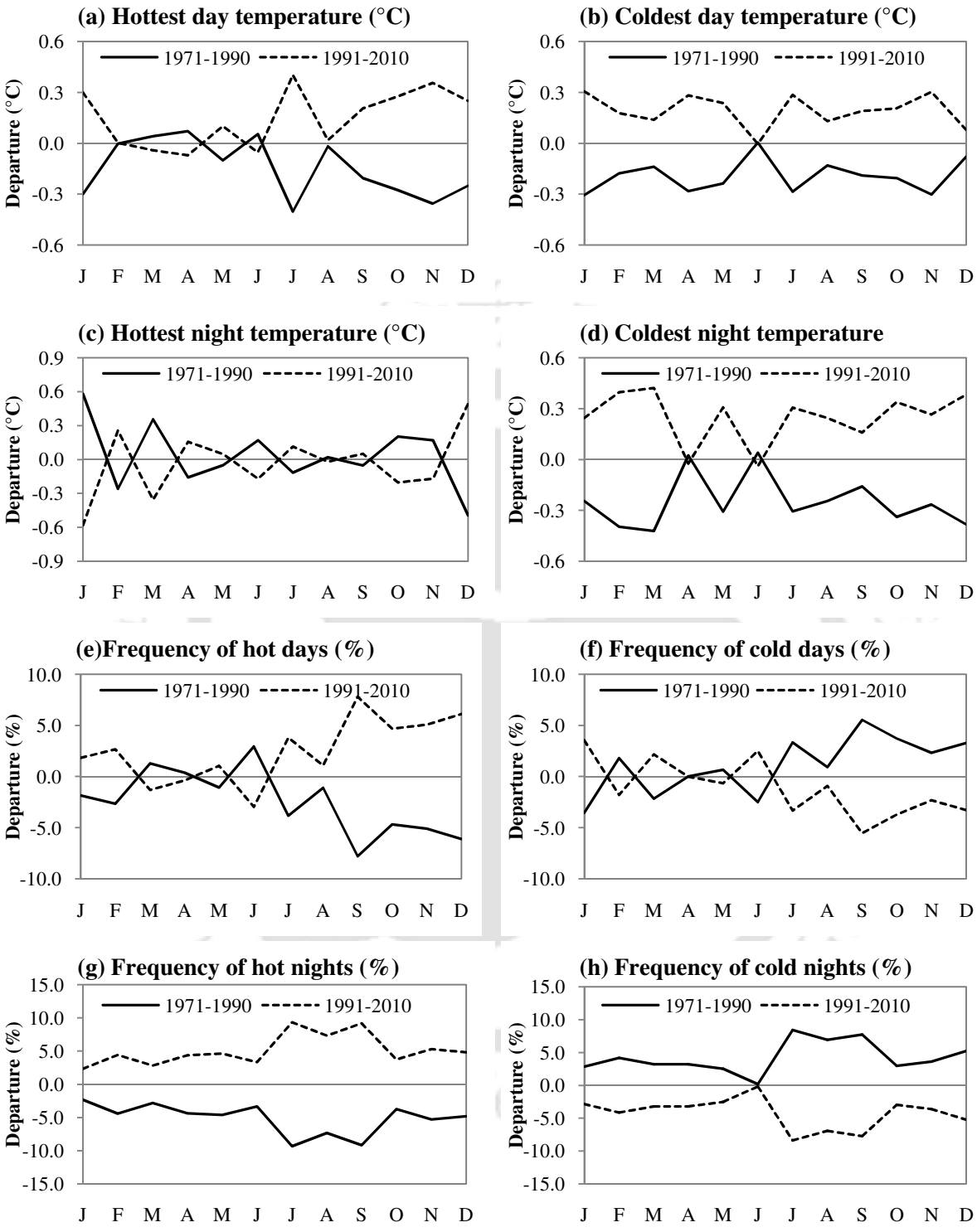

Fig. 4.26 Monthly departures of intensity and frequency of hot and cold events during two sub-periods (1971–1990 and 1991–2010) in the Brahmaputra valley

The coldest day temperature was more in all the months except June during sub-period 1991–2010. The magnitude of changes in TXx are more in July, September, October, November and December and January (0.2–0.4°C) compared to other months. Coldest night temperature was more (except April and June) during the sub-period 1991–2010.

Similarly, both the number of hot days and hot nights showed increase in frequencies while number of cold days and cold nights showed decrease in frequencies in almost all months (Fig. 4.26). Both number of hot days and hot nights (TX90p and TN90p) showed increase in the frequencies in almost all months (except TX90p in March and June) during 1991–2010. On the other hand, both number of cold days and cold nights (TX10p and TN10p) showed decrease in frequencies in almost all months (except TX10p in January, March and June).

4.3.7 Trend of sunshine duration

4.3.7.1 Monthly trends

The monthly trend of sunshine duration (SSH) during 1971–2010 in the Brahmaputra valley as estimated by non-parametric Sen's slope method is presented in Table 4.16. Except in September, decreasing trend of SSH was observed in all the months with its significant values during January to June, August and December in the Brahmaputra valley. No trend could be detected in the month of September. Among the remaining months, maximum decrease of SSH was observed in the month of March (–0.75 hr/decade) followed by February (–0.54 hr/decade) and January (–0.50 hr/decade) in the valley. Station level analysis indicated maximum decrease in SSH during December, January and February at Guwahati followed by Thakurbari – both located in the central part of the valley (Table 4.16). On the other hand, it showed an increasing trend in the month of July and September at Thakurbari and in September at Dibrugarh (Table 4.16).

.4.3.7.2 Seasonal and annual trends

Trend analysis during different seasons indicated statistically significant decreasing trends of SSH during all the seasons in the Brahmaputra valley as a whole (Table 4.16). Maximum decrease was noticed during pre-monsoon season (–0.50 hr/decade) followed by winter (–0.47 hr/decade), monsoon (0.26 hr/decade) and post-monsoon (–0.15 hr/decade)

seasons. Among different stations, maximum decrease was observed during winter at Guwahati (–0.82 hr/decade) and Tezpur (–0.70 hr/decade) of central part; pre-monsoon at Jorhat (–0.40 hr/decade) and post-monsoon at Dibrugarh (–0.40 hr/decade) – both located in the eastern part of the Brahmaputra valley (Table 4.16).

Table 4.16 Monthly, seasonal and annual trends of sunshine duration (hr/decade) in the Brahmaputra valley during 1971–2010

Months/ seasons	Guwahati	Thakurbari	Jorhat	Dibrugarh	Brahmaputra Valley
Jan	**–0.95**	**–0.75**	**–0.41**	–0.33	**–0.50**
Feb	**–0.82**	**–0.80**	**–0.28**	–0.38	**–0.54**
Mar	**–0.61**	–0.50	**–0.74**	**–0.50**	**–0.75**
Apr	**–0.30**	**–0.73**	**–0.36**	–0.10	**–0.41**
May	**–0.33**	0.00	–0.08	–0.33	**–0.26**
Jun	–0.25	**–0.76**	**–0.41**	**–0.57**	**–0.32**
Jul	–0.22	0.33	–0.17	–0.06	–0.19
Aug	**–0.36**	–0.50	**–0.38**	–0.17	**–0.38**
Sep	–0.14	0.75	0.00	0.39	0.00
Oct	**–0.33**	–0.13	–0.15	–0.20	–0.20
Nov	**–0.39**	–0.30	–0.06	**–0.68**	–0.15
Dec	**–0.68**	**–0.50**	–0.16	–0.10	**–0.27**
Winter	**–0.82**	**–0.70**	**–0.27**	**–0.29**	**–0.45**
Pre-monsoon	**–0.48**	–0.46	**–0.40**	**–0.33**	**–0.50**
Monsoon	**–0.25**	0.00	**–0.23**	–0.11	**–0.26**
Post-monsoon	**–0.40**	**–0.30**	–0.07	**–0.40**	**–0.15**
Annual	**–0.50**	**–0.36**	**–0.25**	**–0.20**	**–0.33**

Trends estimated by Sen's slope method, values rendered in bold indicate statistical significance at 95% confidence level according to the Mann–Kendall test.

The annual mean SSH in the Brahmaputra valley decreased by a rate of 0.33 hr/decade during 1971–2010, which was found to be statistically significant at 95% confidence level according to the Mann–Kendall test (Table 4.16). The decrease of SSH was statistically significant at all the four locations of the valley. However, the magnitude of decrease was highest at the stations located in the central part (Guwahati and Thakurbari) compared to the stations located in the eastern part (Jorhat and Dibrugarh) of the valley (Table 4.16). The results agree with studies of Jaswal (2009) who reported significant reduction of SSH

in NE India and Indo–Gangetic plains on annual and seasonal basis. Significant decreasing trend of sunshine duration at different locations of Assam was observed in few recent studies (Jaswal, 2009; Jhajharia and Singh, 2011). During the months of December, January, February and early March the weather is generally fair in the region and no decrease in SSH is expected. However, SSH has significantly decreased during these months also. It points out to the fact that the amount of aerosols which reflect the incident solar radiation might be increasing during these months, resulting in decreased SSH and increased minimum temperature. In a recent study, Pathak et al. (2012) reported highest aerosol optical depth (AOD) during pre-monsoon and lowest during post-monsoon season at Dibrugarh. During winter, local production contributed to observed appreciable continental average (CA) type aerosols while pre-monsoon was dominated by both local and transported aerosols of urban/industrial and biomass burning (UB) and desert dust (DD) type (Pathak et al. 2012). This suggest that the recent spurt in construction works, local deforestation and forest fires in the neighboring countries might have contributed to the aerosol-pool and has increased the reflected portion of solar radiation during these two seasons. Seasonal changes in sunshine are partly related to seasonal rainfall pattern. Lowest decrease of SSH during post-monsoon indicates the influence of southwest monsoon in washing down pollutants and increasing the atmospheric transmissivity compared to other seasons in the Brahmaputra valley.

Climate change is a reality in the study area and impacts have been observed both in short and long term with respect to key identified variables like temperature, rainfall and sunshine hours in the Brahmaputra valley. The trends and variability are however not necessarily always identical with global and national averages although they are broadly in agreement with generic observations. Further implications of these changes w.r.t. two major crops – rice and tea grown in the area were investigated subsequently as has been reported in chapter 5 and chapter 6.

Chapter 5

Impact of Climate Change on Rice Productivity: An Empirical Statistical and Simulation Modeling Approach

In this chapter, the effect of climate trends on fluctuations on winter rice yields in Jorhat district located in the upper Brahmaputra valley was assessed by empirical statistical model. Quantitative relationship between rice yield and climate variables were derived using yield and climate data between 1985 and 2010 to assess the impact of climate change and variability on observed yield trend. Further, the impact of climate change on rice productivity was assessed by using CERES-Rice dynamic crop simulation model. Before running the model for different climate change scenarios, the model was calibrated and validated using five years experimental data of Jorhat under the agroclimate of upper Brahmaputra valley.

5.1 Introduction

Rice (*Oryza sativa* L.) is the most important food in the diets of Asian, African and Latin Americans; in fact, it serves as a basic staple for more than half of the world's population (Yoshida 1981; Peng et al. 1995; Maclean et al. 2002). Ninety per cent of the world's rice is produced in Asia, where irrigated and rainfed rice ecosystems forms the mainstay of food security (Wassmann et al. 2009). India has the world's largest area (41.8 mha in 2009–10) devoted to rice cultivation, and it is the second highest producer of rice after China (Fig 5.1), contributing 24% and 19% of the world rice area and rice production (FAO 2010), respectively. Contributing over 43 percent to the India's food grain production, rice is grown under four different ecologies (irrigated ecology, rainfed shallow lowland, rainfed upland and deepwater ecology), with the irrigated ecology accounting for the largest area and highest production and productivity closely followed by rainfed shallow lowlands (Siddiq 2000). The pre-dominantly rainfed eastern zone (east and northeast India), accounts for the largest area (63% of total) and production in the country but with lowest productivity (Siddiq 2000, Krishnan et al. 2007). Global climate change has potential for grave consequences because of its potential threat to rice productivity. Climate change is expected to result in increases in rainfall variability, mean and night-

time air temperatures, concentration of carbon dioxide and cloudiness – all of which will adversely affect growth, development and yield of rice (Peng et al. 1995; Matthews et al. 1996; Wassmann et al. 2009). A precise understanding of the relationship between location-specific climate variability and rice yield is critical for sustaining the productivity.

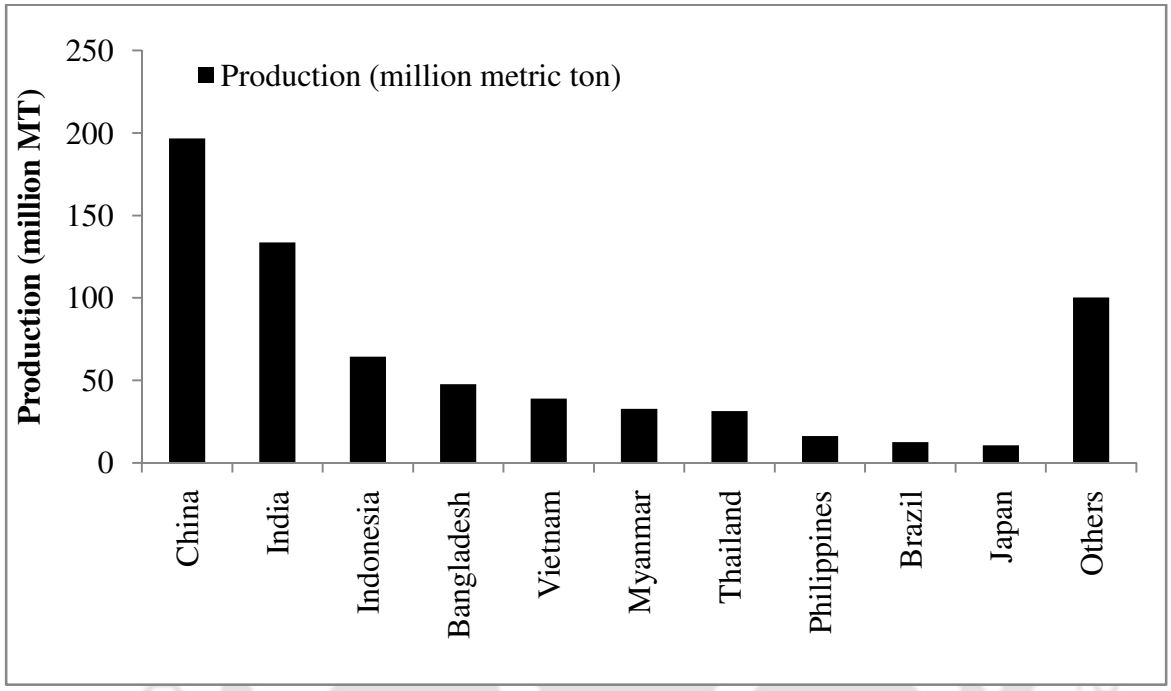

Fig. 5.1 Rice production (million MT) in top ten countries in the world

5.2 Study site

The study area was Jorhat which is located in the eastern part of the Brahmaputra valley (Fig 5.2). With a geographical area of 2,85,332 ha, the district is situated between 26°20′ to 27°10′ North latitude and 95°57′ to 94°37′ East longitude. Most part of the district is covered by alluvium deposited by the river Brahmaputra and its tributaries. About 70% of the area of the district has a slope of 3% or less. The general elevation of the district ranges from 80 (The Majuli island in the northern part) to 200 m (southeastern part boarding Nagaland) above mean sea level. The soils of the district are generally course textured i.e., loamy sand, sandy loam and silt loam. The soils of low lands of floodplain are strongly acidic (pH 5.0–6.0) however under submerged condition it raises to more than 6.0 (Vadivelu et al. 2004b). The soils of Majuli island are neutral (pH 6.7–7.3). The climate of the area is humid sub-tropical with an average annual maximum and minimum temperature

of 28.2 and 19.1°C, respectively. The annual total rainfall ranges from 1564 mm to 2414 mm with a mean of 1950 mm. However, during the rice cropping season (June/July to Nov/Dec), the average seasonal maximum and minimum temperature are 29.5°C and 21.4°C respectively. Overall, 70% of the total rainfall occurs during the rice growing season. Annual rainfall in the district varies from 1776 mm (Nematighat) to 1923 mm (Titabar). Jorhat is typically a rice growing district where 57% of total geographical area is covered by rice (Vadivelu et al. 2004b). Winter rice (*kharif*) is cultivated in more than 90% of total rice growing area of the district.

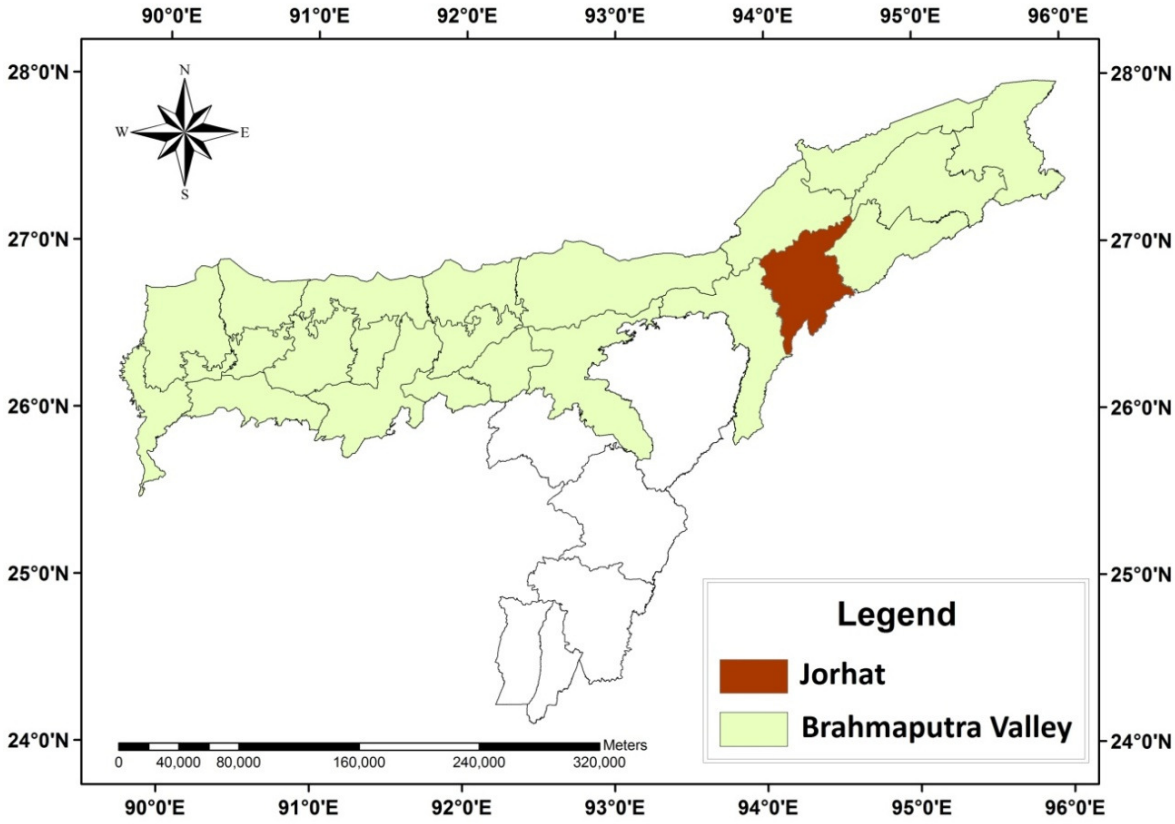

Fig. 5.2 Location map of study site for rice

5.3 Materials and Methods

5.3.1 Observed impact of climate on rice productivity

5.3.1.1 Yield data

Since yield/productivity data of rice is available for administrative districts, the Jorhat district was selected due to long-term data availability and closer representativeness of the

entire study area. Aggregate-level rice yield data for the period from 1985 to 2010 of the district were collected from the Directorate of Economics and Statistics, Guwahati, Government of Assam, India.

5.3.1.2 Climate data

Monthly total rainfall, number of rainy days, maximum temperature, minimum temperature and hours of sunshine duration data recorded at Assam Agricultural University, Jorhat were collected for the period 1985–2010. These were assumed to be representative of the entire district considering the homogeneity of landscape and climate. The observatory was installed in 1974 under the guidance of technically qualified officers of India Meteorological Department (IMD), Pune, India. The instruments had been calibrated as and when needed according to the IMD standard, and the observations were recorded as per the standard hours covering the study period to maintain homogeneity of readings.

5.3.1.3 Development of statistical model

The responses of climatic parameters are different during different growth stages of crops (Entz and Fowler 1988). As the weather requirements for optimal development are growth-stage dependent, it is necessary to delineate the growth phases and growth stages of rice in order to address the weather relationships affecting this crop (WMO 2010). The growth phases of rice are the vegetative phase, from emergence to panicle initiation (PI) stage; the reproductive phase from PI to completion of flowering stage; and the ripening from end of flowering to grain maturity stage (Tanaka et al. 1964). The duration of reproductive and ripening phases is fixed (approximately one month each) for all rice cultivars and duration of vegetative phase varies among varieties (Fig 5.3). Assessing the effect of climate change during each growing phase will provide a much better understanding of climate change effects on yield formation than the entire cropping season as a whole which can be used as a practical reference for the measures to be taken in near future (Chen et al. 2011).

Normally, rice is transplanted in June/July and harvested in November/December in the study area depending on type of varieties used. The vegetative phase of rice crop corresponds to period from 1st June to 30th September, reproductive phase from 1st October

to 31st October, and ripening phase from 1st November to 30th November, as per the normal rice calendar followed by the farmers in the study area.

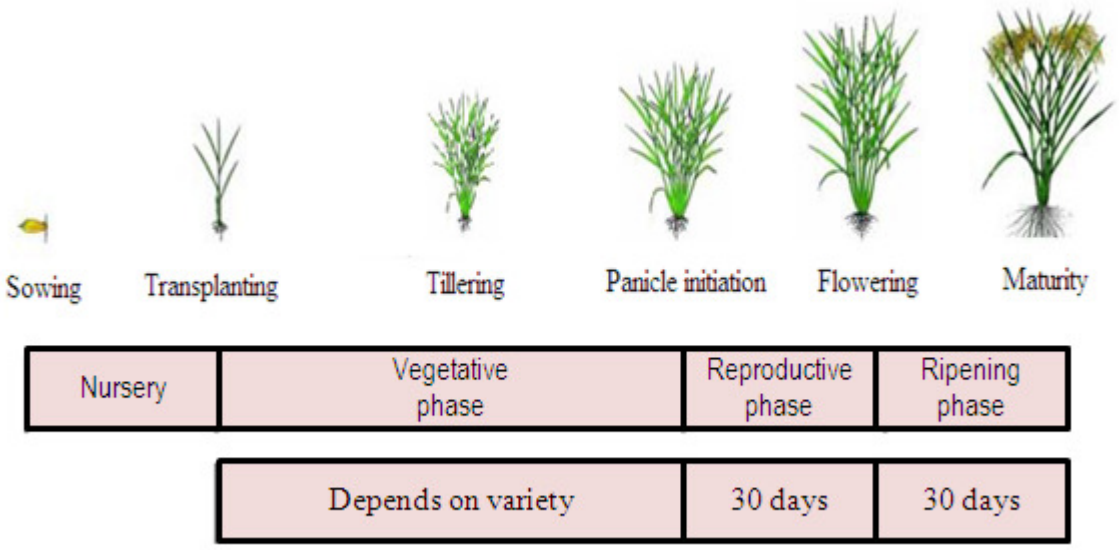

Fig. 5.3 Growth phases of rice plant

Accordingly, phenophase-wise (vegetative, establishment to panicle initiation; reproductive, panicle initiation to flowering; ripening, flowering to mature grain) mean maximum temperature (TX) in °C, mean minimum temperature (TN) in °C, total rainfall (R) in mm, total number of rainy days (RD) in days and mean sunshine duration (SSH) in hours along with their variability terms (CvTX, CvTN, CvR, CvRD and CvSSH) were computed from the climate data collected for the period 1985–2010. The intra-seasonal variability (measured by coefficient of variation) of the climate variables were calculated for the vegetative phase (June to September) only.

Empirical (regression) model was developed using historical data on both rice yield and climate variables to estimate the changes in yield as a result of changes in different climate variables in the study area. Crop yield is a function of crop input, technology, management, soil quality (non-climatic) and climate factors (You et al. 2009). To remove the influences of non-climatic factors from observed rice yield, a first difference time series was computed for both the yields and the climate variables by subtracting the

previous year's value from each year (Nicholls 1997). The use of first difference method removes the possible confounding effects of non-climatic factors (Nicholls 1997). Multiple regression model was developed with first difference of rice yield as the response variable, and first differences of climate variables as predictor variables. The multiple regression takes the form:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_k X_k + \varepsilon \quad (5.1)$$

Where,

Y is the dependent variable

$\beta_0, \beta_1, ..., \beta_k$ are parameters

$X_1, X_2, ..., X_k$ are independent variables

k is the number of observations

ε the error term

To estimate the relative contributions of each independent climate variable in determining rice yield variability, backward selection procedures were used for regression analysis (Mather 1976; Rowhani et al. 2011). The backward elimination procedure is basically a sequence of tests for significance of explanatory variables. Starting out with the maximum model, it then attempts to remove one variable at a time by determining whether the least significant variable currently in the model can be removed because its p-value is less than the user specified value (p=0.15). This procedure continues until all independent variables have p-values below the specified significance level. Each model has been checked for multicollinearity by the computation of Variance Inflation Factor (VIF) following O'Brien and Robert (2007) which measure how highly correlated each independent variable is with the other predictors in the model. The values larger than 10 for a predictor imply large inflation of standard errors of regression coefficients due to this variable being in the model.

Multiple regression analysis of historical climate data and crop yield record has been used successfully and widely used in establishing relationships between crop yield and climate change globally and regionally in recent past (Lobell et al. 2005, Lobell and Field 2007; Iglesias and Quiroga 2007; Almaraz et al. 2008; Zhang et al. 2010).

5.3.2 Projected impact of climate change on rice productivity

To evaluate the impact of climate change on productivity of rice the dynamic crop growth model Crop Estimation through REsource and Environment Synthesis (CERES) embedded in Decision Support System for Agrotechnology Transfer (DSSAT) was used. The DSSAT Cropping System Model (CSM) v4.5 is a software application programme that comprises crop simulation models for over 28 crops (Hoogenboon et al. 2010). The DSSAT model was developed by International Benchmark Site Network for Agrotechnology Transfer (IBSNAT) in 1989 (Tsuji et al. 1998). For DSSAT to be functional, it is supported by data base management programmes for soil, water, and crop management and environment data, and by utilities and application programmes (Hoogenboom et al. 2010). The DSSAT-CSM simulates growth and development of a crop over time, as well as soil water, carbon and nitrogen processes and management practices (Jones et al. 2010). The main components and modular structure of DSSAT Cropping System Model is shown in Fig. 5.4. These include:

- A main driver program, which controls timing of each simulation
- A Land unit module, which manages all simulation processes which affect a unit of land
- Primary modules that individually simulate the various processes that affect the land unit including weather, plant growth, soil processes, soil-plant-atmosphere interface and management practices.

Collectively, these components simulate the changes over time in the soil and plants that occur on a single land unit in response to weather and management practices (Jones et al. 2010). DSSAT and its crop simulation models have been used for many applications ranging from on-farm and precision management to regional assessments of the impacts of climate variability and climate change and have been in use for more than 20 years in over 100 countries worldwide (Hoogenboom et al. 2010).

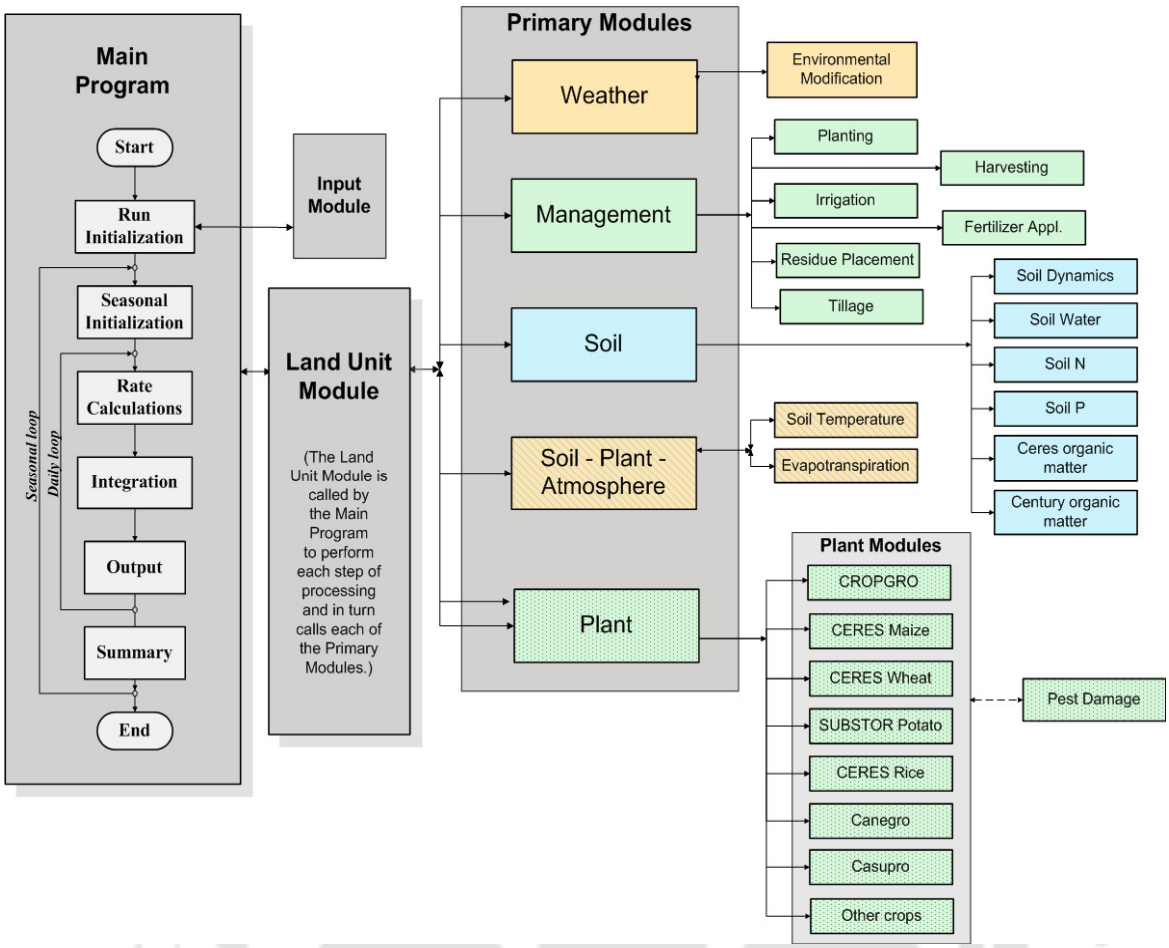

Fig. 5.4 Overview of the components and modular structure of DSSAT v4.5 (Jones et al. 2010)

5.3.2.1 Description of CERES-Rice model

The CERES-Rice, as available in DSSAT v4.5 (Hoogenboom et al. 2010), is a physiologically based, management oriented model of rice crop growth and development (Singh et al. 1993) that was developed to predict the duration of growth, the average growth rates, and the amount of assimilate partitioned to the economic yield components of the plant (Ritchie et al. 1998). The model utilizes carbon, nitrogen, water and energy balance principles to simulate the processes that occur during the growth and development of rice plants within an agricultural system. CERES-Rice model simulates rice crop growth and development from either sowing or transplanting to harvest maturity and is based on the physiological processes that describe the response of rice to local soil and weather conditions (Tsuji et al. 1998; Hoogenboom et al. 2004). CERES-rice model require information about plant environment (water and soil), cultivar genetics and agricultural

management practices. Daily maximum and minimum temperature, rainfall, CO_2 concentrations and solar radiation determine respiration and photosynthetic rates, available water and evapotranspiration rates. A soil profile provides information about available nutrients and root-zone moisture processes. Cultivar genetics determine the type of crop that is grown, including biophysical characteristics determining plant development and vulnerability to environmental stresses. Management practices dictate the date, method and geometry of planting, as well as any applications of irrigation, fertilizer or chemicals.

Simulation of the duration of each phonological stage uses the concept of thermal time or degree-days and photoperiod as defined by the genetic characteristics of the crop. Crop growth is simulated by employing a carbon balance approach in a source-sink system. Photosynthesis is the process whereby the plant converts intercepted light into carbohydrates. It is initially assumed to be controlled only by solar radiation and temperature, and later modified by the effect of stresses due to temperature, water and fertilizer. The analytical relationships of soil water balance and nitrogen transformation and uptake leading to the quantification of these stress factors are presented by Jones & Kiniry (1986). Daily rate of gross photosynthesis is calculated for rice crop canopy as a function of daily accumulated solar radiation, day length, extinction coefficient of light within canopy, light transmissibility of single leaf at light saturation and the leaf area index. Leaf area expansion in the model is taken to be a function of leaf growth at a particular time and the number of leaves per plant at that time, which in turn is calculated using the phyllochrom concept. Leaf expansion is also taken as a function of the plant's genetic characteristic for tillering. A portion of the carbohydrate synthesized, termed the net photosynthate, is used in the synthesis of plant tissue and the rest is used in respiration to maintain the existing tissue. The net photosynthate produced is shared between the shoot and the root. The shoot biomass is partitioned further between leaf, stem, panicle and grain, according to the functional relations, which govern these partitioning at different growth stages. The tillering growth in the model is taken as a function of the number of leaves per plant emerging at a particular time, the fraction of carbohydrates going to the leaves at that time, the pant's genetic characteristic for tilleting, and a tillering population factor (Alocilja 1987). The soil water balance is determined on a daily basis as a function of precipitation, irrigation, transpiration; soil evaporation, runoff, and drainage from the

bottom of the profile. The soil water is distributed in several layers with depth increments specified by the user (Ritchie and Godwin 1989; Ritchie 1998). Detailed description of the model structure and initial validation was given by Alocilja (1987) and Alocilja and Ritchie (1988). Model components are given in Appendix B. It is important to note that, as with the construction of any other crop simulation models; CERES-rice model was also built on certain assumptions. The problem of pest, weeds, diseases, and toxicities of the soil as well as soil salinity/acidity and soil erosion problems are also not covered by the model. Except for nitrogen, it is assumed that there are no nutrient deficiencies or toxicities. The damaging effects of catastrophic weather events and deteriorated soils are not taken into account by the model. With these limitations, the CERES-Rice model simulates the effects of weather, cultivar, management practices, soil-water and nitrogen fertilizer on growth and yield of rice (Alocilja and Ritchie 1988).

Several studies have demonstrated the utility of CERES-rice model for impact assessment of climate change in India (Hundal and Kaur 1996; Saseendran et al. 2000; Aggarwal and Mall 2002; Pathak et al. 2003; Lal et al 1998; Lal 2010; Subash and Ram Mohan 2012). In this study, CERES-Rice model of DSSAT v4.5 has been selected to simulate the growth and yield of winter rice for different climate change scenarios under the sub-tropical humid climate of upper Brahmaputra valley after careful evaluation of the model in the study area by utilizing secondary experimental data.

5.3.2.2 Details of field experiments

The variety specific experimental data (for five years) on rice required for evaluation of CERES-rice model were obtained from All India Coordinated Research Project on Agro-Meteorology (ICAR), located at Assam Agricultural University, Jorhat, Assam. A view of the experimental location is shown in Fig. 5.5.

5.3.2.2.1 Selection of variety

A long duration (150–155 days), photoperiod insensitive winter rice variety “Ranjit” (TTB 101-17) was selected for all the seasons of the experiment. This rice variety is one of the popularly cultivated varieties in the Brahmaputra valley during *sali* (*kharif)* season. Ranjit is recommended for shallow submergence (0–30 cm water depth) areas during *sali* season

in Assam. The parentage of the variety was *Pankaj/Mahsuri*. It is a semi-tall (105–110 cm) variety with moderate tillering ability (10–12 tillers). The panicle length is 28 cm with 194 grains/panicle. The potential yield of the variety is 6.0 t/ha and at about 4.9 t/ha at frontline demonstration (FLD) in farmers fields (Siddiq 2000).

5.3.2.2.2 Crop management data

The rice variety Ranjit was transplanted in three different dates during *kharif* seasons of 1998, 1999, 2003, 2004 and 2005. Transplanting dates during 1998, 1999, 2003, 2004 and 2005 respectively were 22nd June, 7th July and 22nd July; 20th June, 5th July and 20th July; 24th June, 8th July and 26th July; 24th June, 7th July and 24th July and 21st June, 6th July and 22nd July. There were 20 rows per plot and 25 hills per row. Thirty-day old seedlings were transplanted at a depth of 3-4 cm at a spacing of 20 cm by 20 cm of hill and row spaces. The number of seedlings per hill was two. The N fertilizer (40 kg N/ha in the form of urea) was applied in three applications. The first half of urea was applied during final land preparation; the remaining half was applied in two equal splits after 30 and 60 days of transplanting. In addition, P_2O_5 and K_2O – 20 kg/ha each in the form of Single Super Phosphate (SSP) and Muriate of Potash (MOP) were also applied during final puddling. All other agronomic practices such as weeding and plant protection measures were standard and uniform for all the planting dates. The crop was raised as rainfed. The required data were collected in standard format in each season for calibration and validation of CERES-Rice model (Table 5.1).

Fig. 5.5 A view of the experimental site at Jorhat

Table 5.1 Details of crop data collected during 2004 for evaluation of CERES-Rice model

Parameters	Early	Normal	Late
Transplanting date	24-06-2004	08-07-2004	24-07-2004
Panicle initiation date	09-09-2004	23-09-2004	06-10-2004
Anthesis date	18-10-2004	23-11-2004	04-11-2004
Physiological maturity date	14-11-2004	23-11-2004	04-12-2004
Grain yield (kg/ha)	4690	4500	4380
Weight of grain (mg/unit)	0.023	0.023	0.022
Number of grains/m^2	37260	34383	33384
Number of grains/panicle	162	157	156
Maximum leaf area index	7.01	6.65	6.34
Tops weight at maturity (kg/ha)	9950	9000	8820
By-product harvest (kg/ha)	5260	4500	4440
Planting depth (cm)	3-4	3-4	3-4
Row spacing and plant population	20 cm x 20 cm	20 cm x 20 cm	25 hills/m^2
	25 hills/m^2	25 hills/m^2	25 hills/m^2
Planting method and distribution	Transplants, hills	Transplants, hills	Transplants, hills
Fertilizer (N:P:K in kg/ha)	40:20:20	40:20:20	40:20:20

5.3.2.2.3 Weather data

The weather file of DSSAT software includes information on location of the weather station (latitude and longitude), daily values of incoming solar radiation (MJ/m^2/day), maximum and minimum air temperature (°C) and rainfall (mm) as minimum data set. Required data (maximum temperature, minimum temperature, rainfall and bright sunshine hours) during experimental period (section 5.3.2.2.2) were collected from Assam Agricultural University, Jorhat where the observatory is located near the experimental site. As the model requires daily total solar radiation, it is derived from bright sunshine hours using Angstrom equation by the model (Saseendran et al. 2000).

5.3.2.2.4 Soil data

The required soil data of the model include soil classification, surface slope, soil color, permeability, and drainage class. Soil profile data by soil horizons include: upper and lower horizon depths (cm), saturation water content, upper and lower limit (field capacity

and wilting point), percentage sand, silt, and clay content, bulk density, organic carbon, pH in water, aluminum saturation, and potential root distribution and depth. Soil data of the experimental site was collected from the Department of Soil Science, Assam Agricultural University, Jorhat (Table 5.2). The soil of the experimental area is characterized as fine, mixed, hyperthermic family of *Humic Endoaquepts*. It is alluvium-derived, poorly drained, nearly level to very gently sloping flood plains of the Brahmaputra valley. The soil is very deep; thickness of the A horizon is 16 to 20 cm while B horizon is 70 to 80 cm thick. The texture is silt loam at the surface horizon and silty clay loam or clay loam or clay at the lower horizons. The bulk density of the soil ranges from 1.5 to 1.8 gm/cm^3. The saturation percentage varies from 20% to 49%.

Table 5.2 Soil profile data of the experimental site at Jorhat

Depth (cm)	Clay (%)	Silt (%)	Stones (%)	Bulk density (gm/cm^3)	Organic carbon (%)	pH (1:2.5 H_2O)	Soil nitrogen (%)	CEC (meq/100g)
0–5	17.1	15.8	0	1.5	0.85	5.5	0.08	5.8
0–15	17.1	15.8	0	1.5	0.83	5.5	0.05	5.8
15–30	20.8	13.5	0	1.4	0.68	5.7	0.04	4.4
30–45	32.7	20.4	0	1.5	0.46	6.0	0.02	6.2

5.3.2.3 Evaluation of CERES-Rice model

Model calibration or parameterization is the adjustment of parameters to the local conditions so that simulated values compare well with the observed ones (Timsina and Humphreys 2006). Calculation of the genetic coefficient of cultivars is the first step in the conventional use of the CERES models. The genetic coefficients characterize the growth and development of varieties differing in maturity (Timsina and Humphreys 2006). A genetic coefficient calculator (Gencalc) was developed by Hunt et al. (1993) to facilitate determination of genotype specific coefficients that are made available by the DSSAT system. In the present study, the Gencalc was used for calculation of eight genetic coefficients required for rice crop simulations. A detailed description of the cultivar coefficients used by the CERES-Rice model is presented in Table 5.3.

Table 5.3 Description of genetic coefficients used in CERES-Rice simulation model

Name	Description
Development aspects	
Juvenile phase coefficient (P1)	Time period (expressed as growing degree days GDD in °C above a base temperature of 9°C) from seedling emergence during which the rice plant is not responsive to changes in photoperiod. This period is referred to as the basic vegetative phase of the plant.
Critical photoperiod (P2O)	Critical photoperiod or the longest day length (in hours) at which the development occurs at a maximum rate. At values higher than P2O developmental rate is slowed, hence there is delay due to longer day lengths.
Photoperiodism coefficient (P2R)	Extent to which phasic development leading to panicle initiation is delayed (expressed as GDD in °C) for each hour increase in photoperiod above P2O.
Grain filling duration coefficient (P5)	Time period (in GDD °C) from beginning of grain filling (3 to 4 days after flowering) to physiological maturity with a base temperature of 9°C.
Growth aspects	
Spikelet number coefficient (G1)	Potential spikelet number coefficient as estimated from the number of spikelets per g of main culm dry weight (less lead blades and sheaths plus spikes) at anthesis. A typical value is 55
Single grain weight (G2)	Single grain weight (g) under ideal growing conditions, i.e. non limiting light, water, nutrients, and absence of pests and diseases
Tillering coefficient (G3)	Tillering coefficient (scaler value) relative to IR64 cultivar under ideal conditions. A higher tillering cultivar would have coefficient greater than 1.0
Temperature tolerance coefficient (G4)	Temperature tolerance coefficient. Usually 1.0 for varieties grown in normal environments. G4 for japonica type rice growing in a warmer environment would be 1.0 or greater. Likewise, the G4 value for *indica* type rice in very cool environments or season would be less than 1.0

Data from six field experiments (3 dates of transplanting) conducted during *kharif* seasons of 2004 and 2005 for rice cv. Ranjit in conjunction with requisite soil and weather parameters were used to derive its genetic coefficients. The order of priority in which the coefficients were modified, was phenolgical coefficients related to flowering and maturity dates (P1, P2O, P2R and P5) followed by the crop growth coefficients related with grain filling rate and grain number per plant (G1, G2, G3 and G4) following Hunt and Boote (1998). To begin with, the genetic coefficients of rice cv. IR-36 available in the list provided with DSSAT package were taken as the starting assumption for the calculation

and further these coefficients were modified following an iterative procedure (Hunt et al. 1993) to match the simulated values with the observed values – mainly flowering duration, maturity duration, grain yield, grain weight and harvest index of rice cv. Ranit.

The model validation stage involves the confirmation that the calibrated model closely represents the real situation (Van Keulen 1976). The procedure consists of a comparison of simulated output and observed data that have not been previously used in the calibration process. The experimental data collected in 1998, 1999 and 2003 were used for validation of CERES-Rice model. As part of the calibration and validation process the simulated data for anthesis date, maturity date and grain yield were compared with the observed values.

Different statistical indices were used for evaluation of simulation performance, including root mean square error (RMSE) (Wallach and Goffinet 1987) and index of agreement (*d*-value) (Willmott 1982). The computed values of RMSE, normalized RMSE and *d*-value determine the degree of agreement between the predicted values with their respective observed values, and a low RMSE value and d-value that approaches one are desirable. The RMSE was calculated according to Eq. 5.2.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \qquad (5.2)$$

where *Pi* and *Oi* refer to predicted and observed values for the studied variables, respectively. Normalized RMSE ($RMSE_n$) gives a measure (%) of the relative difference of simulated versus observed data. The simulation is considered excellent with a normalized RMSE less than 10%, good if the normalized RMSE is greater than 10 and less than 20%, fair if the normalized RMSE is greater than 20% and less than 30%, and poor if the normalized RMSE is greater than 30% (Jamieson et al. 1991). The $RMSE_n$ (Loague and Green 1991) was calculated following Eq. 5.3.

$$RMSE_n = \left[\frac{RMSE \text{ x } 100}{M}\right] \qquad (5.3)$$

where M is the mean of the observed variable.

The index of agreement (*d*) proposed by Willmott et al. (1985) was estimated (Eq. 5.4).

$$d = 1 - \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (|P_i'| - |O_i'|)^2} \right], 0 \le d \le 1 \quad (5.4)$$

where n is the number of observations, P_i the predicted observation, O_i is a measured observation, $P_i' = P_i - M$ and $O_i' = O_i - M$ (M is the mean of the observed variable). According to the *d*-statistic, closer the index value is to one, better the agreement between the two variables that are being compared and vice versa.

5.3.2.4 Design of experiment for evaluating climate change impact on rice productivity

A widely accepted approach to analyse the possible effects of different climate change scenarios on crop yield is to determine the incremental changes (anomalies) to temperature, precipitation, CO_2, etc., and apply these changes uniformly to a baseline climate (Rosenzweig and Iglesias 1994). A 30-year continuous record of recent climate data is widely used for creating a baseline climate (Rosenzweig and Parry 1994) because a 30-year period is likely to contain wet, dry, warm, and cool periods and is therefore considered to be sufficiently long to define a region's climate. Lin (1996) recommended creating a baseline period that is much longer than 30 years including recent data for more reliable results. Following this, the 'current climate baseline' for the study area was created by using daily weather data for the period 1971–2010. The weather data (maximum temperature, minimum temperature, rainfall and bright sunshine hours) were collected from Tocklai Experimental Station (1971–1979), Jorhat and adjacent Assam Agricultural University (1980–2010). Solar radiation was calculated from daily bright sunshine hour (Saseendran et al. 2000).

5.3.2.4.1 Control experiment

The CERES-Rice model, run with the baseline climate data as input for weather, is considered as the control experiment to compare performance of rice crop under climate changed scenarios with climate unchanged scenarios. Soil data, variety (genetic coefficient) and crop management data (except the transplanting dates) as used in model calibration and validation (section 5.3.2.2) were also used in the control experiment. Instead of considering a particular date of transplanting for impact analysis, six

transplanting dates starting from 20th June to 9th August at an interval of 10 days (TP1: 20th June, TP2: 30th June, TP3: 10th July, TP4: 20th July, TP5: 30th July and TP6: 9th August) were considered for realistic results. This option was expected to help in identifying the easiest adaptation strategy (Krishnan et al. 2007) as the 'adjustment of transplanting dates' for the study area which may help to offset detrimental effects of climate change, if any on rice productivity. The relative yield changes under different climate change scenarios referred to yields predicted over the baseline climate were used in this analysis rather than absolute yields.

5.3.2.4.2 Sensitivity scenarios

The sensitivity of the CERES-Rice model to temperature, CO_2 levels, rainfall and solar radiation were analyzed by arbitrarily creating anomalies in the baseline climate data created. The potential yield of rice variety Ranjit was simulated under different combinations of CO_2 and temperature including with the 'fixed increment' changes in CO_2 (390, 400, 450, 500, 550, 600, 650 and 750 ppm) and temperature (ambient, +1, +2, +3, +4, +5, +6 and +7) individually, and with all combinations of these levels of CO_2 and temperature. For simplicity, anomalies ranging from ±10% to ±20% of growing season rainfall over the observed baseline climate data were used for rainfall sensitivity experiment. To study the physiological effects of solar radiation, levels ranging from –1 MJ/m^2/day to 3 MJ/m^2/day with an increment of 1 MJ/m^2/day were used. The inbuilt weather generator of the DSSAT software generated the modified weather data accordingly over the baseline, and these data were used as the daily weather inputs for CERES-Rice model.

5.3.2.4.3 Building up of climate change scenarios

To create climate change scenarios for the study area, output of global circulation models (GCMs) available in literature were not considered in this study because of their already recognized relatively poor micro-level resolution, inadequate coupling of atmospheric and ocean processes, apparently poor simulation of cloud processes and inadequate representation of the biosphere and its feedbacks (Krishnan et al. 2007). The poor resolution is likely to be significant in the northeastern parts of India where the relief is varied and local climate may be quite different from the average across the area used by

GCMs. An alternative to global modeling is regional climate modeling. Regional climate models (RCM) can better take into account of regional geography and topography (e.g. mountains and oceans), and are therefore better at representing local variations in climate. Regional models that give fine resolution climate information over limited areas are being coupled into GCMs to produce climate information for impact assessments.

To provide an estimate of the overall effect of climate change on rice productivity, different possible scenarios were considered in simulation of CERES-Rice model based on the Hadley Centre's high-resolution RCM – PRECIS (Providing REgional Climate for Impact Studies) output which had been run at the Indian Institute of Tropical Meteorology (IITM), Pune, at 50 km x 50 km horizontal resolution for A1B scenario over South Asian domain (MoEF 2010) as well as taking current trends of temperature, solar radiation and rainfall in the baseline climate data of the study area. The output of Q14 (Quantifying Uncertainty in Model Prediction) simulation of PRECIS indicated an increase of monsoon rainfall by 8% and post-monsoon rainfall by 4% over 1961–1990 in the 2030s (2020–2050) in northeastern part of India. The temperature scenario represented an increase in temperature in the order of 1.6°C during monsoon season and 2.3°C during post-monsoon season over 1961–1990 baseline (MoEF 2010). The limitations of these projections are based on a small number of simulations from one regional climate model.

As the baseline scenario of the study area already contained weather data up to 2010, temperature increments were kept within 1.5°C. Although post-monsoon temperature is predicted to rise at a higher magnitude than monsoon season temperature, temperature increments were added uniformly for simplicity. Similarly, rainfall anomalies were also added in the baseline scenario uniformly over the entire rice growing season.

Temperature scenarios were built by adding 0.5°C, 1.0°C and 1.5°C in the baseline temperature data (Table 5.3). In order to assess the impact of any future increase or decrease in the observed rainfall in the study area, a 10% decrease and 10% increase in rainfall was considered in model simulations. Recent observations as well as climate model simulations indicate that future temperature change linked to global warming might be characterized by a marked asymmetry between daytime and maxima nighttime minima (Karl et al. 1991). The increase in temperature would be more pronounced in the nighttime

temperature, thus leading to a decline in diurnal temperature range. This asymmetry between daytime and nighttime temperature was also considered in the model simulation (Scenario G and H). Due to non-availability of future solar radiation scenario in literature, observed solar radiation trend in baseline data (1971–2010) were considered, while building the solar radiation scenario for coming 30 years. The observed linear trend of solar radiation during rice growing season of 1971–2010 was –0.038MJ/m^2/day/year. Assuming this trend will continue more or less consistently in the coming 30 years, solar radiation during rice growing season is likely to decline by 1.14 MJ/m^2/day in 2040.

The CO_2 concentration considered for the model simulations is based on the Business-as-usual scenario of IPCC (IPCC 1994) with a 1.3% per year compounded increase of CO_2, yielding an average equivalent CO_2 concentration of about 660 ppm for the 2040–2049 decade. The equivalent concentration represents CO_2 and other greenhouse gases. As such, the actual plant usable CO_2 concentration is only about 460 ppm (Sinha 1993). Hence, a value of 460 ppm of CO_2 concentration has been used in all simulations (Table 5.3). Altogether, eight scenarios were built with different combinations of temperature and rainfall along with an atmospheric CO_2 concentration of 460 ppm and solar radiation (–1MJ/m2/day). In addition to these, scenario I was built considering the observed linear trend of maximum temperature, minimum temperature and growing season rainfall data during the baseline (1971–2010) of the study area for 2040 (Table 5.3).

Table 5.4 Climate change scenarios considered in climate change impact studies on rice

Scenarios	CO_2 concentration (ppm)	Changes over baseline climate			
		Solar radiation (MJ/m^2/day)	Tmax (°C)	Tmin (°C)	Rainfall (%)
A	460	–1	0.5	0.5	–10
B	460	–1	0.5	0.5	+10
C	460	–1	1.0	1.0	–10
D	460	–1	1.0	1.0	+10
E	460	–1	1.5	1.5	–10
F	460	–1	1.5	1.5	+10
G	460	–1	0.5	1.5	0
H	460	–1	1.0	2.0	0
I	460	–1	0.2	0.5	–10

5.4 Results and Discussion

5.4.1 Descriptive statistics

The mean average yield of winter rice in Jorhat district during 1985–2010 was 1665 kg/ha with a coefficient of variation of 15%. The yield of winter rice showed high inter-annual variability during 1985-2010. The inter-annual variability of rice yield along with area and production during the study period is depicted in Fig. 5.6. Highest yield (2120 kg/ha) was recorded during 1991. Lowest yield of 1169 kg/ha was recorded in 1988 due to flood followed by 1198 kg/ha in 2006 due to erratic and deficient monsoon rainfall.

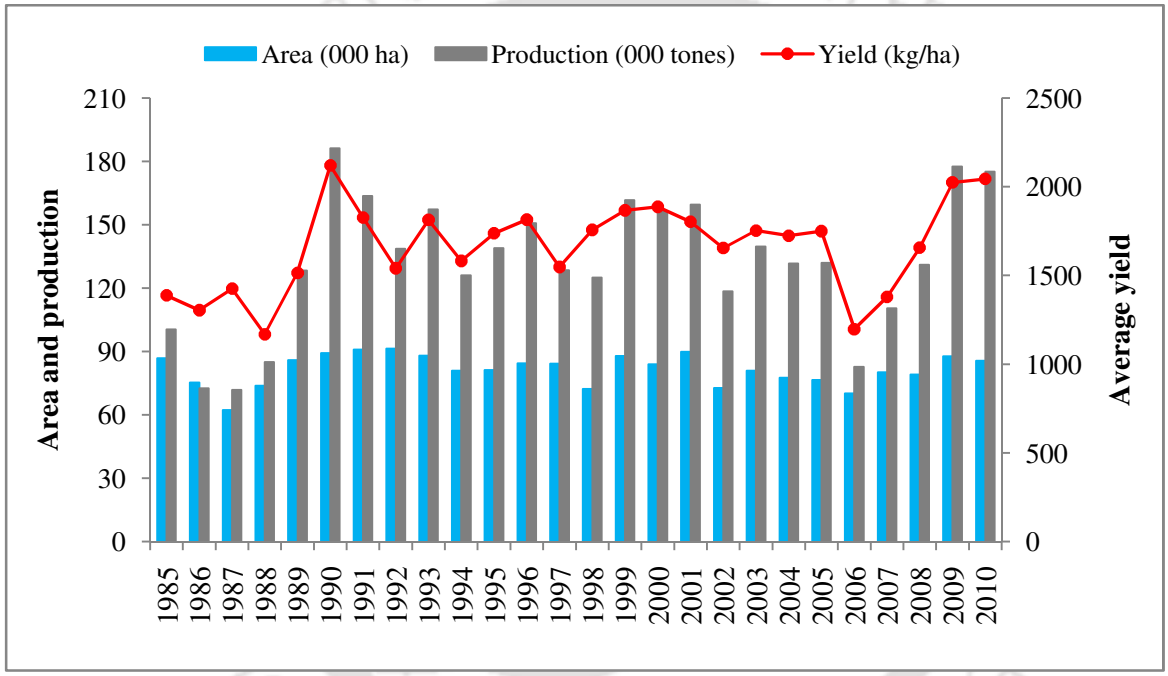

Fig. 5.6 Area, production and average yield of winter rice in Jorhat district during 1985–2010

On an average, a total of 1338 mm of rainfall was received during the growing season of winter (*kharif*) rice in 70 rainy days during 1985–2010 (Table A.3 and Fig. 5.7). Total rainfall received during vegetative phase (June–September) was the highest (1196 mm in 62 rainy days) and the lowest during ripening (November) phase (20 mm in 2 rainy days) of the crop. Though the coefficient of variation of rainfall during vegetative phase was only 14%, it varied between 23% (August) and 38% (September) in different months at vegetative phase showing large intra-seasonal variability. Coefficient of variation of

rainfall and number of rainy days during reproductive phase was highest (69% and 39% respectively) as this phase coincides with the withdrawal phase of monsoon season from this region. Mean temperature during vegetative phase was 28.5°C and in different individual months of this phase, mean temperatures were below 29°C in the study area (Table A.3). Mean maximum temperature ranged between 31.1°C–32.6°C with a mean of 31.8°C during vegetative phase. During reproductive and ripening phase, it ranged between 28.5°C–31.0°C (mean 29.8°C) and 25.5°C–28.5°C (mean 27.2°C) respectively.

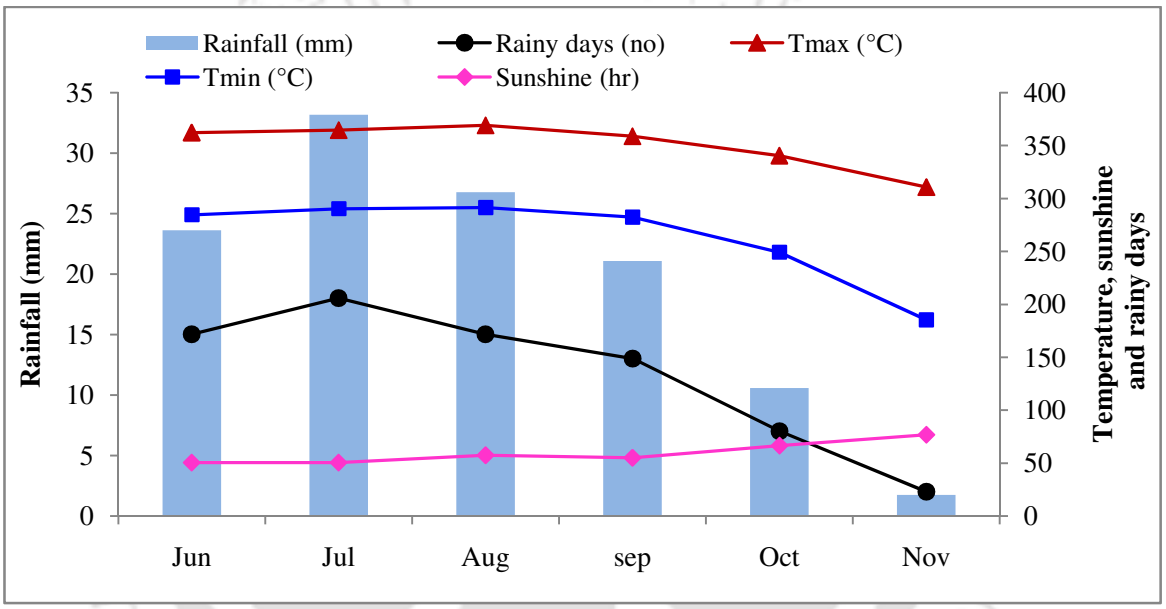

Fig. 5.7 Mean climatic conditions in rice (*kharif*) growing season (1985–2010) in the study area

Mean minimum temperature distribution also followed a similar pattern as that of mean maximum temperature during different growth phases (Fig. 5.7). It ranged between 24.4°C–25.8°C (mean 25.1°C), 20.0°C–23.9°C (mean 21.8°C) and 14.8°C–17.7°C (mean 16.2°C) during vegetative, reproductive and ripening phases of rice respectively during the study period 1986–2010 (Table A.3). Due to cloudy weather, bright sunshine received during the vegetative phase was relatively low (4.7 hr) with a CV of 13%. During different months of this phase, CV varied between 21% (Aug/Sep) and 26% (June). On an average, 5.8 hrs and 6.7 hrs of bright sunshine were received during reproductive and ripening phases respectively (Table A.3).

5.4.2 Observed impact of climate change on rice productivity

The result of multivariate regression analysis between first difference of yield and first differences of climatic variables is presented in Table 5.5. Variability of number of rainy days ($\Delta CvTN_{JJAS}$), minimum temperature (ΔTN_{JJAS}), variability of minimum temperature ($\Delta CvTN_{JJAS}$) and sunshine duration (ΔSSH_{JJAS}) during vegetative phase; rainfall (ΔR_{Oct}), number of rainy days (ΔRD_{Oct}) and minimum temperature (ΔTN_{Oct}) during reproductive phase and number of rainy days (ΔRD_{Nov}) during ripening phase of winter rice were the statistically significant variables which together explained at least 79% of the yield variance during 1986–2010. Variability of number of rainy days ($\Delta CvRD_{JJAS}$), variability of minimum temperature ($\Delta CvTN_{JJAS}$) during vegetative phase and number of rainy days during reproductive phase (RD_{Oct}) were statistically significant at 1% level. Relationship between the individual climatic variables and yield changes of rice are depicted in Fig. 5.8

Table 5.5 Multivariate linear regression model between first differences of yield (kg/ha) and climatic conditions during 1986–2010 for winter rice in Jorhat district

Source	Estimate	Std. error	t-Value	p-Value
Intercept	21.219	22.312	0.951	0.356
$\Delta CvRD_{JJAS}$	−28.050	8.092	−3.467	0.003
ΔTN_{JJAS}	277.788	124.365	2.234	0.040
$\Delta CvTN_{JJAS}$	−163.712	33.771	−4.848	0.000
ΔSSH_{JJAS}	−121.936	42.008	−2.903	0.010
ΔR_{Oct}	0.775	0396	1.960	0.068
ΔRD_{Oct}	−41.632	10.964	−3.797	0.002
ΔTN_{Oct}	−90.185	35.832	−2.517	0.023
ΔRD_{Nov}	−38.834	13.776	−2.819	0.012

$R^2 = 0.791$, Adjusted $R^2 = 0.687$, F = 0.000

[R= total rainfall (mm), RD= number of rainy days (days), TN= minimum temperature (°C), SSH= sunshine duration (hr), Cv= intra-seasonal variability (%)]

To estimate the role of individual climatic variables in recent yield trends, observed trends in climate variables were multiplied by the yield response computed in the regression model (Table 5.5) and results are presented in Table 5.6. Decrease in ΔRD_{Oct}, increase in ΔTN_{JJAS} and ΔSSH_{JJAS} were the major variables responsible for the observed yield trend (9.96 kg/ha/year) during 1986–2010 in the study area.

The negative impact of increased variability of rainfall distribution ($\Delta CvRD_{JJAS}$) during vegetative phase on rice yield was −1.4±2.87%. Coefficient of variation of number of rainy days (ΔCvRD) during vegetative phase increased during 1986–2010 which indicated occurrence of mid-season drought due to uneven rainfall distribution. As moisture stress during vegetative phase reduces plant height, tiller number and leaf area (Yoshida 1981), its increased variability during 1986–2010 exerted a negative influence on rainfed rice yield in the study area.

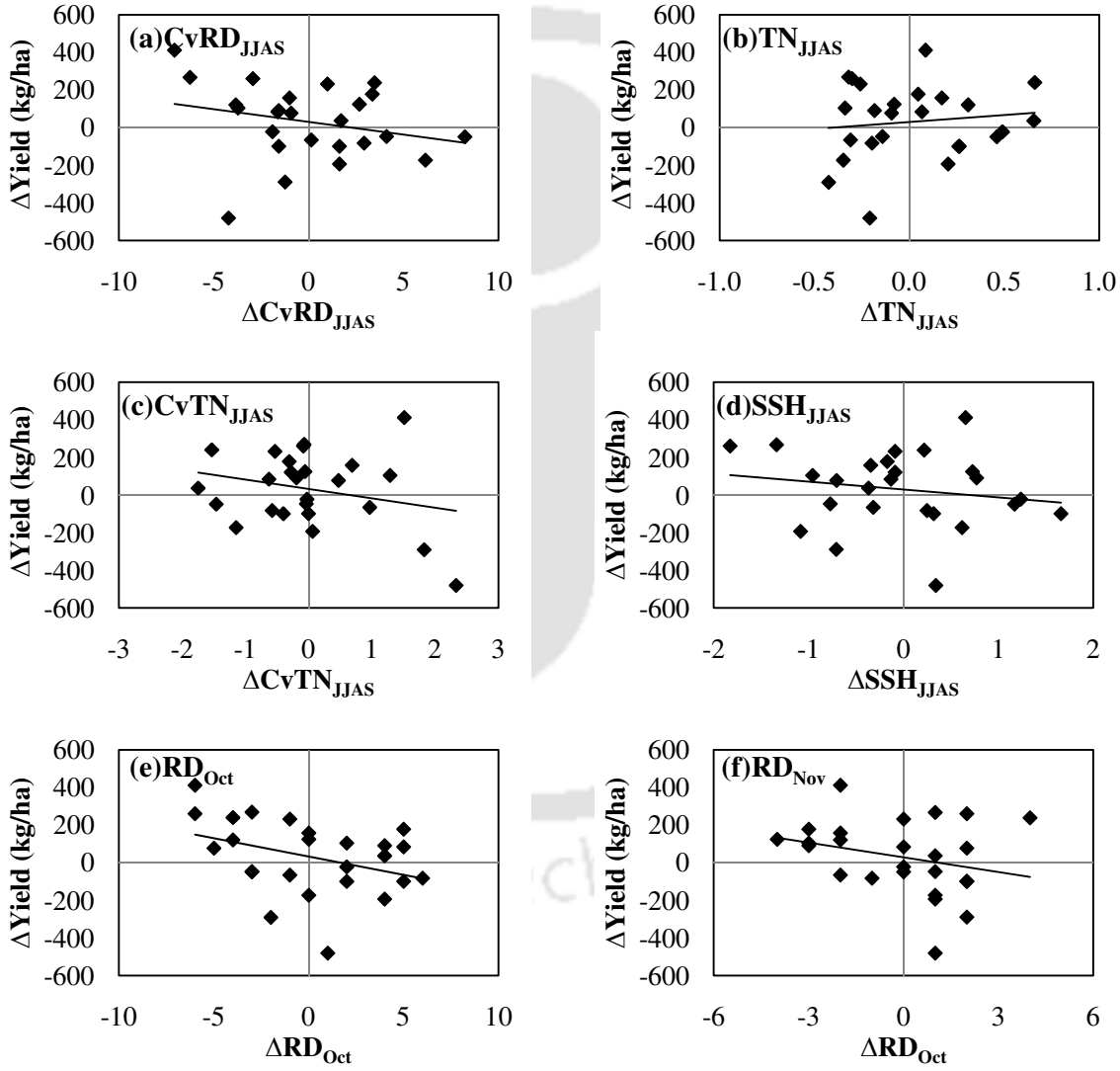

Fig. 5.8 Scatter plots of change in rice yield vs. change in climatic parameters during 1986–2010

Minimum temperature during vegetative and reproductive phases of rice crop was increased by 0.035°C/year and 0.037°C/year respectively during 1986–2010. Result presented in Table 5.6 indicated positive yield impact (41.5±4.45%) due to rise in minimum temperature during vegetative phase and negative yield impact (−33.1±3.96%) due to its rise during reproductive phase indicating relative variable temperature preferences over the two growth phases. On the other hand, increased variability of minimum temperature during vegetative phase was found exert a negative influence (−28.3±2.06%) on rice yield during the study period (Table 5.6).

Table 5.6 Observed trends in climatic parameters and their estimated impact on yield (1986–2010). Observed yield trend during 1986–2010 was 9.963 kg/ha/year.

Phase	Variable	Observed linear trend	Estimated impact (kg/ha/yr)	% Impact on observed yield
Vegetative	$\Delta CvRD_{JJAS}$	0.005	−0.14 ± 0.04	−1.41 ± 2.87
	ΔTN_{JJAS}	0.035	4.14 ± 1.85	41.54 ± 4.46
	$\Delta CvTN_{JJAS}$	0.017	−2.82 ± 0.58	−28.26 ± 2.06
	ΔSSH_{JJAS}	−0.022	2.68 ± 0.92	26.93 ± 3.43
Reproductive	ΔR_{Oct}	−1.424	−1.10 ± 0.56	−11.08 ± 5.08
	ΔRD_{Oct}	−0.129	5.37 ± 1.41	53.91 ± 2.62
	ΔTN_{Oct}	0.037	−3.30 ± 1.31	−33.13 ± 3.96
Ripening	ΔRD_{Nov}	0.035	−1.36 ± 0.48	−13.64 ± 3.53

Reproductive phase in rice is more sensitive to higher temperature than the vegetative phase (Yoshida 1981). High temperature stress during reproductive phase (flowering) affects pollen formation and development, damage insemination and cause spikelet sterility (Yoshida 1981). Sun and Huang (2011) reported that seedling, booting and heading stages of rice crop were the most sensitive stages to minimum temperature stress in China. Tao et al. (2008) estimated that rice yields in northeast China increased by 4.5% to 14.6% per °C in response to increase in minimum temperature during 1951–2002. Decrease in sunshine duration by 0.022 hr/day during vegetative phase showed a positive influence on yield (Table 5.6) which might be due to its role in reducing maximum temperature which had shown negative correlation with yield. Lobell (2007) also found that rising of maximum temperature was more harmful to rice yields than minimum temperature.

The correlation between first differences of yield and number of rainy days during reproductive (ΔRD_{Oct}) and ripening phases (ΔRD_{Nov}) was negative (Fig. 5.8e and f). Decrease of rainfall during the study period (1986–2010) by 14.2 mm/decade in the reproductive phase ((ΔR_{Oct}) exerted a negative influence (−11.1±5.08%) whereas reduction in number of rainy days during the same phase was found to show positive yield impact. Number of rainy days in reproductive phase decreased by 0.13 day/year during 1986–2010 and the resultant positive yield impact was 53.9 ± 2.62% (Table 5.6). On the contrary, rainy days during maturity phase of rice showed an increasing trend during 1986–2010 which exerted a negative influence on yield of rice by −13.6±3.53%.

5.4.3 Future impact of climate change on rice productivity

The primary interest of this section was to assess the changes in productivity of rice under conditions of elevated CO_2 as well as other environmental stresses caused by future climate change using CERES-Rice dynamic crop simulation model. The model was calibrated and evaluated utilizing secondary experimental data of the study site before simulating rice yields under different climate change scenarios.

5.4.3.1 Calibration of CERES-Rice model

The genetic coefficients of rice derived from experimental data during 2004 and 2005 for the variety *Ranjit* are given in Table 5.7.

Table 5.7 Calibrated genetic coefficients for the rice variety *Ranjit*

Sl No	Genetic coefficients	Unit	*Ranjit*
1	Juvenile phase coefficient (P1)	GDD (°C)	1100.0
2	Critical photoperiod (P2O)	h	12.4
3	Photoperiodism coefficient (P2R)	GDD (°C)	250.0
4	Grain filling duration coefficient (P5)	GDD (°C)	320.0
5	Spikelet number coefficient (G1)	–	44.0
6	Single grain weight (G2)	mg	0.023
7	Tillering coefficient (G3)	–	0.90
8	Temperature tolerance coefficient (G4)	–	1.00

The juvenile phase coefficient (P1), photoperiodism coefficient (P2R) and grain filling duration coefficient (P5) of rice cv. Ranjit were 1100 degree-days, 250 degree days and 350 degree days (°C), respectively. Because of its longer duration, *Ranjit* had the highest juvenile phase coefficient. The critical photoperiod (P2O) was 12.4 hours.

Table 5.8 Simulated and observed phenological events and grain yield from model calibration during 2004 and 2005 for rice variety *Ranjit* under different transplanting dates

Year	Date of transplanting	Anthesis date (DAT)		Physiological maturity date (DAT)		Grain yield (kg/ha)	
		Observed	Simulated	Observed	Observed	Observed	Simulated
2004	24 June	116	113	143	142	4690	4632
	08 July	108	109	137	142	4500	4699
	24 July	104	106	132	139	4380	4483
2005	22 June	103	106	138	132	4500	4553
	06 July	100	104	133	133	4275	4344
	25 July	97	101	129	131	3750	3821
RMSE			3.0		4.4		105
Normalized RMSE			2.9		3.2		2.4
d-value			0.91		0.72		0.97

DAT days after transplanting

5.4.3.2 Validation of CERES-Rice model

The data from field experiments conducted in each of the year 1998, 1999 and 2003 were used to validate the calibrated CERES-Rice model. The results indicated that simulation of main physiological events viz. anthesis and physiological maturity dates were in close agreement with observed ones and RMSE ranged from 5.1 to 5.5 days (Table 5.9) respectively. The variation in simulated yields over the observed yields was within ±16% for all the transplanting dates with a RMSE value of 401 kg/ha. The *d*-value was found to be low (0.12) due to lower yields observed in third transplanted crop during 1998 and 2003 (Table 5.9). The normalized RMSE value was below 10%. These results indicated that the CERES-Rice v4.5 model is capable enough in estimating growth and yield of rice with reasonable accuracy under the prevailing agro-climatic conditions of upper Brahmaputra valley and hence can be considered as a reasonably reliable model for use in climate risk assessment studies in the study area.

Table 5.9 Simulated and observed phonological events and grain yield from model validation during 1998, 1999 and 2003 for rice variety *Ranjit* under different transplanting dates

Year	Date of transplanting	Anthesis date (DAT)		Physiological maturity date (DAT)		Grain yield (kg/ha)	
		Observed	Simulated	Observed	Observed	Observed	Simulated
1998	22 June	112	107	138	131	4795	4720
	07 July	110	102	136	128	4380	4813
	22 July	108	100	132	126	3960	4585
1999	20 June	106	108	140	134	4204	4624
	05 July	100	103	134	130	4387	4630
	20 July	97	101	127	130	4150	4717
2003	24 June	113	108	140	134	4550	4220
	22 June	108	103	137	133	4230	4413
	07 July	103	102	133	136	3980	4385
RMSE			5.1		5.5		401
Normalized RMSE			4.8		4.1		9.3
d-value			0.54		0.40		0.12

5.4.3.3 Growth and yield of rice under baseline scenario

After careful calibration and evaluation of the CERES-Rice model, the model was run using baseline climate scenario (1971–2010) for 6 different transplanting dates and results are presented in Table 5.10. Number of days taken for anthesis of rice plant was the highest in early transplanted crop (TP1 and TP2) than that of late transplanted crop (TP5 and TP6). The 20th June transplanted one took 109 days to flower in comparison to 102 days for 30th July ones. However, late transplanted crop took more days for physiological maturity due to their exposure to comparatively lower mean temperature as well as lower solar radiation regimes during grain filling period (Fig. 5.9 and Table 5.10) than earlier transplanted ones. Mean temperatures during grain filling period of 20th June transplanted crop was 25°C where as it was 17°C in the case of 9th August transplanted ones. Consequently, the growing degree-day (GDD) requirement (250°C) of grain filling period (P5) of the variety *Ranjit* (Table 5.7) was accumulated in 19 days compared to 35 days in the case of 9th August transplanted one (Table 5.11). The simulated grain yield was maximum (4801 kg/ha) in 20th July transplanted crop (TP4) due to more number of panicles/m^2 compared to that of other transplanting dates. Harvest index, the ratio of grain yield and total dry matter,

was lower in late transplanted (TP5 and TP6) crop compared to earlier transplanted crops (TP1 and TP2).

Table 5.10 Phenology, grain yield and harvest index of winter rice under the baseline climate scenario (1971–2010) at Jorhat

Parameters	Early		Normal		Late	
	20th Jun (TP1)	30th Jun (TP2)	10th Jul (TP3)	20th Jul (TP4)	30th Jul (TP5)	9th Aug (TP6)
Days to anthesis	109	107	104	104	102	103
Days to maturity	136	135	136	139	142	150
Grain yield (kg/ha)	4407	4532	4576	4801	4631	4478
Harvest Index (%)	32.3	31.9	31.2	31.2	29.2	27.7

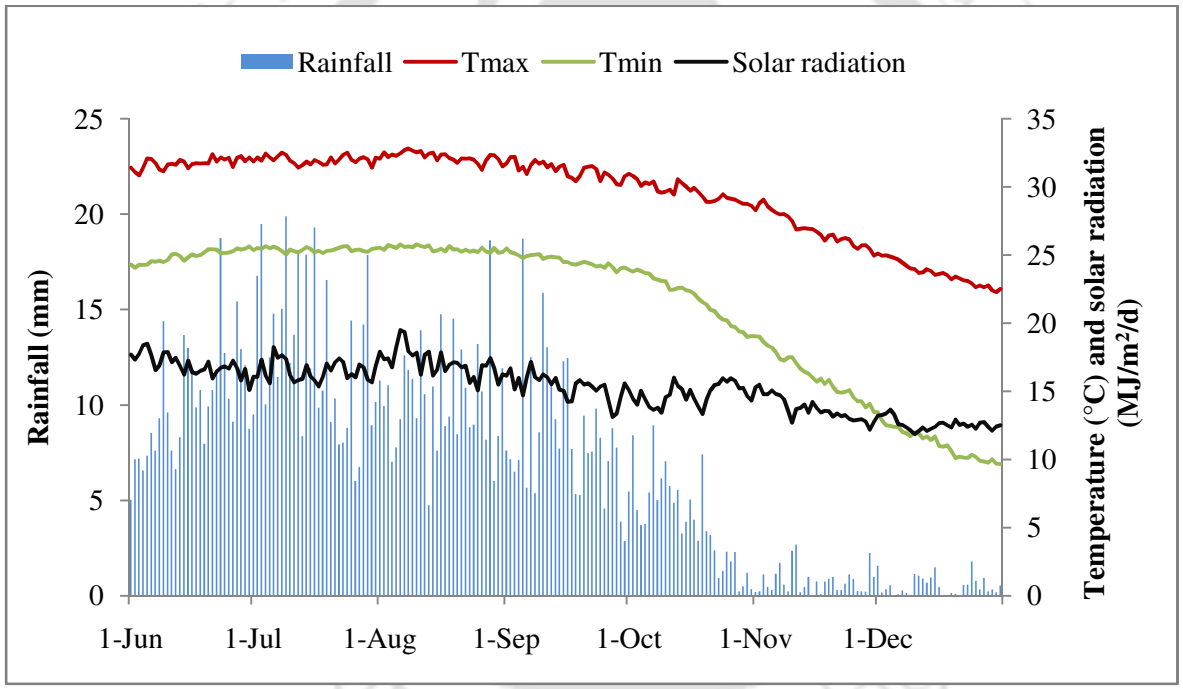

Fig. 5.9 Changes in mean daily rainfall, temperature and solar radiation during rice (*kharif*) growing season at Jorhat (1971–2010)

5.4.3.4 Sensitivity Analysis of CERES-Rice Model

The sensitivity of the CERES-Rice model to temperature, CO_2 levels, rainfall and solar radiation were analyzed by creating anomalies in the baseline climate data (1971–2010) created. The simulated yields were expressed as percentage change over baseline yields in all the transplanting dates considered in this study.

Table 5.11 Duration of different phases of rice and their exposure to environmental factors at different transplanting dates at Jorhat (PI: Panicle initiation, GF: Grain filling)

Variable	Trans-planting dates	Transplant-ing to end of juvenile	End of juvenile to PI	PI to end of leaf growth	End of leaf growth to start of GF	Grain filling phase	Trans-planting to harvest
Duration (days)	TP1	48	24	37	7	19	136
	TP2	47	22	38	7	20	135
	TP3	48	18	38	8	23	136
	TP4	47	17	40	8	26	139
	TP5	48	13	41	10	29	142
	TP6	48	11	44	11	35	150
Maximum temperature (°C)	TP1	32	32	31	30	29	31
	TP2	32	32	31	30	29	31
	TP3	32	32	30	29	28	31
	TP4	32	31	30	29	26	30
	TP5	32	31	30	27	25	29
	TP6	32	31	29	26	24	28
Minimum temperature (°C)	TP1	25	26	25	23	21	24
	TP2	26	25	24	22	19	24
	TP3	25	25	24	20	17	23
	TP4	25	25	22	18	15	22
	TP5	25	24	21	17	13	21
	TP6	25	24	20	15	11	19
Mean temperature (°C)	TP1	29	29	28	26	25	28
	TP2	29	29	27	26	24	27
	TP3	29	28	27	25	23	27
	TP4	29	28	26	23	21	26
	TP5	29	28	25	22	19	25
	TP6	28	27	24	20	17	24
Total rainfall (mm)	TP1	578	257	303	43	52	1234
	TP2	553	229	285	30	23	1122
	TP3	541	183	243	14	19	1000
	TP4	485	167	189	6	21	868
	TP5	497	106	141	9	20	773
	TP6	477	61	110	8	18	674
Solar radiation ($MJ/m^2/day$	TP1	17	17	15	14	15	16
	TP2	17	16	15	14	15	16
	TP3	17	16	15	16	14	16
	TP4	17	16	15	15	13	15
	TP5	17	15	15	14	13	15
	TP6	16	15	15	13	12	14

5.4.3.4.1 Model sensitivity to CO_2

The result of the CO_2 sensitivity experiment (Table 5.12) indicated that overall CO_2 fertilization effect on rice yield was positive but the rate of increase in yield over the baseline was not large when other factors were kept constant. The mean relative yield increased gradually from 20th June transplanted crop (0.3%) to 30th July transplanted crop (2.0%) which might be due to gradual decrease in growing season rainfall with corresponding delay in transplanting dates (Table 5.11).

Table 5.12 Relative changes (%) in winter rice yield over base yield (1971–2010) under fixed CO_2 scenarios at Jorhat

CO_2 concentration	Relative yield (%) under different transplanting dates						Average
(ppm)	20th Jun	30th Jun	10th Jul	20th Jul	30th Jul	9th Aug	
450	0.4	1.2	1.4	0.3	0.7	0.2	0.7
500	0.1	1.3	1.4	1.0	1.7	2.1	1.3
550	1.5	1.9	–0.1	1.4	1.7	1.3	1.3
600	–0.3	0.6	1.5	1.8	2.4	2.3	1.4
650	0.2	0.1	1.2	1.7	2.3	2.2	1.3
700	0.8	1.1	0.2	1.1	1.7	1.3	1.0
750	–0.5	0.0	1.0	2.3	3.5	2.1	1.4
Average	0.3	0.9	1.0	1.4	2.0	1.6	1.2

Generally, an increase in CO_2 level in the atmosphere would increase crop yield mainly by stimulating photosynthetic processes and improving water use efficiency by increasing the number of productive tillers per plant (Baker et al. 1990). The observed yield gain due to CO_2 enhancement in the study site was much lower compared to that in other parts of India (Hundal and Kaur 1996; Lal et al. 1998; Aggarwal and Mall 2002). Long (1991) reported that CO_2 fertilization effect on crop yield may not be manifested under conditions where some other growth factors are limiting such a low temperature and light. Low response of elevated CO_2 concentrations on winter rice in the study area might be due to prevailing low air temperature and high rainfall during the rice growing season. Mean air temperature during transplanting to harvest period of rice under different transplanting dates in the study area was 28°C or less (Table 5.11) which might not be sufficient for manifestation of the fertilizing effects of CO_2.

5.4.3.4.2 Model sensitivity to temperature

Biomass yield of a crop can be taken as a product of the rate of biomass accumulation times the duration of growth. The rate of biomass accumulation is determined by the photosynthetic rate minus the respiration rate (Saseendran et al. 2000). Photosynthetic process is governed by solar radiation while respiration is governed by ambient air temperature (Lal 2010). Higher temperature shortens the rice growth duration; consequently reduces the time period available to the plant for accumulation of photosynthates. Therefore, the biomass accumulation is greatly influenced by ambient air temperature. Results of temperature sensitivity experiment (Table 5.13) indicated that at current (2010) level of atmospheric CO_2 concentration (390 ppm), enhancement of air temperature by 1°C, 2°C and 3°C, potential rice yield increased over control by 3.5%, 7.9% and 11.6% respectively. Temperature enhancement beyond 3°C showed a declining trend in mean relative yield in all transplanting dates except TP6, where relative yield started to decrease beyond 4°C (Table 5.13). Mean relative yield was found to decrease by −11.4% when temperature was enhanced by 7°C over the baseline scenario.

Table 5.13 Relative changes (%) in winter rice yield over base yield (1971–2010) under fixed temperature scenarios at Jorhat

Temperature (°C)	Relative yield (%) under different transplanting dates						Average
	20th Jun	30th Jun	10th Jul	20th Jul	30th Jul	9th Aug	
+1	1.9	4.9	4.2	1.1	4.2	4.5	3.5
+2	7.9	6.8	6.1	3.4	9.4	13.7	7.9
+3	17.4	14.4	9.5	4.8	11.7	12.0	11.6
+4	16.7	13.1	7.6	6.5	6.9	13.4	10.6
+5	16.5	12.3	5.4	1.6	4.3	6.8	7.7
+6	−0.5	−3.3	5.8	−0.8	1.4	1.8	0.7
+7	−11.7	−13.7	−15.9	−16.7	−5.5	−4.2	−11.4
Average	6.9	4.9	3.2	0.0	4.6	6.9	4.4

5.4.3.4.3 Model sensitivity to interaction of temperature and CO_2 levels

While predicting the effects of potential future global warming on rice yields, studies that examine the effects and interactions of both temperature and CO_2 enrichment are far more relevant than studies that examine only the effects of CO_2 or temperature enrichment (Nakagawa et al. 2000). The net effect of an increase in CO_2 and temperature is complicated and depends on the relative effects of both variables in a given region (Pathak

et al. 2003). The interaction effect of temperature (0, +1°C, +2°C, +3°C, +4°C, +5°C and +6°C) and atmospheric CO_2 concentration (390, 450, 550, 650 and 750 ppm) showed that for all the CO_2 levels considered, the CERES-Rice model predicted increasing yields of rice due to an increase in air temperature up to 5°C (Table 5.14).

Table 5.14 Relative changes (%) in winter rice yield over the base yield (1971–2010) under fixed temperature and CO_2 scenarios at Jorhat

CO_2 concentration (ppm)	Temperature increments (°C)							Average
	0	+1	+2	+3	+4	+5	+6	
390	0.0	3.5	7.9	11.6	10.7	8.2	0.7	6.3
450	0.7	5.4	6.1	11.6	12.3	10.8	3.9	7.3
550	1.3	7.0	8.0	9.6	13.2	14.1	8.9	8.9
650	1.3	8.8	9.3	10.5	12.9	15.3	11.3	9.9
750	1.4	8.8	11.6	13.4	13.4	17.8	14.1	11.4
Average	0.8	7.0	8.6	11.3	12.5	13.2	7.8	8.8

(Temperature increments are above the baseline (1971-2010) temperature for the study area. Changes are averaged over all six transplanting dates)

Mean relative yield increase was 7% at +1°C and increased linearly up to 13.2% at +5°C followed by a sharp decrease at +6°C temperature (Table 5.14 and Fig. 5.10a). Similarly, for all the temperature increments considered, mean relative yield increased from 6.3% at 390 ppm (2010 level) to 11.4% at 750 ppm of CO_2 concentration (Table 5.14 and Fig. 5.10b). Relative yield increase over the base yield was maximum (17.8%) at +5°C air temperature and 750 ppm CO_2 concentrations (Table 5.14) under the prevailing condition of study area. Any further rise in temperature from +5°C with 750 ppm CO_2 leads to a decline in relative yield. The result also indicated that the positive effect of elevated CO_2 on rice yield (550 ppm, 650 ppm and 750 ppm) was cancelled out at temperature >5°C at existing level (2010) of input management in the study area (Table 5.14). On the contrary, positive effect of 450 ppm of CO_2 was cancelled out at a temperature >4°C (Table 5.14).

This result disagrees with Aggarwal and Mall (2002) and Krishnan et al (2007). From simulation studies using ORYZA and CERES-Rice model, Aggarwal and Mall (2002) reported that an increase of 2°C, 4.4°C and >5°C temperature will cancel out the positive

effects of 450 ppm, 550 ppm and 650 ppm CO_2 respectively in rice yields over eastern India. Krishnan et al. (2007) reported that positive effect of 600 ppm and 700 ppm CO_2 concentration on rice yield in eastern India (mean of 10 sites) will be nullified at +2°C temperature over baseline – a much lower margin compared to margins reported by Aggarwal and Mall (2002). Krishnan et al. (2007) used a baseline scenario taking only three years weather data (2001–2003) for simulation leading to a narrow margin for nullifying the CO_2 fertilization effect. Saseendran et al (2000) also reported that the physiological effect of CO_2 at 425 ppm concentration compensated for the yield losses due to increase in temperature up to 2°C in Kerala state, India.

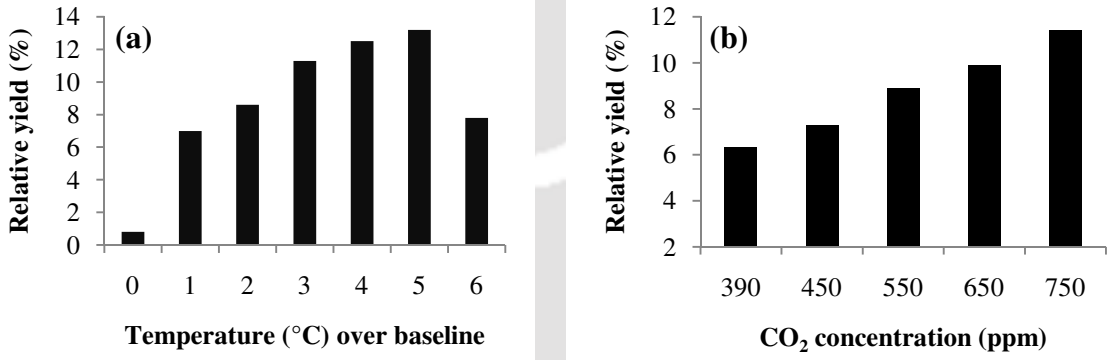

Fig 5.10 Mean relative (%) yield of rice due to enhancement of (a) air temperature at different CO_2 levels and (b) CO_2 concentrations at different air temperatures

This result indicated that the effects of elevated CO_2 on relative rice yield enhancement are strongly temperature dependent (up to +5.0°C) in the study area. Baker and Allen (1993) also reported that the CO_2 fertilization effect was greater at warmer temperatures than at cooler temperatures. Since one of the major effects of elevated CO_2 on net photosynthesis is through the suppression of photorespiration, it could be expected that optimum temperature for photosynthesis shifts upwards as CO_2 increases (Horie 2000). This type of interaction of temperature and CO_2 on leaf level photosynthesis has been defined by Long (1991) for some C_3 species including rice and has been confirmed by Lin et al. (1997) and Nakagawa et al. (1997) for rice. Based on CERES-Rice simulation studies, Zhiqing et al. (1994) reported that an increase in temperature alone would decrease rice yield but that enhanced photosynthesis caused by increased CO_2 concentration can compensate for this

effect. In a similar study in the Philippines, a 2°C rise in temperature caused yield decrease of 15% to 27% at different locations but the increase in CO_2 concentration to 550 ppm nullified this effect (Crisanto and Leandro 1994).

5.4.3.4.4 Model sensitivity to rainfall

Relative yield change due to rainfall increment or decrement by ±10% and ±20% over the baseline was found to be insignificant but the direction of change was important. The relative yield increase due to increase of growing season rainfall by 10% and 20% over the baseline showed a positive trend while it was negative due to increase of rainfall amount by the same magnitudes (Table 5.15).

Table 5.15 Relative changes (%) in winter rice yield over the base yield (1971–2010) under fixed rainfall scenarios

Change in rainfall (%)	Relative yield (%) under different transplanting dates						Average
	20th Jun	30th Jun	10th Jul	20th Jul	30th Jul	9th Aug	
– 10	0.2	–0.7	1.1	–0.5	0.7	0.3	0.2
– 20	0.1	0.7	3.3	1.1	1.4	–0.9	0.9
+ 10	0.2	–0.8	–0.4	0.0	0.0	–0.8	–0.3
+ 20	–0.6	0.7	0.3	–1.0	–1.3	–2.4	–0.7

This might be due to the fact that the study area is located in high rainfall zone and further increase in rainfall amount would increase the chance of flooding. Similar observations from Philippines and Indonesia were also reported. In parts of Philippines, simulated rice yields were decreased by 10% increase in rainfall, due to flooding in the areas with already high seasonal rainfall. For similar regions in Indonesia yields did not reduce with about 10% decrease in seasonal rainfall (Buan et al. 1996). Though the relative yield increase of rice was not significant due to changes in rainfall up to ± 20%, its distribution will play a major role in rice yield variability as observed in section 5.3.2. In the event of decrease of growing season rainfall by 20%, crop transplanted on 10th July performed better compared to other transplanting dates (Table 5.15). From a simulation study using InfoCrop model, Kumar et al. (2011) reported that the rainfed rice in NE region of India will not be able to

get the CO_2 fertilization benefits at the present input status since rainfall will not be a limiting factor in the region despite the projected 10% reduction in *kharif* season rainfall.

5.4.3.4.5 Model sensitivity to solar radiation

The sensitivity of the CERES-Rice model to solar radiation showed that with decrease in solar radiation by 3.0 MJ/m^2/day from baseline at an increment of 1.0 MJ/m^2/day, relative yield decreased while increase in solar radiation at the same magnitude increased yield (Table 5.16). For every 1.0 MJ/m^2/day decrement of solar radiation (up to 3.0 MJ/m^2/day) from the baseline, relative yield decrease was 1%. Solar radiation increment up to 2.0 MJ/m^2/day over baseline level showed an increase in relative yield.

Table 5.16 Mean predicted change (%) in winter rice yield over base yield (1971–2010) under fixed solar radiation scenarios

Solar radiation (MJ/m^2/day)	Relative yield (%) under different transplanting dates						Average
	20th Jun	30th Jun	10th Jul	20th Jul	30th Jul	9th Aug	
−1	0.2	−1.3	−0.5	−2.1	−0.8	−3.3	−1.3
−2	−2.9	−3.4	−1.3	−2.3	−1.4	−5.3	−2.7
−3	−3.6	−7.1	−4.1	−3.9	−1.4	−2.9	−3.8
+1	0.4	1.1	2.5	1.0	0.8	0.1	1.0
+2	0.9	1.1	3.9	1.6	2.7	2.7	2.2
+3	2.5	2.0	2.6	1.7	2.3	1.3	2.1

A decrease in radiation reduces photosynthesis and results in decline in yield, while an increase in radiation improves photosynthesis (Horie et al. 1995). Pathak et al. (2003) using CERES-Rice model showed that decrease of solar radiation by 1.7 MJ/m^2/day, had reduced the rice yields from 10.9 to 10.3 ton/ha during 1985–1999 in the Indo-Gangetic Plains of India.

5.4.3.5 Yield of rice under different climate change scenarios

Predicted changes (%) in rice yield with respect to the control under different climate change scenarios and transplanting dates are presented in Table 5.17. Mean relative yield increase of rice was positive under all the climate change scenarios considered (Table 5.17) irrespective of transplanting dates. Late transplanted crop (30th July and 9th August) showed maximum benefit irrespective of the climate change scenarios considered.

Scenarios A–F showed relative role of temperature and rainfall perturbations at fixed levels of CO_2 and solar radiation on yield changes. Increase of mean air temperature from 0.5°C to 1.5°C at an increment of 0.5°C increased the yield linearly from 3.0% to 6.2% when growing season rainfall was decreased by 10% (scenarios A, C and E) over control (Table 5.17). But the magnitude of changes in yield got lowered down when growing season rainfall was increased by 10% over control (scenarios B, D and F). Among these scenarios, an increase of air temperature by 1.5°C and decrease of growing season rainfall by 10% (scenario E) showed the maximum yield increase (6.2%). In contrast, increase of growing season rainfall by the same rate lowered this level to 3.6% (scenario F). Among different transplanting dates, the relative yield increase was the highest (above 10%) in 9th August transplanted crop (Table 5.17) in these two climate change scenarios (scenarios E and F).

Table 5.17 Impact of different climate change scenarios on productivity of winter rice

Scenario	Percentage change in yield over control						Average
	20th June	30th June	10th July	20th July	30th July	9th August	
A	1.0	3.4	2.3	0.9	4.5	6.1	3.0
B	0.2	3.0	1.8	−0.8	2.0	4.4	1.8
C	2.6	5.6	3.9	2.1	7.1	7.1	4.7
D	5.7	5.6	4.1	0.0	2.9	7.6	4.3
E	6.2	8.5	0.9	1.4	8.8	11.3	6.2
F	5.2	−0.1	0.4	−0.9	6.7	10.3	3.6
G	4.7	4.6	2.4	2.8	5.2	8.0	4.6
H	6.3	0.4	0.4	−0.2	5.0	8.0	3.3
I	3.6	−0.6	2.6	0.2	3.8	2.9	2.1

Scenarios G and H illustrated the role of asymmetrical increase of daytime and nighttime temperature on rice yield at constant level of CO_2 concentration (460 ppm), solar radiation (−1MJ/m^2/day) and rainfall (baseline). Mean relative yield increase was more (4.6%) in scenario G (Tmax: +0.5°C and Tmin: 1.5°C) than in scenario H (Tmax: +1.0°C and Tmin: +2.0°C) indicating an asymmetrical increase up to a certain level of temperature increase (Tmean +1.0°C) to be beneficial. The beneficial impact of minimum temperature increase on observed rice yield was also reflected by the statistical model described in section 5.4.2. Interestingly, the crop transplanted on 9th August showed relative yield increase at the same magnitude (8%) in both the scenarios (Table 5.17). The crop transplanted on 9th August showed highest yield increase (8%) in both the scenarios (G and H), probably due

to the lowering of diurnal temperature differences (Fig. 5.5). Though the rice cv. Ranjit is not generally recommended for transplanting beyond July, adapting to other shorter duration photosensitive cultivars might get benefit from the climate change scenarios E, F, G and H in near future. Scenario I, which was based on the observed trends of solar radiation, temperature and rainfall of the baseline (1971–2010) data, also indicated a marginal yield increases due to climate change. The result is consistent with the findings of Saseendran et al. (2000) and Krishnan et al. (2007).

Over all, rice yield is likely to be impacted favourably under the projected climate change scenario studied under the agroclimate of upper Brahmaputra valley. This result of the CERES-Rice model simulations indicated a clear evidence for an increase of rice yield under different climate change scenarios considered at current (2010) level of crop inputs and management. The relative yield increase due to climate change was as high as 11% if the transplanting time is suitably adjusted, though the CERES-Rice model as available currently lack demonstrated strengths in assessing risk related to extremes events, pests, diseases, and nutrients other than nitrogen. Moreover, use of crop models for impact assessment of climate change suffers from other typical limitations and uncertainties such as non-consideration of future socio-economic trends, including land use, technological improvements and changes in soil fertility etc. Crop variety, crop management practices and soil fertility levels vary from one field to another, and also from farmer to farmer.

Chapter 6

Impact of Climate Change on Tea Productivity: An Empirical Statistical Approach

In this chapter, the effect of climate change trends on the fluctuations of seasonal tea yields has been assessed by using empirical models. Quantitative relationship between tea yields and climatic variables were developed using monthly data between 1991 and 2010 to assess the impact of climate change and variability on the observed yield trends. Non-climatic influences such as introduction of new variety, effect of age and changes in crop management practices were eliminated by detrending (explain) the tea yield data. In a step forward, predictive models were developed to predict the likely impact of future changes in mean climate as well as its variability on the yield of tea.

6.1 Introduction

Tea (*Camellia sinensis* (L.) O. Kuntze) is a member of the *Theaceae* family. It is an evergreen understory shrub from the genus *Camellia* that includes some 82 species (Banerjee 1992a). Of all the *Camellia* spp., tea is the most important both commercially and taxonomically and is cultivated to produce a stimulant brew. The two main varieties of tea are *Camellia sinensis* var. *assamica* with relatively large, leaves, and *Camellia sinensis* var. *sinensis* with small semi-erect leaves. The *assamica* tea originated from the forests of Assam in north-eastern India and the *sinensis* tea originated from Sichuan province of south-western China (Van der Vossen and Wessel 2000). Both these areas are normally characterized by a monsoon climate with high rainfall and high humidity during warm wet summers and cool dry winters. Following extensive selection and hybridization, most commercial tea today display vegetative characteristics intermediate between these two main types (Mondal et al. 2004). Commercially, tea is grown for its tender shoots, which tend to comprise two or three leaves and an apical bud. Shoots are generally plucked by hand at periodical intervals to produce either 'black' (i.e., withered and fermented) or 'green' (i.e., withered but unfermented) tea.

Tea is a leading cash crop in world agriculture and is grown in more than 32 countries in an area of 2.8 million ha (Tea Statistics Tea Board of India 2010). The main tea producing

countries are China, India, Sri Lanka, Kenya, Indonesia, Turkey, Iran, Georgia, Japan, Vietnam, Bangladesh, Argentina, Malawi, Uganda, Zimbabwe and Tanzania. Among them, China and India are the leading tea producers producing 1,475 and 966 million kg respectively in 2010 (Fig 6.1), whereas the world tea production was 4,162 million kg in that year (Tea Statistics Tea Board of India 2010).

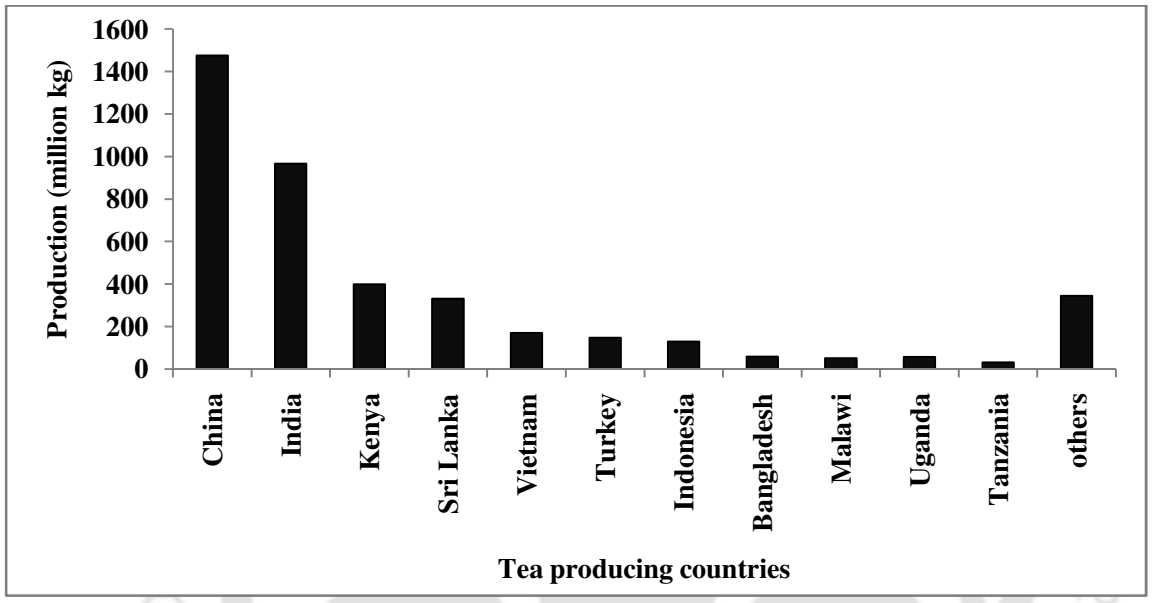

Fig. 6.1 Major tea producing countries in the world and respective productions in 2010

India is the second largest producer of tea, the largest consumer and the fourth largest exporter (after Sri Lanka, Kenya and China) in the world (Tea Statistics Tea Board of India 2010). With an annual tea production of 480 million kg and an average yield of 1,534 kg/ha in 2007 it covers approximately 17% of the world's tea production (Tea Statistics Tea Board of India 2010). Tea industry is of considerable importance in the national economy of India in terms of income generation, earning foreign exchange, employment generation and contribution to national exchequer.

Assam is the largest producer of tea contributing 53.2% of the total area and 51.43% of total production in the country (Tea Statistics Tea Board of India 2007a, 2007b). About 88% of Assam's tea area is concentrated in the Brahmaputra valley alone (Fig 6.2) with a production of 390 million kg (90% of State's total tea production). The area, production and average yield of tea in the Brahmaputra valley during 1961–2007 are shown in Fig. 6.3

which showed decline in productivity since mid-90s. Stagnation in tea productivity and decline of tea quality are seen as major problems by the tea industry in India during recent past (Dutta et al. 2010). This has attributed to several factors, such as old age of tea bushes, increased climate variability, declining soil health and increased incidence of pests and diseases (Dutta 2008). The increasing climate vulnerability has resulted in a significant drop in tea productivity in spite of adoption of improved management practices by the tea estates (Ramakrishna et al. 2013). The productivity of tea in the Brahmaputra valley has declined in recent past (Fig. 6.3).

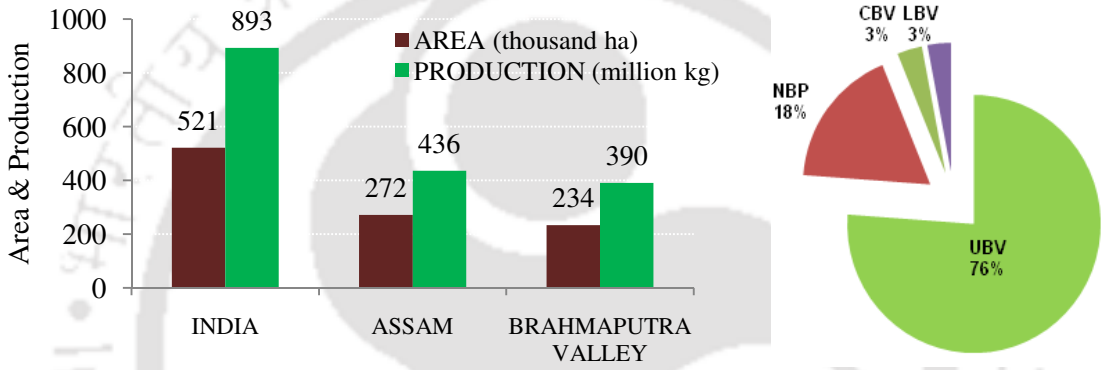

Fig. 6.2 Area and production of tea in India, Assam and the Brahmaputra valley [Source: Tea Statistics Annual Report Tea Board of India (various issues)]

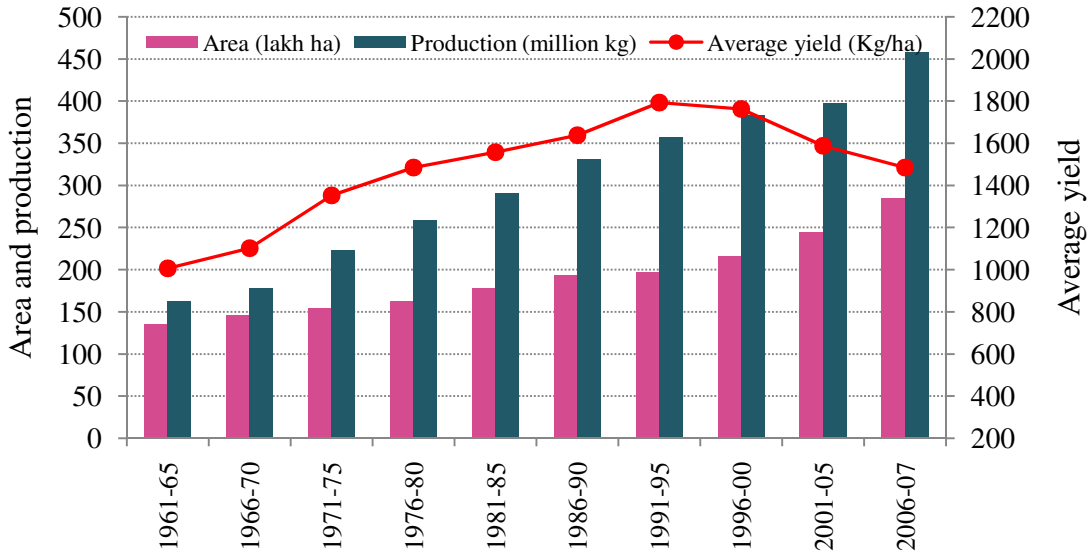

Fig.6.3 Area, production and yield of tea in the Brahmaputra valley during 1961–2007 [Source: Tea Statistics Annual Report Tea Board of India (various issues)]

6.2 Study site

The study was based on the estate level tea yield data collected from the Kakajan Tea Estate, operated by Amalgamated Plantations Private Limited, located in Jorhat district of upper Brahmaputra valley (Fig. 6.4). The district is known as the 'Tea Capital of the World'. Tea occupies 9% of the total geographical area of the district (Vadivelu et al. 2004b). Detailed description of the district has been given in the previous chapter (section 5.2).

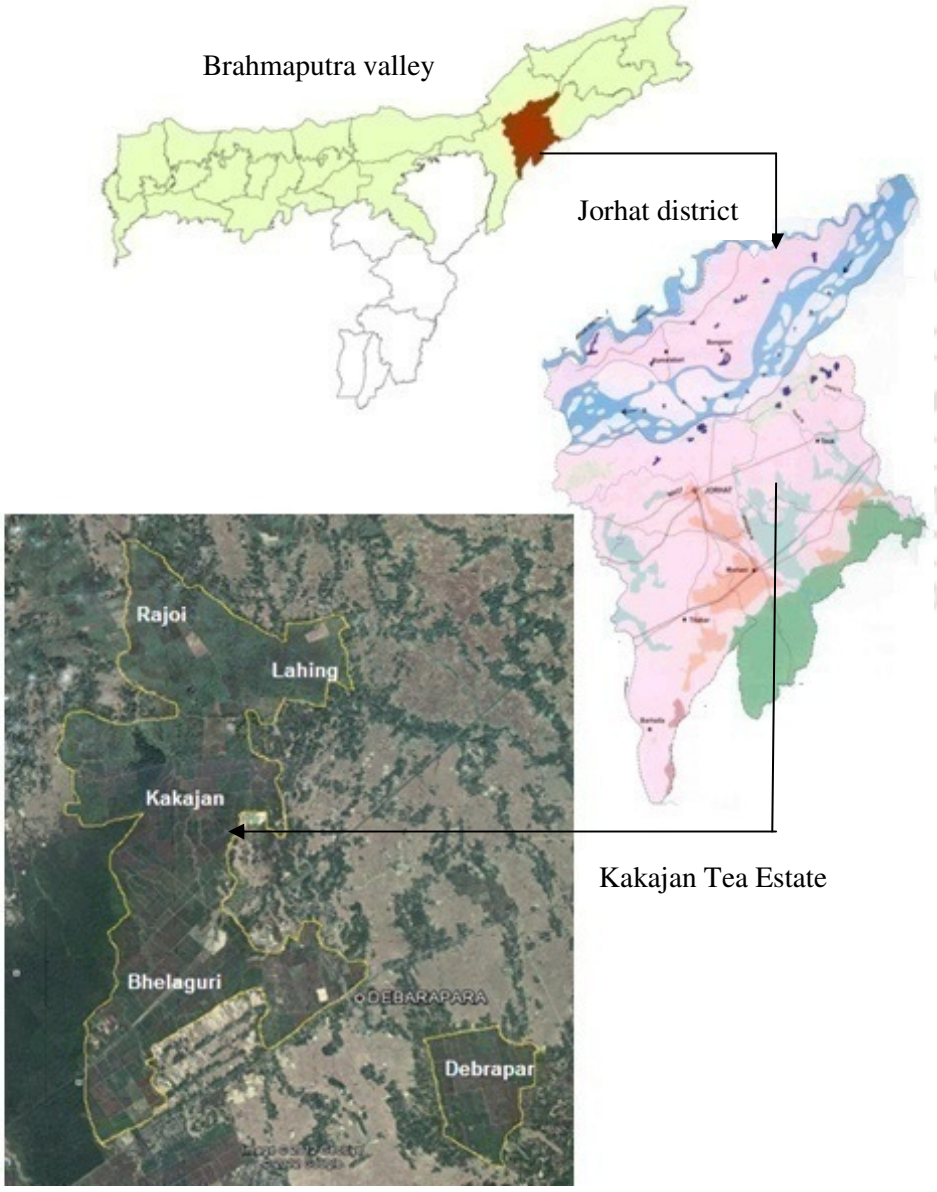

Fig 6.4 Location map of the study site for tea

6.2.1 Climatic characteristics

Climate of the study area is sub-tropical humid with an average annual maximum and minimum temperature of 28.2°C and 19.1°C, respectively. It receives an average rainfall of 2076 mm out of which 87% falls between April and September. The other months also receive occasional rainfall (Vadivelu et al. 2004b). However, the period between November and March remains dry and deficit. On an average, 65% of the total rainfall occurs during the monsoon season, followed by 25% during pre-monsoon, 8% and 2% during post monsoon and winter season respectively. Based on the climatic water balance of the study area (Fig 6.5), the year could be broadly divided into four groups from the point of view of crop-weather studies:

- the dry period during the cold weather from December to February when both rainfall and soil moisture are low and PET exceeded rainfall,
- the period of early rains (March-May) when rainfall exceeded PET and the soil moisture content was fairly high to serve as refill for the soil,
- the period of monsoon rains (June–September) when the rainfall was considerably higher than PET and is sufficient to keep the soil fully saturated, and
- the retreating monsoon period from October to November when the rainfall is almost the same as PET in October and less in November and the soil moisture content is somewhat higher than the period of December to February.

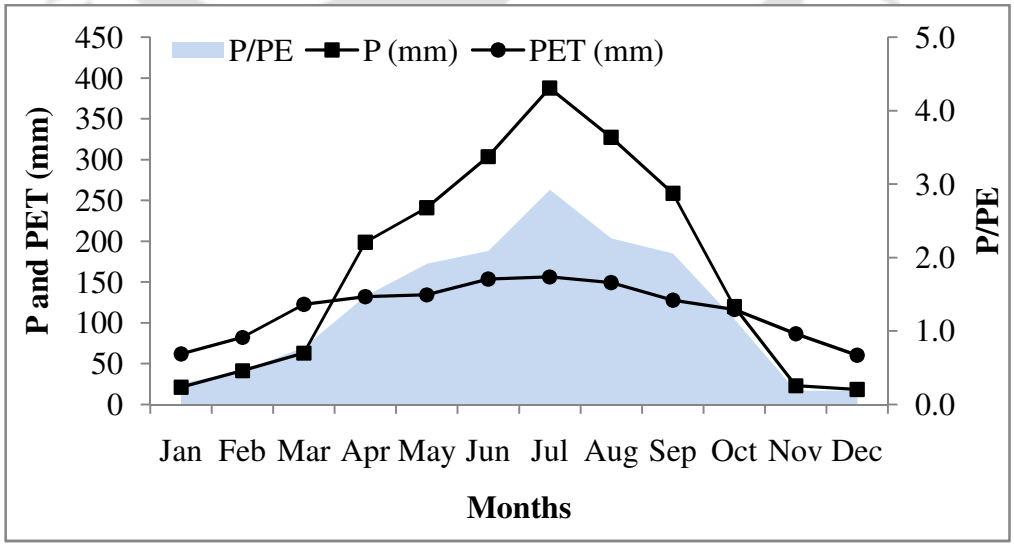

Fig 6.5 Identification of water availability periods at Jorhat (Source: AAU Jorhat, 2006)

6.2.2 Soils characteristics

A common characteristic exhibited by the soils is the acidity (pH) in which the tea plant grows best (Othieno 1992), most satisfactory pH values vary between 4.0 and 6.0. An important soil physical requirement for tea plant production is deep and well drained soil, with a minimum depth of two metres and an aggregated or crumb soil structure with about 50% pore spaces (Dey 1969). Tea grows on soils of practically any texture ranging from sandy loam to clays, including silts and loams of all types. However, the lighter sandier soils have a lower field capacity than the heavier clay soils and require a good distribution of rainfall and nutrients. Although the water requirements of the tea plant is high, pore spaces should never get saturated or waterlogged as this is harmful to plant growth. The period between land preparation and tea establishment is normally the most prone to erosion (Othieno 1975) but as the tea bush matures and attains a ground cover canopy of above 60%, soil erosion and run-off becomes negligible (Othieno and Laycock 1977).

The soil of the study area is characterized as fine loamy, mixed, hyperthermic family of *Typic Dystrudepts*. The location of the garden is characterized by alluvium-derived, well drained, very gently sloping uplands (Vadivelu et al. 2004a). The soil is very deep; thickness of A horizon is 10 to 20 cm while that of B horizon is 70 to 100 cm thick. The texture is sandy loam at the surface horizon and sandy clay loam at the lower horizons. The bulk density of the soil is less than 1.5 gm/cm^3. The saturation percentage varies from 12% to 22%. The organic matter content of the surface horizon is 1.38% and its value decreases with depth (Table 6.1). The pH of the soil is 4.1 (Vadivelu et al. 2004a).

Table 6.1 Physico-chemical properties of the soils of Kakajan Tea Estate (Teok series)

Depth	Particle size distribution (%)			Organic	pH	CEC	$Ca^{2+}+Mg^{2+}$
(cm)	Sand	Silt	Clay	carbon (%)	(1:2.5 H_2O)	cmol (p^+)kg^{-1}	
0–11	78.0	12.8	9.2	1.38	4.2	4.1	0.6
11–28	65.0	26.7	8.3	0.44	4.1	3.5	0.5
28–69	56.5	26.7	16.8	0.40	4.1	4.7	0.6
69–115	50.0	18.8	31.2	0.29	4.1	6.8	0.6

6.3 Materials and methods

6.3.1 Yield data

Indian tea estates generally range in size between 100ha and 500 ha. Each estate is divided into sections, typically of a size between 10ha and 15 ha. Some big estates have divided the entire estate into divisions. Sections contain tea plants of different varieties, of a different age, and are managed on an individual basis. Tea yield data are generally available at the level of estate and for individual sections.

Monthly tea production (made tea) data at the division level from 1991–2010 were collected from the Kakajan tea estate, owned by Amalgamated Plantations Private Limited (Formerly Tata Tea Limited) located in the Jorhat district of upper Brahmaputra valley. The estate has plantations in an area of 1,683 ha, distributed in 5 divisions (Fig 6.4), 213 plantations sections (Table 6.2), and covered by plants of different age and cultivars (Table 6.3). The number of sections varies from 29 to 63 in different divisions, having a total of 206 sections in the estate. The data related to area under plantation, date of planting and harvest details were available at section level. These data were also collected for calculation of average yield (kg/ha) from the production data. The total area harvested in each division in a particular year was calculated from the section level data collected. Then for each division, the monthly average yields were obtained by utilizing data on monthly production and total area harvested. Finally, area-weighted average yield (kg/ha) of made tea at estate level were calculated from the division level yield data.

Table 6.2 Details of the Kakajan tea estate

Division	Area (ha)	Number of sections	Size of sections (ha)
Kakajan	363.98	43	0.50 – 22.29
Rajoi	383.43	40	3.00 – 24.83
Lahing	213.84	31	1.94 – 12.37
Debrapar	478.47	63	1.55 – 16.71
Bhelaguri	243.71	29	2.00 – 16.72
Entire estate	1683.43	206	0.50 – 24.83

Table 6.3 Composition of cultivars in the Kakajan tea estate

Cultivar type		Cultivars
1.	Old Seed *Jats*	Monipuri, Betjan, Tingamira, Khowang, Kakajan, Nokhoti, Debrapara, Doolia, Joypuri, Rangamattee
2.	Selected vegetative clones	TinAli-17, Panitola-126, S3A3
3.	Tocklai, TRA released vegetative clones	TV-1, TV-9, TV-18, TV-20, TV-22, TV-23, TV-25
4.	Tocklai, TRA released Bi-clonal Seed Stocks	Stock 203, Stock 462, Stock 463

6.3.2 Climate data

Data related to rainfall and temperature was collected for the period 1995–2010 from the Kakajan tea estate. The data were scrutinized carefully by comparing them with the data recorded at neighbouring Meteorological Observatory of Tocklai Experimental Station (TES) and Assam Agricultural University (AAU), located approximately 10 km west and southwest of Kakajan tea estate respectively. The dataset related to monthly rainfall and number of rainy-days was calculated by averaging the data recorded at TES and AAU. Accordingly, temperature, and sunshine duration data were also computed by averaging the TES and AAU data and assumed to be representative of the entire estate. Different climate variables were grouped into four seasons according to climatic water balance of the study area (section 6.2.1). The notation and units are given below:

Let R stand for the total rainfall in mm, TX is the maximum temperature in °C per day, TN is the minimum temperature in °C per day, TM the mean temperature in °C per day (average of maximum and minimum temperature), DTR the diurnal temperature range in °C per day (corresponding difference in temperature), and SSH is the average number of bright sunshine hours per day. Let the subscripts 1, 2, 3 and 4 stands for the periods December (preceding year) to February, March to May, June to September and October to November of the current season. Thus, R_1 stands for the rainfall, TX_1 the maximum temperature, TN_1 the minimum temperature, TM_1 the mean temperature, DTR_1 the diurnal temperature, SSH_1 the average sunshine hours for the period December to February (winter season). In addition to these, variability of each of the climatic variables was also

computed by the coefficient of variation (CV) and was computed as the seasonal ratio of the standard deviation to the mean of each climate variables.

6.3.3 Statistical analysis

The impact of climate change on observed yield trend as well as its projected impact on future yield was based on empirical statistical modeling approach. Being a perennial crop, yield of tea is influenced by the weather conditions of the preceding months or seasons in addition to the plucking season's weather (Sen et al. 1966). Moreover, there exist short-term variation of weather within a growing season (Fordham 1977) and variation between seasons of the year (Barua 1969). Therefore, considering the monthly production pattern as well as climatic water balance of the study area, monthly tea yield data were grouped into three components: the early crop during March to May, main crop during June to September and late crop during October to December. To reduce the number of predictor variables for a relatively short 20-year yield time series, only seasonal averages of different climatic variables were taken into consideration. Apart from measuring the seasonal climate means, variables capturing intra-seasonal variability in temperature and rainfall were also included in this analysis. The variability was measured by the coefficient of variation (CV) calculated as the seasonal ratio of the standard deviation to the mean of each climate variables (Rowhani et al. 2011). Accordingly, climate variables (mean and variability) of winter and pre-monsoon for early crop; winter, pre-monsoon and monsoon seasons for main crop and monsoon and post-monsoon season for late crop were considered in the analysis. Correlation analysis was also performed between seasonal tea yields (early, main and late) and monthly climate variables and discussed suitably as and when the context came in the result and discussion part. The procedures leading to the development of statistical models for assessing the observed and projected climate on tea yield have been discussed in the following section 6.3.3.1.

6.3.3.1 Model for estimating observed impact of climate on productivity

The impact of climate variables (mean and variability) on observed yield trends of early, main and late crop was assessed by developing multiple regression models between first difference of yields (response variables) and first differences of climate variables as predictor variables (Nichols 1997; Lobell et al. 2005). The importance of first difference

method in removing the influence of technology trends from crop yields have been discussed in the previous chapter (section 5.3.1.3). These first-difference values of yield and climate were used to regress in a linear model for each pair of climate and yield data to derive the responses of yield to different climate variables (Zhang et al. 2010). To estimate the relative contribution of each independent climate variable in determining tea yield variability, backward selection procedures were adopted for the regression analysis (Mather 1976; Rowhani et al. 2011). Each model has been checked for multicollinearity by the computation of Variance Inflation Factor (VIF) following O'Brien and Robert (2007).

6.3.3.2 Model for estimating projected impact of climate on productivity

The use of statistical yield models was necessitated by the lack of process-based models for tea crop. One advantage of statistical models is that they intrinsically account for a wide variety of mechanisms (influence of pests, pathogens) that can influence yields in a changing climate (Lobell et al. 2006), which are omitted from most process-based models. However, unlike process-based models, statistical model do not allow explicit consideration of management changes and CO_2 increases in assessing future impact, which may also alter the effect of climate on yields in the future.

In this study, possible effects of projected changes of climate (mean and variability) on tea yields were assessed by developing multiple linear regression models between actual yields of early-, main- and late crop (dependent variables) and mean climatic parameters and their variability terms (independent variables) for the period 1991–2010 (Equation 5.1). A time variable (year 1991, 1992, ------, 2010) was included in these linear models to capture yield changes related to non-climatic factors and other technological development (Rowhani et al. 2011). The multicollinearity between the explanatory variables in each model has been checked by the computation of Variance Inflation Factor (VIF) following O'Brien and Robert (2007). In order to figure out the most important yield influencing variables among all the explanatory variables, a stepwise backward variable selection criteria based on R^2 was adopted (Mather 1976; Rowhani et al. 2011).

As the method of the computation of the yield levels under future climate change scenario was not identical with the method of computation of fitted yields under the observed climatic conditions, yield levels have been calculated by using the baseline weather data.

The baseline scenario of the study area is based on 40 years data (1971-2010) has been discussed in Chapter 5 (section 5.3.2.4). Accordingly, the relative changes in yields were worked out by comparing the generated yields under the baseline scenario with generated yields under the climate change scenarios. The main goal was to quantify the sensitivity of tea crop to expected changes in mean state as well as variability of temperature, rainfall, rainy days and sunshine duration, which can provide a basis for prioritizing adaptation efforts.

6.3.3.3 Building up of climate change scenarios

The adopted seasonal temperature and rainfall scenario for 2030 was based on the recent MoEF (2010) report, details of which have been discussed in section 5.3.2.4.3. The temperature scenario represented an increase in temperature of the order of 2.0°C during winter, 2.2°C during pre-monsoon, 1.6°C during monsoon and 2.3°C during post-monsoon seasons in 2030s over the baseline (1961–1990). The intra-seasonal and inter-seasonal variability of temperatures is likely to increase by 10% in 2030s. An increase in monsoon and post-monsoon rainfall by 7% and 4% and decrease of winter and pre-monsoon rainfall by 20% and 15% respectively over 1961–1990 was projected during 2030s over the baseline (1961–1990). A decrease in number of rainy days by 20% during winter, 10% during monsoon season and increase by 10% during post-monsoon season is expected. Coefficient of variation of rainfall during winter and pre-monsoon seasons is likely to decrease by 10% over the baseline due to the projected decline in total rainfall during the two seasons. For sunshine duration scenario, the observed linear trend of bright sunshine duration data during the baseline (1971–2010) of the study area was considered in building up of sunshine duration scenario, assuming that the observed trend will continue more or less consistently in the coming 30 years.

6.4 Results and Discussion

6.4.1 Descriptive Statistics

The average annual yield of Kakajan Tea Estate during 1991–2010 was 1688 kg/ha with a standard deviation (SD) and coefficient of variation (CV) of 155 kg/ha and 9% respectively during 1991–2010. The annual yield varied between 1,390 kg/ha to 1976 kg/ha during the study period. The yields at the very low ends may be due to the

replanting. Among the five divisions, average annual yield was highest in Kakajan division (1,818 kg/ha) and lowest in Rajoi division (1,539 kg/ha). Within different seasons, average yield was 1007 kg/ha in main crop, with a range of 800 kg/ha to 1159 kg/ha during 1991–2010 (Fig. 6.6). Average yield of early crop was 252 kg/ha (145 kg/ha – 318 kg/ha) while it was 429 kg/ha (314kg/ha – 494 kg/ha) in the case of late crop (Fig. 6.6). Inter-annual variability of early crop yield was maximum (CV 26%) while it was lower in main and late crop with a CV of 9% and 10% respectively. The distribution of tea bushes under different age-groups in the entire estate as on 2011 is shown in Fig. 6.7. It has been observed that the age of 50% of the tea bushes are under 50 years.

Table 6.4 Descriptive tea yield (annual crop) statistics for different divisions and at estate level (kg/ha) during 1991–2010

Division	Minimum	Maximum	Mean	SD	CV (%)
Kakajan	1437.3	2075.8	1817.6	179.9	9.9
Rajoi	1069.6	1876.2	1539.0	233.6	15.2
Lahing	1173.4	1807.1	1540.4	173.7	11.3
Debrapar	1306.1	1928.2	1678.5	188.5	11.2
Bhelaguri	1410.5	2142.1	1795.0	178.4	9.9
ESTATE	1390.3	1976.3	1687.7	156.4	9.3

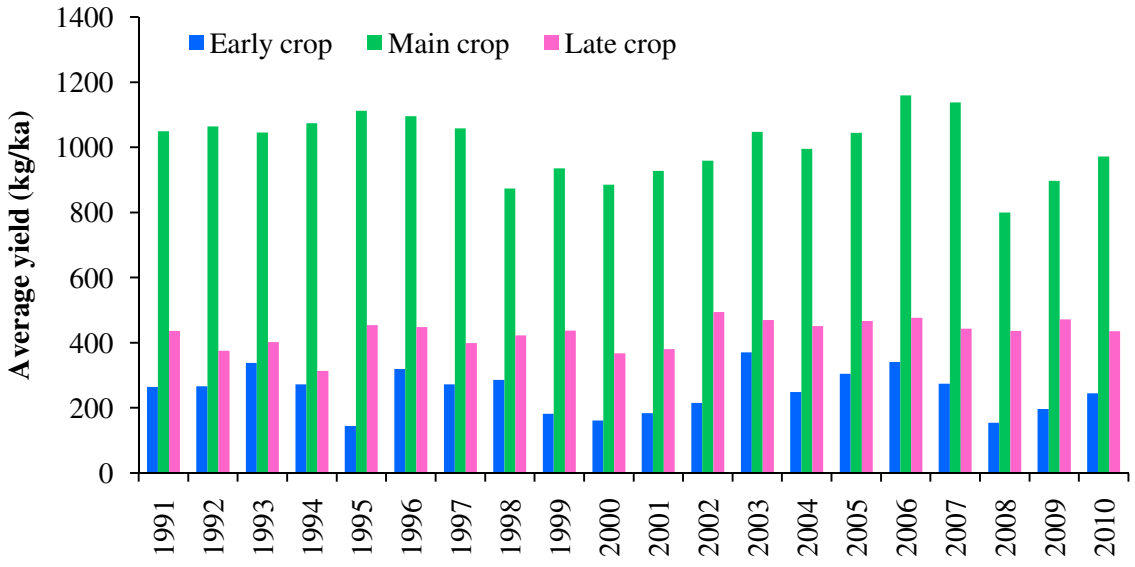

Fig. 6.6 Average yield of tea (kg/ha) in three different plucking seasons (early, main and late) during (1991–2010)

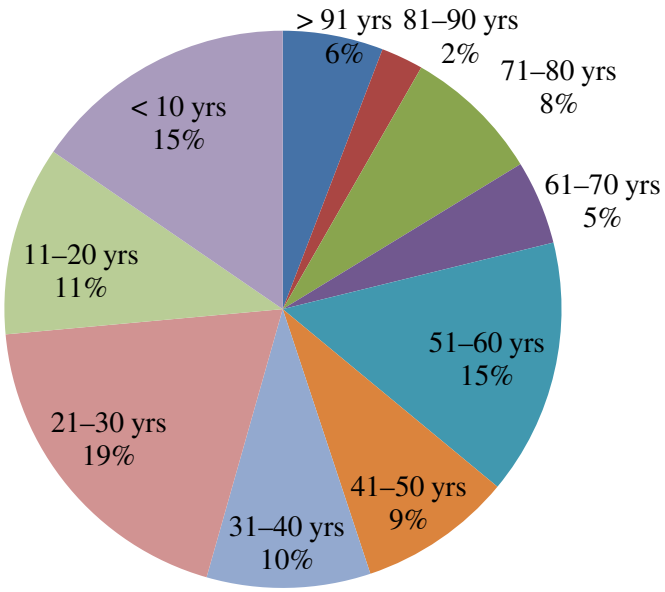

Fig 6.7 Area under different age group of tea bushes as on 2011 in the Kakajan tea estate

6.4.2 Observed impact of climate change on tea productivity

Impact of climate trends on observed yield trends (early, main and late) during 1991–2010 were assessed by multivariate regression analysis between first difference of yield and first differences of climate variables (mean and variability). The main goal of this study was to determine the degree to which recent climate changes have impacted tea yield.

6.4.2.1 Impact on early crop

In case of early crop, the results (Table 6.5) indicated significant positive yield responses to rainfall variability (ΔCvR_1), number of rainy days (ΔRD_1), mean and intra-seasonal variability of winter temperature (ΔTM_1 and $\Delta CvTM1$) and negative yield responses to pre-monsoon rainfall variability (ΔCvR_2) and mean temperature (ΔTM_2). These variables together explained about 94% of the observed yield variance during 1991–2010. Among these, ΔRD_1, ΔTM_1 and ΔTM_2 were statistically significant at 99% level of confidence (Table 6.5). Though these three factors together could explain about 64% of yield variance during the study period, inclusion of their variability terms improved the explanatory power of the model substantially. The relationship between individual climate variable and yield changes of early crop are shown in Fig. 6.8.

Table 6.5 Multivariate linear regression model between first differences of yield (kg/ha) and climate variables during 1992–2010 for early crop of tea

Source	Estimate	Std. error	t-Value	p-Value
Intercept	0.307	6.101	0.050	0.961
ΔCvR_1	1.837	0.608	3.021	0.012
ΔCvR_2	−1.719	0.728	−2.361	0.038
ΔRD_1	19.458	2.446	7.956	<0.0001
ΔTM_1	109.137	16.095	6.781	<0.0001
ΔTM_2	−10.775	14.697	−6.857	<0.0001
$\Delta CvTM_1$	15.015	2.941	5.106	0.000
$\Delta CvTM_2$	12.999	2.604	4.991	0.000

$R^2 = 0.944$, Adjusted $R^2 = 0.908$, F = < 0.0001

[R= total rainfall (mm), RD= number of rainy days (days), TM= mean temperature (°C), Cv= intra-seasonal variability (%); 1 and 2 denote winter and pre-monsoons season respectively]

To estimate the role of individual climate variable on observed yield trend during the study period 1992–2010, the trends of climate variables were multiplied by the yield responses computed in Table 6.5 and the results are presented in Table 6.6. These impacts reflect only the climatic influences, which were captured by the empirical model.

Table 6.6 Observed trends in climatic parameters and their estimated impact on yield of early crop (1992–2010). Observed yield trend during 1992–2010 was −1.45 kg/ha/yr

Variable	Trend	Estimated impact (kg/ha/yr)	% impact
ΔCvR_1	0.009	0.18 ± 0.06	12.55 ± 0.48
ΔCvR_2	−0.316	0.54 ± 0.23	37.45 ± 0.61
ΔRD_1	−0.325	−6.32 ± 0.79	−436.12 ± 0.18
ΔTM_1	0.068	7.42 ± 1.09	511.82 ± 0.21
ΔTM_2	0.032	−3.22 ± 0.47	−222.40 ± 0.21
$\Delta CvTM_1$	−0.002	−0.03 ± 0.01	−2.07 ± 0.28
$\Delta CvTM_2$	−0.041	−0.53 ± 0.11	−36.76 ± 0.29

The results emphasized the significant positive impact of increase in winter mean temperature during 1992–2010 by 0.068°C/yr on yield of early crop by 7.42±1.09 kg/ha/yr. On the other hand, negative impact due to decrease of RD_1 and increase in TM_2 during 1992–2010 on yield was −6.32±0.79 kg/ha/yr and 3.22±0.47 kg/ha/yr respectively (Table 6.5). The estimated impact due to observed variability of winter and pre-monsoon rainfall during 1992–2010 on yield of early crop was positive. Similarly, deceased variability of

winter and pre-monsoon temperature on yield trend during the study period was negative (Table 6.5).

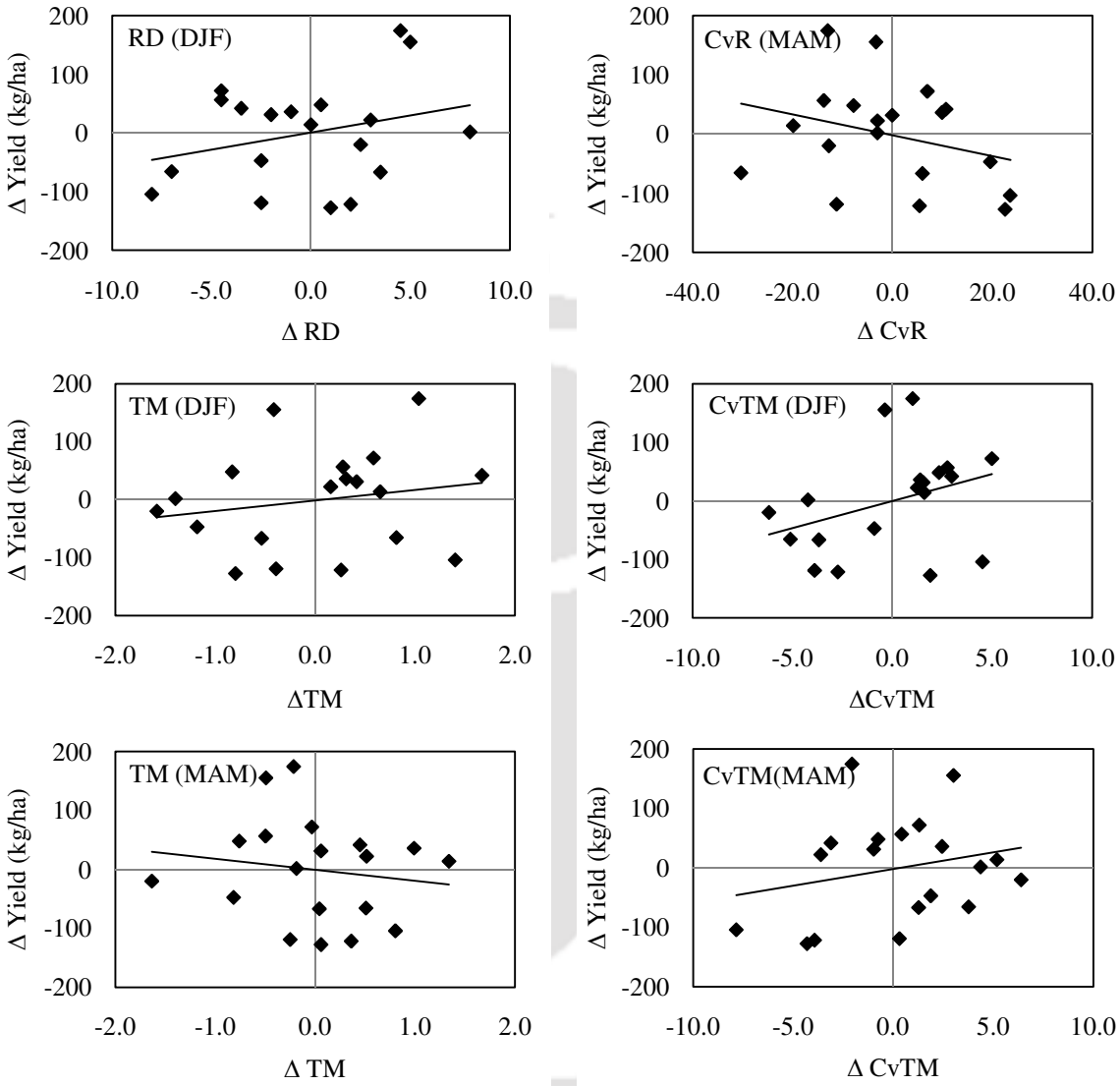

Fig. 6.8 Scatter plots of change in tea yield (early crop) vs. change in climatic parameters

6.4.2.2 Impact on main crop

The results of multivariate regression between the first differences of yield of main crop and climatic variables are presented in Table 6.7. In case of main crop, statistically significant negative yield responses to number of rainy-days (ΔRD_3) during monsoon season and sunshine hours (ΔSSH_1) during winter season was observed. The impact of pre-monsoon rainfall (ΔR_2) and variability of number of rainy-days ($\Delta CvRD_2$) to the yield

trend was positive. Statistically significant positive yield responses to mean temperature and its variability during monsoon season were also observed. These variables together explained at least 84% of the yield variance during 1991–2010. The relationship between individual climate variable and yield changes of main crop are shown in Fig. 6.9.

Table 6.7 Multivariate linear regression model between first differences of yield (kg/ha) and climatic conditions during 1992–2010 for main crop of tea

Source	Estimate	Std. error	t-Value	p-Value
Intercept	−3.759	13.276	−0.283	0.783
ΔR_2	0.477	0.105	4.552	0.001
ΔR_3	0.226	0.113	2.005	0.073
ΔRD_3	−10.619	2.499	−4.250	0.002
$\Delta CvRD_1$	2.752	1.410	1.952	0.079
$\Delta CvRD_2$	5.804	1.595	3.639	0.005
ΔTM_3	99.234	41.500	2.391	0.038
$\Delta CvTM_3$	27.586	13.622	2.025	0.070
ΔSSH_1	−70.528	22.023	−3.202	0.009

$R^2 = 0.836$, Adjusted $R^2 = 0.705$, $F = 0.004$

[R= total rainfall (mm), RD= number of rainy days (days), TM= mean temperature (°C), SSH= sunshine duration (hr), Cv= intra-seasonal variability (%); 1, 2 and 3 denote winter, pre-monsoon and monsoon seasons respectively]

The impact of individual climate variable on observed yield trend of main crop during 1992–2010 was assessed and the results are presented in Table 6.8. It has been observed that recent decreases in monsoon season rainfall (10.63 mm/yr) and increases in number of rainy days (0.13 day/yr) exerted a negative influence on tea yield (main crop). The estimated negative impact of monsoon season rainfall and that of number of rainy days on tea yield was 48.26±2.49% and 27.27±1.17%, respectively (Table 6.8). The positive impact of increased monsoon season mean temperature (0.018°C/yr) during 1992-2010 on observed yield trend was positive (35.84 ± 2.08%). The estimated impact due to increase of pre-monsoon rainfall (ΔR_2) on yield trend was positive (26.1±1.10%), whereas, its distribution ($\Delta CvRD_2$), which exhibited an increasing trend during 1991-2010, showed a negative yield impact (−11.18±1.37%).

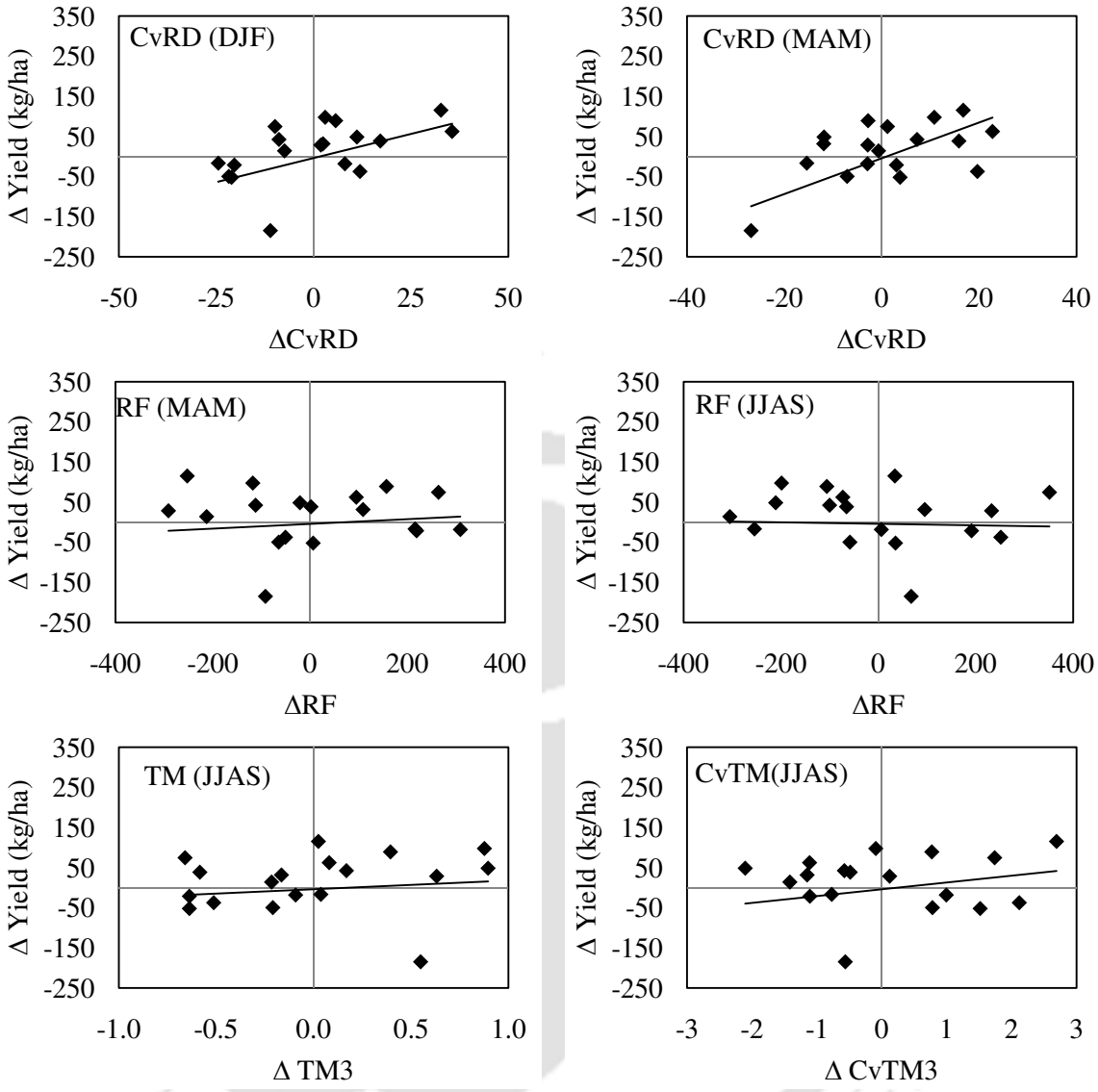

Fig. 6.9 Scatter plots of change in tea yield (main crop) vs. change in climatic parameters during 1991–2010

On the contrary, impact of increasing trend of winter rainfall distribution (($\Delta CvRD_1$) on main crop yield was found to be positive (Table 6.8). Correlation analysis showed that the relation between main crop yield and number of rainy days during February was positive and significant (0.661) while it was negative during January. Consequently, increased variability of rainfall distribution ($\Delta CvRD_1$) (higher number of rainy days in February and less in January) during winter should lead to an increase in main crop yield, which was observed in the present study (Table 6.7).

Table 6.8 Observed trends in climatic parameters and their estimated impact on yield of main crop (1992–2010). Observed yield trend during 1992–2010 was –4.984 kg/ha/yr.

Source	Trend	Estimated impact (kg/ha/yr)	% impact
ΔR_2	2.728	1.30 ± 0.29	26.09 ± 1.10
ΔR_3	–10.630	–2.41 ± 1.20	–48.26 ± 2.49
ΔRD_3	0.128	–1.36 ± 0.32	–27.27 ± 1.17
$\Delta CvRD_1$	0.322	0.89 ± 0.45	17.78 ± 2.55
$\Delta CvRD_2$	–0.096	–0.56 ± 0.15	–11.18 ± 1.37
ΔTM_3	0.018	1.79 ± 0.75	35.84 ± 2.08
$\Delta CvTM_3$	0.001	0.03 ± 0.01	0.55 ± 2.46
ΔSSH_1	–0.014	0.99 ± 0.31	19.81 ± 1.56

Decrease of sunshine duration during winter season was found to show a positive impact (Table 6.8) on main crop yield (19.8±1.56%) possibly due to its role in decreasing diurnal temperature range (DTR) during winter season. Mean maximum temperature, DTR and sunshine duration during winter season had shown negative correlation with main crop yield during 1991–2010.

6.4.2.3 Impact on late crop

The regression analysis results for late crop and climatic parameters are shown in Table 6.9. Statistically significant positive yield responses to post-monsoon rainfall (ΔR_4), temperature (ΔTM_4) and sunshine hours (ΔSSH_4) was observed during 1991–2010.

Table 6.9 Multivariate linear regression model between first differences of yield (kg/ha) and climatic conditions during 1992–2010 for late crop of tea

Source	Estimate	Std. error	t-Value	p-Value
Intercept	1.812	5.281	0.343	0.737
ΔR_4	0.422	0.096	4.371	0.001
$\Delta CvRD_4$	–1.220	0.253	–4.820	0.000
ΔTM_3	101.107	22.618	4.470	0.001
ΔTM_4	23.191	9.918	2.338	0.038
ΔSSH_3	–21.316	10.628	–2.006	0.068
ΔSSH_4	74.054	9.677	7.653	<0.0001

R^2 = 0.892, Adjusted R^2 = 0.838, F = < 0.0001

[R= total rainfall (mm), RD= number of rainy days (days), TM= mean temperature (°C), SSH= sunshine duration (hr), Cv= intra-seasonal variability (%); 3 and 4 denote monsoon and post-monsoon seasons respectively]

However, yield responses to variability of number of rainy days during post-monsoon ($\Delta CvRD_4$) and sunshine duration during monsoon season (ΔSSH_3) were negative. Except sunshine duration during monsoon (ΔSSH_3), all other parameters were found to be statistically significant at 95% level of confidence. These variables together explained about 89% of the yield variance of late crop during 1991–2010. The relationship between individual climate variable and yield changes of late crop are shown in Fig. 6.10. The estimated impact of individual climatic variables on yield trend of late crop is presented in Table 6.10.

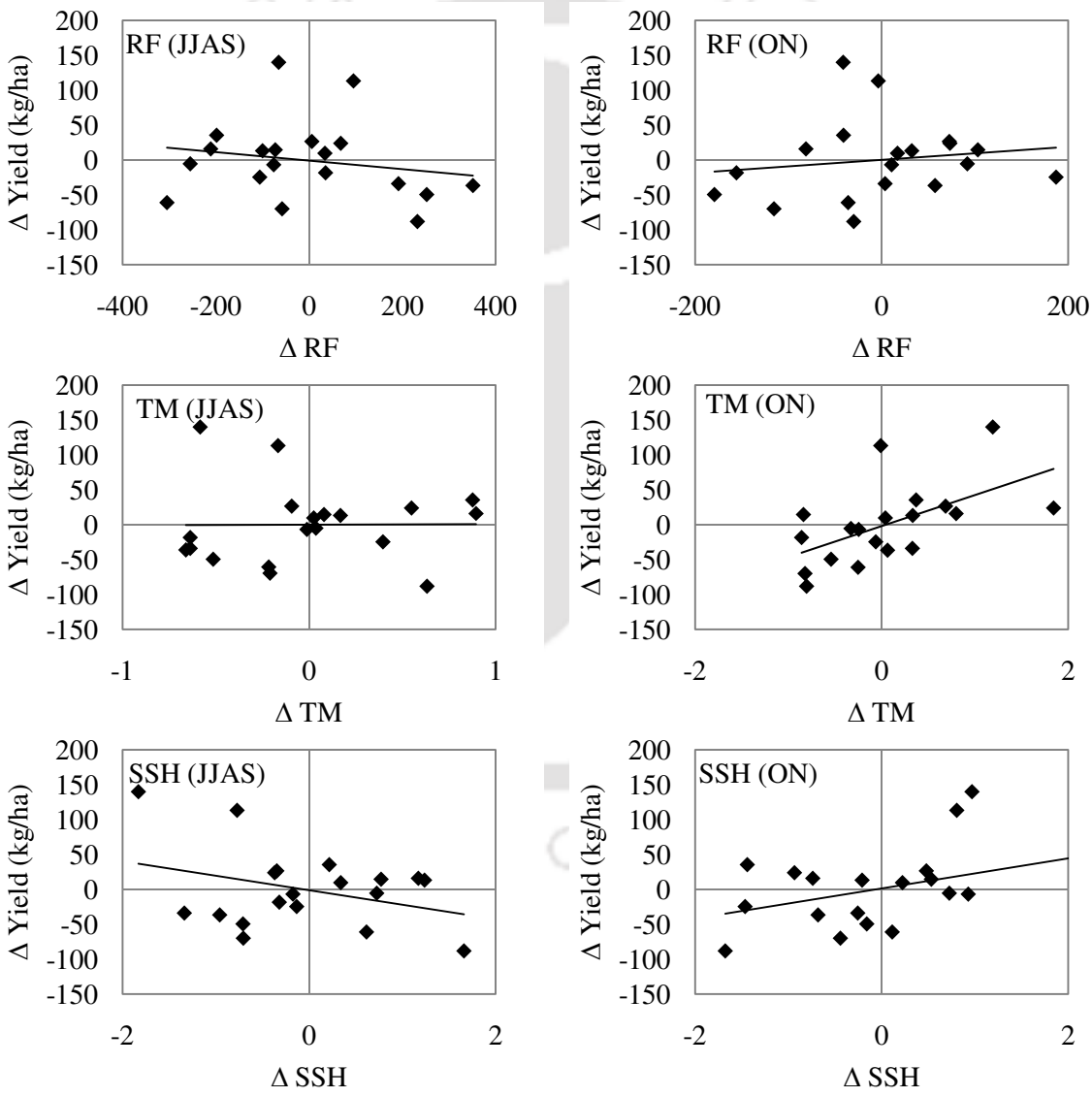

Fig. 6.10 Scatter plots of change in tea yield (late crop) vs. change in climatic parameters during 1991–2010

It has been observed that recent decreases in post-monsoon rainfall and sunshine hours exerted a negative influence on the yield of late crop during the study period. The impact due to decrease of post-monsoon rainfall by 2.9 mm/year during 1992–2010 on yield of late crop was −27.05±1.03%. Decrease in variability of number of rainy days ($CvRD_4$) during post-monsoon season caused the yield to increase by 15.56±0.94% (Table 6.10). On the contrary, the positive impact of recent increases in mean temperature during monsoon and post-monsoon season on observed yield trend was +40.27±1.01% and +10.26±1.93%, respectively.

Table 6.10 Observed trends in climatic parameters and their estimated impact on yield of late crop (1992–2010). Observed yield trend during 1992–2010 was 4.519 kg/ha/yr.

Source	Trend	Estimated impact (kg/ha/yr)	% impact
ΔR_4	−2.899	−1.22 ± 0.28	−27.05 ± 1.03
$\Delta CvRD_4$	−0.578	0.71 ± 0.15	15.56 ± 0.94
ΔTM_3	0.018	1.82 ± 0.41	40.27 ± 1.01
ΔTM_4	0.020	0.46 ± 0.20	10.26 ± 1.93
ΔSSH_3	−0.043	0.92 ± 0.46	20.28 ± 2.25
ΔSSH_4	−0.014	−1.04 ± 0.14	−22.94 ± 0.59

Correlation analysis indicated that both rainfall and number of rainy days during October was negatively correlated with yield (late crop) while this relationship was positive during November. Total number of rainy-days during post-monsoon season was 8 (6 in October and 2 in November) during the study period. This indicated that reducing rainfall variability (more number of rainy days in November and less in October) will have a positive impact on yield of late crop.

6.4.3 Projected impact of climate change on tea productivity

The responses of tea yield to projected changes in climate variables (mean and variability of mean air temperature, rainfall amount, rainfall distribution and sunshine duration) were assessed by developing yield predictive models utilizing 20 years (1991-2010) monthly yield and weather data. Indeed, the main goal of this study was to quantify the sensitivity of tea crop to expected changes in mean and variability of major climate variables, which may provide a basis for prioritizing adaptation strategies in tea sector in near future.

6.4.3.1 Impact on early crop

The predictive model developed by regressing actual yield of early crop and climatic parameters is shown in Table 6.11 and Fig 6.9. The model has a R^2 value of 0.951. Number of rainy days and mean temperature during winter (RD_1 and TM_1) and mean temperature during pre-monsoon (TM_2) are the potent climate variables for determining future yield variability of tea during early season and all the three parameters are significant at 99% level of confidence (Table 6.11).

Table 6.11 Predictive model for tea yield (early crop) developed from stepwise multiple regressions relating tea yield to climatic variables during 1991–2010

Source	Estimate	Std. error	t-Value	p-Value
Intercept	223.127	250.535	0.891	0.391
CvR_1	2.096	0.586	3.578	0.004
CvR_2	−1.617	0.724	−2.233	0.045
RD_1	21.424	1.897	11.291	<0.0001
TM_1	124.278	16.279	7.634	<0.0001
TM_2	−106.920	15.257	−7.008	<0.0001
$CvTM_1$	11.909	2.703	4.407	0.001
$CvTM_2$	13.421	2.504	5.360	0.000

$R^2 = 0.951$, Adjusted $R^2 = 0.923$, $F = < 0.0001$

Thus the predictive model for early crop is

$$\hat{Y}_e = 223.1 + 2.0CvR_1 - 1.6CvR_2 + 21.4RD_1 + 124.3TM_1 + 11.9CvTM_1 - 106.9TM_2 + 13.4CvTM_2$$

[$\hat{Y}_e$ = predicted yield (kg/ha) of early crop, R= total rainfall (mm), RD= number of rainy days (days), TM= mean temperature (°C), Cv= intra-seasonal variability (%); 1 and 2 denote winter and pre-monsoons season respectively]

The increase in number of rainy-days and mean temperature are the only important climatic factors associated with the early crop, the increase in rainy-days and temperature being associated with an increase yield. The yield of early crop is likely to be impacted positively under the combined climate change scenario considered (−10% CvR_1, +5% CvR_2, −20% RD_1, +0.75°C TM_1, 0.5°C TM_2, +10% $CvTM_1$ and +10% $CvTM_2$) for the study area. The magnitude of increase in yield of early crop is about 9% over the base yield for this scenario. Keeping other variables constant at baseline level, decrease of rainy-days

by one day, decreases tea yield by 10% over the base yield. Winter warming, particularly at night is beneficial but warming during pre-monsoon months is found to be harmful for yield of early crop. Increase in winter mean temperature by 0.5°C and 1.0°C over baseline, the yield increased by 29% and 57% over base yield respectively. On the contrary, for every 0.5°C increase in pre-monsoon mean temperature, the resultant yield decrease is 25%. The relationship between intra-seasonal variability and yield is negative for CvR_2 and positive for CvR_1, TM_1 and TM_2, albeit to a lesser extent.

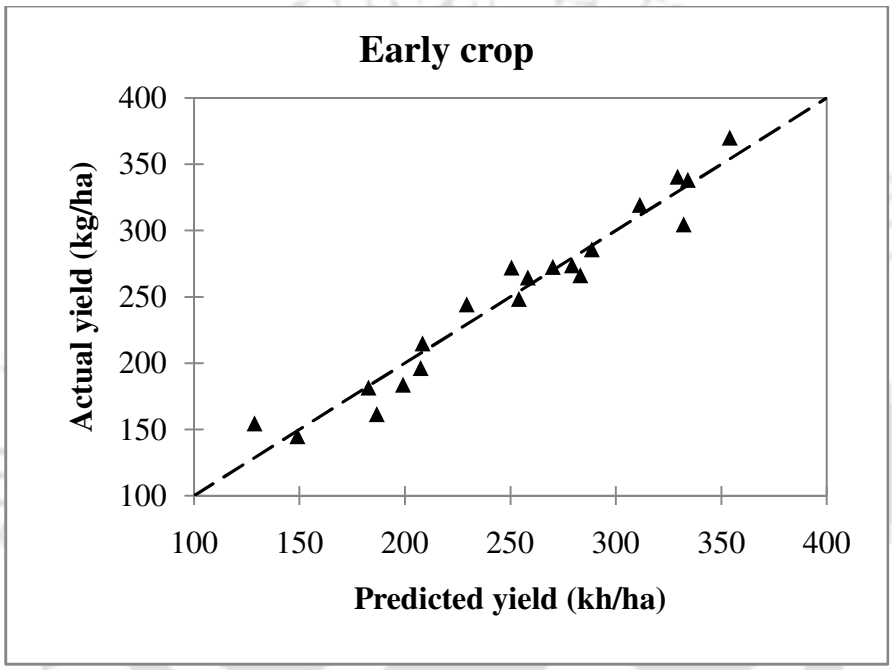

Fig. 6.11 Yield predictive model for early crop of tea

6.4.3.2 Impact on main crop

The yield predictive model developed for main crop of tea is shown in Table 6.12 and Fig. 6.10. Rainfall and its variability of distribution during pre-monsoon (R_2 and $CvRD_2$), total rainfall and rainy days during monsoon (R_3 and RD_3), and sunshine duration during winter, pre-monsoon and monsoon seasons (SSH_1, SSH_2 and SSH_3) are the important factors for predicting future yield of tea during main season (June-September).

Except RD_3, all other variables were significant at 95% level of confidence (Table 6.12). For the over-all climate change scenario considered (−10% R_2, +5% R_3, −10% RD_3, +10% $CvRD_2$, −10% SSH_1, −15% SSH_2 and −10% SSH_3), the yield of main crop is likely to

increase by about 13% over the base yield during 2030s. Decrease in pre-monsoon rainfall (R_2) by 10% showed a negative impact of 2% over base yield. If the intra-seasonal variability of rainy-days during pre-monsoon season ($CvRD_2$) is increased by 10%, yield increases by 1%. Under the scenario of 5% increase in rainfall (R_3) and 10% decrease in number of rainy-days (RD_3) during monsoon, a positive yield impact of 5% was observed.

Table 6.12 Predictive model for tea yield (main crop) developed from stepwise multiple regressions relating yield to climatic variables during 1991–2010

Source	Estimate	Std. error	t-Value	p-Value
Intercept	828.341	252.000	3.267	0.007
R_2	0.491	0.123	3.979	0.002
R_3	0.451	0.123	3.660	0.003
RD_3	−4.026	2.604	−1.546	0.148
$CvRD_2$	7.145	1.728	4.136	0.001
SSH_1	−144.283	28.355	−5.088	0.000
SSH_2	−58.704	21.731	−2.701	0.019
SSH_3	153.885	30.874	4.984	0.000

$R^2 = 0.820$, Adjusted $R^2 = 0.715$, $F = 0.001$

Thus the predictive model for main crop is

$$\hat{Y}_m = 828.3 + 0.49R_2 + 0.45R_3 - 4.0RD_3 + 7.1CvRD_2 - 144.3SH_1 - 58.7SH_2 + 153.9SH_3$$

[$\hat{Y}_m$ = predicted yield (kg/ha) of main crop, R= total rainfall (mm), RD= number of rainy days (days), TM= mean temperature (°C), SSH= sunshine duration (hr), Cv= intra-seasonal variability (%); 1, 2 and 3 denote winter, pre-monsoon and monsoon seasons respectively]

When only number of rainy-days during monsoon was decreased by 20% over the baseline, relative yield increased by 5%. Negative correlation of main crop yield with number of rainy days (r= −0.297) and relative humidity (r= −0.266) and positive correlation with sunshine duration (r = 0.418) supports this observation. This result indicated that reduction of number of rainy-days without reducing the quantum of rainfall during monsoon season is beneficial for yield of main crop. This is because more rainy days during monsoon season generally make the tea bushes susceptible for attack by pests and diseases due to increased cloudiness, humidity and excessive wetness. Similarly, more day-time rain will invariably reduce the sunshine hour required for photosynthesis and vegetative growth.

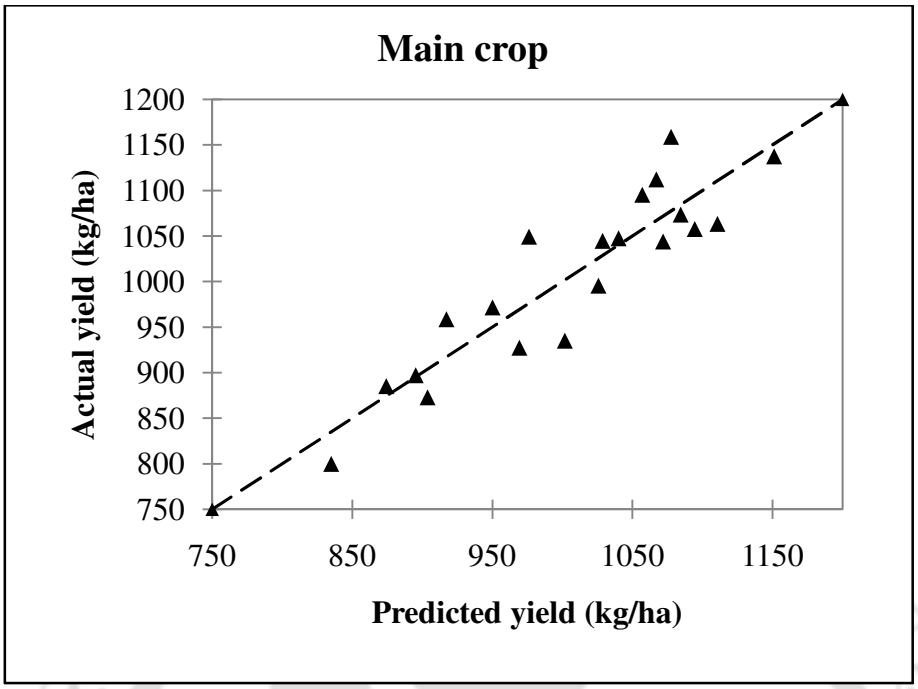

Fig. 6.12 Yield predictive model for main crop of tea

6.4.3.3 Impact on late crop

The predictive model developed for late crop (R^2= 0.811) indicated that all the model parameters are significant at 5% level (Table 6.13 and Fig. 6.11). Yield of late crop is likely to be increased by 9% over the base yield under the over-all climate scenario (+5% R_4, +10% $CvRD_4$, +0.5°C TM_3, −10% SSH_3 and −5% SSH_4) considered for 2030s at current level of management. With improved management and technology, an increase of late crop yield is 19% over base yield in 2030s for the combined climate change scenario considered. Mean temperature during monsoon (TM_3) and sunshine duration during post-monsoon (SSH_4) season were the two most important variables for this predicted yield increase.

An increase of TM_3 by 0.5°C increases yield by 12% and decrease of SSH_4 by 10% over baseline scenario reduces yield by 10%. More sunshine hours during post-monsoon will increase the mean temperature, which may delay the onset date for winter dormancy in tea shoots. This situation may allow the grower to have an extended period of harvest. When post-monsoon rainfall alone is increased by 10% over the baseline, the resultant yield

increase was only 2%. The positive role of decreased rainfall variability has also been observed in recent yield trend (Table 6.10).

Table 6.13 Predictive model for tea yield (late crop) developed from stepwise multiple regressions relating yield to climatic variables during 1991–2010

Source	Estimate	Std. error	t-Value	p-Value
Intercept	−8621.878	2045.376	4.21	0.001
R_4	0.531	0.119	4.473	0.001
$CvRD_4$	−1.424	0.337	−4.232	0.001
TM_3	105.387	25.894	4.070	0.001
SSH_3	−28.176	10.817	−2.605	0.022
SSH_4	72.192	12.788	5.645	<0.0001
Time	2.858	1.101	2.595	0.0222

$R^2 = 0.811$, Adjusted $R^2 = 0.723$, $F = 0.000$

Thus the predictive model for late crop is

$$\hat{Y}_l = -8621.9 + 0.53R_4 - 1.4CvRD_4 + 105.4TM_3 - 28.2SSH_3 + 72.2SSH_4 + 2.9Time$$

[$\hat{Y}_l$ = predicted yield (kg/ha) of late crop, R= total rainfall (mm), RD= number of rainy days (days), TM= mean temperature (°C), SSH= sunshine duration (hr), Cv= intra-seasonal variability (%); 3 and 4 denote monsoon and post-monsoon seasons respectively]

These findings indicated that the adaptation strategies related to water management will be more effective in November considering the positive impact of warming on yield during this period. Air temperature during post-monsoon season was found to correlate positively with late crop yield (r= 0.335 for maximum temperature and r= 0.321 for minimum temperature). The influence of non-climatic factors (clones, fertilizers, pesticides, irrigation etc) on yield seems to have played a prominent role only towards the end of the plucking season. Irrigation during November/December coupled with fertilizer application during late September with available soil moisture from monsoon rain will invariably increase yield of late crop. A major portion of nutrients applied during the main cropping period get washed away due to leaching / runoff from high and intense monsoon rainfall.

It is observed that the influence of climate parameters particularly rainfall distribution and mean temperature during winter season is more sensitive for the yield of early crop of tea – the increase in number of rainy days and mean temperature being associated with an

increase in yield. These two parameters during post-monsoon season are also significant in determining yield of late crop.

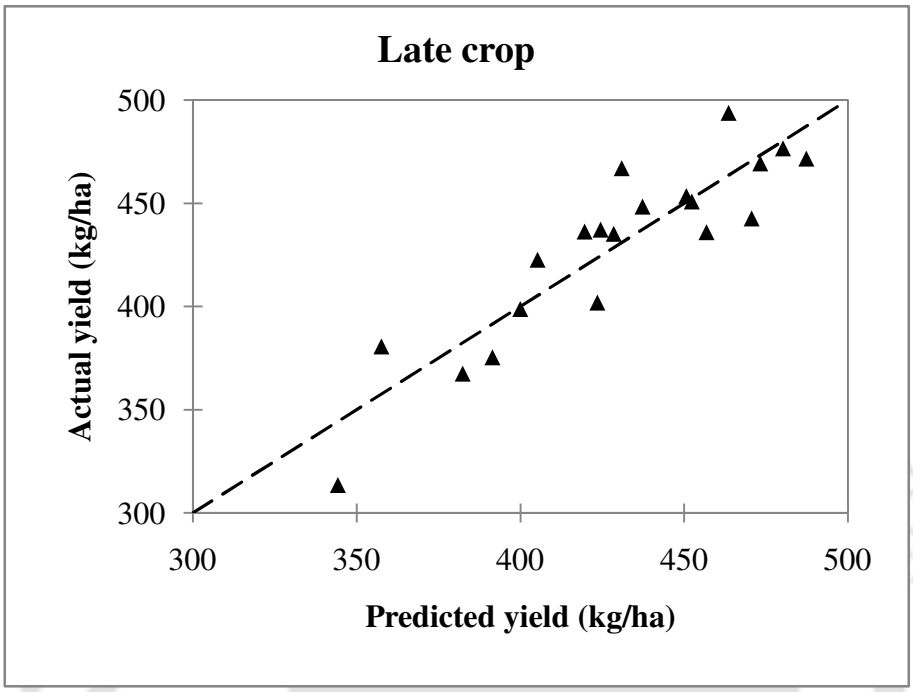

Fig. 6.13 Yield predictive model for late crop of tea

In the Brahmaputra valley, tea bushes remain dormant during winter season. Barua (1969) stated that winter dormancy sets in tea shoots when the day length falls below 11h 10m duration and this duration lasts for at least 6 weeks. Low temperature and day length apparently interacts in inducing this dormancy but their respective roles are not clear (Ghosh Hazra 2001). Tandon (1982) reported that the day length does not affect shoot extension when the nights are cool (10°C), but growth rate is depressed by short days (11 h) when nights are warm (20°C). Thus, low response to day length when nights are cool suggests that the yield depression during winter months is more likely to be the result of cold night temperatures than day length. This suggests, warming will reduce the dormancy period during November to March resulting in higher yield during the early part of the season in the study area. But this positive effect of warmer winter on the yield of early crop or warmer post-monsoon on late crop yield will largely be determined by the amount of rainfall received during these two seasons.

With adaptation intervention, particularly by providing 2-3 light irrigation by harvesting water in time of excess rainfall (monsoon) only in un-pruned tea bushes during February may help to enhance positive effect of winter warming on early crop. Similarly light irrigation during mid-November is likely to increase the yield in late crop. Another important adaptation strategy that may be suggested from this study is to grow drought tolerant cultivars or a basket of cultivars in each section to stabilize the productivity of early and late crops. Moreover, mulching which is an important technique for reducing profile water depletion can be adopted particularly in the small tea holdings. Mulching can ideally be done towards the end of monsoon season with Guatemala grass, tea prunings, shade loppings (Ghosh Hajra 2001) and other locally available plant materials particularly in light textured soils. The major conclusion from this study is the impact of climate change and its variability on tea yields under the prevailing agro-climate of upper Brahmaputra valley is likely to be positive in the near future.

Chapter 7

Summary and Conclusions

The work embodied in this thesis attempted to assess the state of climate change in the Brahmaputra valley and consequent implications on productivity of two important crops – rice and tea grown extensively in the study area. At first, considering that the impact of climate change in the study area had not been comprehensively investigated based on measured variables earlier, the trends and fluctuations of the major climate variables in the valley were assessed following suitable statistical techniques. Following this, a quantitative assessment of the impact of observed as well as projected climate change on yield of rice and tea was carried out in the study area within the Brahmaputra valley through the use of established models. The results obtained with respect to different objectives have been briefly summarized in this chapter followed by major conclusions drawn while identifying scope of future research.

7.1 Summary

7.1.1 Trends and fluctuations of rainfall, temperature and sunshine duration

7.1.1.1 Trends of rainfall

Monthly rainfall data, spanning up to 110 years were utilized for trend analysis at different spatial and temporal scales over the Brahmaputra valley. Short-term fluctuations at decadal scale along with frequencies of occurrence of excess and deficient years were identified. Changes in daily rainfall extremes were studied for better understanding the trends.

Annual as well as monsoon rainfall in the Brahmaputra valley showed a weak decreasing trend during the last 110 years with large spatial and temporal variations. These decreasing trends of rainfall in the eastern part of the valley were statistically significant. Significant decreasing trend of monsoon rainfall during the recent 30-year period was due to significant decrease of July and September rainfall and this trend was found to be consistent at different spatial scales. In the last decade (2001–2010) in particular, monsoon rainfall exhibited significant negative deviation from the normal due to three deficient years and absence of excess rainfall years. On the contrary, contribution of pre-monsoon

and post-monsoon rainfall to annual total in the Brahmaputra valley increased during the recent 30-year period. Quantum of pre-monsoon rainfall increased due to significant increase of April rainfall in the western part of the valley whereas quantum of post-monsoon rainfall increased because of increasing tendency of October rainfall all over the valley. Winter rainfall in the valley decreased during the last 30-years due to significant decrease of December rainfall in the eastern and central part.

The threshold based indices (R75 mm, R100 mm and R125 mm) did not exhibit any trend during the last 55 years over the Brahmaputra valley as a whole. However, during 1981–2010, trends of R75 mm and R125 mm during monsoon were negative and the trend of R75 mm during pre-monsoon season was positive, although relatively smaller in magnitudes. The absolute index, Rx1day showed positive trend in the Brahmaputra valley due to its increasing trend mainly in the western part. During the recent 30-year period, trends of Rx1day during pre-monsoon and post-monsoon seasons were positive while it was negative in the monsoon season. Trend of average rainfall during rainy days was positive during pre- and post-monsoon seasons and negative during monsoon season and were spatially coherent. The trends of percentile based indices of rainfall were less prominent during 1955–2010 compared to that of the last three decades in the Brahmaputra valley taken as a whole. During 1981–2010, the fractional contribution of rainfall from extremely wet (R99p), very wet (R95p) and moderate wet (R75p) days to pre- and post-monsoon rainfall totals had increased, while during monsoon season such contribution had decreased.

7.1.1.2 Trends of temperature

Trend analysis of temperature was based on the monthly maximum and minimum temperature data series for the period 1951–2010. Trends of extreme temperature indices were based on 40 years of daily data of four stations. As temperature showed broad spatial coherence on horizontal scale, trend analysis was performed on the spatially averaged data for the Brahmaputra valley taken as a whole.

Annual mean temperature was found to increase significantly due to the rise of both maximum and minimum temperature during 1951–2010. Maximum increase was noticed

in post-monsoon followed by winter seasons. Except for April, all the other months exhibited rising tendencies with statistically significant trends during May to August and during October to December. The accelerated warming observed during the recent three decades in the Brahmaputra valley was 1.6 times higher than the all-India average. Mean maximum temperature increased significantly during monsoon and post-monsoon seasons while during pre-monsoon season, a relatively cooling trend was observed due to statistically significant decrease maximum temperature in April. Among the two climate normal periods, the rate of increase in maximum temperature was 3 times higher during the recent 30 year period compared to that of the period of 1951–1980. Significant increase of annual mean minimum temperature in the valley was mainly due to its accelerated warming during the recent 30-year period during all seasons. Rate of increase of annual mean minimum temperature was 1.5 times higher than that in case of mean maximum temperature for the recent three decades.

Changes in daily extremes related to minimum temperature (TNx, TNn, TN90p and TN10p) were larger than those related to maximum temperature (TXx, TXn, TX90p and TX10p) over the Brahmaputra valley during 1971-2010. All the frequency indices of hot events (above 90^{th} percentile) showed increasing trends while that of the cold events (below 10^{th} percentile) showed decreasing trends. Increase of hot day frequencies (TX90p) during post-monsoon and winter seasons was statistically significant. Significant fall in TXn was observed during pre-monsoon season. Increase in frequencies of hot nights and decrease in frequencies of cold nights during all the seasons was statistically significant. Annual number of days with maximum temperature above 35°C and number of nights above 25°C increased significantly while the number of nights below 10°C decreased significantly. Due to higher magnitudes of nighttime indices compared to those of daytime indices, the diurnal temperature range in the Brahmaputra valley decreased significantly.

7.1.1.3 Trends of sunshine duration

Mean bright sunshine duration in the Brahmaputra valley decreased by 0.33 hr/decade during 1971–2010 with prominent trend since 1990. Maximum decrease was noticed during pre-monsoon season followed by winter, monsoon and post-monsoon seasons. Except in September, which was free from any trend, decreasing trend of sunshine duration

was observed in all the months, with significant values during January to June, August and December in the Brahmaputra valley. Spatially, maximum decrease was observed during winter season at Guwahati and Tezpur of central part; pre-monsoon at Jorhat and post-monsoon at Dibrugarh – both located in the eastern part of the Brahmaputra valley.

7.1.2 Impact of climate change on rice productivity

Quantitative relationship between rice yields and climate variables collected between 1985 and 2010 were developed to assess the impact of climate change (mean and intra-seasonal variability) on the observed yield trend. Rice yield under projected changes in climate was assessed using CERES-Rice dynamic crop simulation model. The model was calibrated and validated utilizing five years experimental data (secondary) on winter rice variety *Ranjit*, conducted under the agroclimatic conditions of upper Brahmaputra valley before running the model for different climate change scenarios.

7.1.2.1 Observed impact on rice

Multivariate regression analysis between first difference of historical rice yield and first differences of climatic variables showed number of rainy days during reproductive phase (ΔRD_{Oct}), minimum temperature (ΔTN_{JJAS}) and sunshine duration (ΔSSH_{JJAS}) during vegetative phase of rice were the major variables responsible for the observed yield trend of during 1986–2010. Positive yield impact (41.54±4.46%) due to rise in minimum temperature during vegetative phase and negative yield impact (−33.1±3.96%) due to its rise during reproductive phase indicated relative variable temperature preferences over the two growth phases of rice crop. Contrary to this, increased intra-seasonal variability of minimum temperature and rainfall distribution during vegetative phase was found to exert a negative influence on yield. Decrease of rainfall during the study period by 14.2 mm/decade in the reproductive phase (ΔR_{Oct}) exerted a negative influence, whereas reduction in number of rainy days during the same phase exerted a positive impact on yield. Increasing trend of number of rainy days during maturity phase of rice was found to show a negative influence on yield of rice in the study area.

7.1.2.2 Projected impact on rice

In order to evaluate impact of climate change on yield of rice, the CERES-Rice v4.5 crop simulation model was calibrated and validated for its suitability under the sub-tropical humid climate of upper Brahmaputra valley. The genetic coefficients were derived for a popular rice crop variety *Ranjit* and used for model evaluation. Simulation of main physiological events and grain yield by the model were in close agreement to observed ones during calibration and validation process and the model is considered as a reasonably reliable tool for use in climate risk assessment studies in the study area.

The sensitivity experiments of the CERES-Rice model to CO_2 concentration changes indicated that an increase in CO_2 concentration from 450 ppm to 750 ppm led to yield increase but the rate of increase over the baseline was not large (>2%). Temperature sensitivity experiment showed that at current level of CO_2 concentration (390 ppm in 2010), enhancement of ambient temperature by 1°C, 2°C and 3°C, potential rice yield increased over baseline by 3.5%, 7.9% and 11.6% respectively. A decrease of 11.4% of mean relative yield was observed when temperature was enhanced by 7°C over the baseline. The interaction effect of temperature (+1°C, +2°C, +3°C, +4°C, +5°C and +6°C) and atmospheric CO_2 concentration (390, 450, 550, 650 and 750 ppm) indicated that for all the CO_2 levels considered, the CERES-Rice model predicted increasing yield due to an increase in air temperature up to 5°C. Mean relative yield increase was 7% at +1°C temperature and increased linearly up to 13.2% at +5°C followed by a sharp decrease at +6°C temperature. Similarly, for all the temperature increments considered, mean relative yield increased from 6.3% at 390 ppm to 11.4% at 750 ppm of CO_2 concentration. Results also indicated that the positive effect of elevated CO_2 level at 550 ppm to 750 ppm on rice yield was neutralized at temperatures above 5°C. However, positive effect of 450 ppm of CO_2 was neutralized at temperatures above 4°C. Relative yield increase due to increase of growing seasonal rainfall by 10% and 20% over the baseline showed a positive trend while increase of growing season rainfall amount by same magnitudes exhibited negative trend. The sensitivity of the CERES-Rice model to solar radiation showed that for every 1.0 MJ/m^2/day decrement of solar radiation (up to 3.0 MJ/m^2/day) from the baseline, relative

yield decrease was 1%. Solar radiation increment up to 2.0 MJ/m^2/day over baseline level showed an increase (2%) in relative yield.

The CERES-Rice model was run for different climate change scenarios, with combinations of temperature and growing season rainfall, along with a 70 ppm enhanced atmospheric CO_2 concentration over 390 ppm in 2010 and a decrement of −1MJ/m^2/day solar radiation over baseline. In all simulations, CO_2 level and solar radiation level were kept constant. Result showed that with an increase of ambient temperature from 0.5°C to 1.5°C at an increment of 0.5°C increased the yield linearly from 3.0% to 6.2% when growing season rainfall was decreased by 10% whereas yield was lowered down to 3.6% when the rainfall was increased 10% over base yield. An increase of ambient temperature by 1.5°C and decrease of growing season rainfall by 10% showed the maximum yield increase (6.2%). Among different transplanting dates, the relative yield increase was the highest (above 10%) when the crop is transplanted on 9th August in these two climate change scenarios.

Two scenarios illustrated the role of asymmetrical increase of daytime and nighttime temperature on rice yield under constant levels of CO_2 concentration (460 ppm), solar radiation (−1MJ/m^2/day) and rainfall (baseline). Mean relative yield increase was 4.6% when increments of maximum (+0.5°C) and minimum (+1.5°C) temperature were asymmetrical. Under the scenario of 1.0°C increase in maximum temperature and 2.0°C increase minimum temperature, the relative yield increase was 3.3% indicating that an asymmetrical increase of temperature up to a certain level was beneficial for rice crop. Rice yield is also likely to increase marginally (2.1%) in 2040, under the scenario that was built based on the observed trends of solar radiation, temperature and rainfall of the baseline data.

7.1.3 Impact of climate change on tea productivity

7.1.3.1 Observed impact on tea

The observed impact of climate variables on tea yield trends during 1991–2010 was assessed empirically utilizing area-weighted estate level yield data. Multivariate regression analysis of first differences of tea yield and first differences of climatic variables explained 84% (main crop) to 94% (early crop) of yield variance during the study period. Winter

rainfall distribution (rainy days) and mean temperature during winter and pre-monsoon seasons were the key factors for the observed negative yield trend of early crop. The positive influence of winter temperature on yield of early crop was nullified by the decreasing trend of number of rainy-days in winter together with increasing trend of mean temperature during pre-monsoon season, causing a net decrease in yield during the study period. In the case of main crop, the observed yield trend was mainly caused by the decreasing trends of amount of rainfall and number of rainy-days (negative impact) together with the increasing trend of monsoonal mean temperature (positive impact). Decreasing trends of rainfall amount and sunshine duration during post-monsoon season had negative influence while increasing trend of mean temperature during monsoon and post-monsoon season exerted a positive influence on the observed yield trend (positive) of late crop during 1992–2010.

7.1.3.2 Projected impact on tea

Projected impact of climate change on tea yields (early, main and late) was determined by developing statistical crop models based on the observed relationship between current climate (mean and variability) and yields at estate level. Possible influences of non-climatic factors on future yield changes were captured by introducing a time variable in these linear multivariate regression models. Sensitivity of the models was tested for the most likely climate change scenarios for the study area. Yield of early crop is likely to be impacted positively under the combined climate change scenario considered for the study area. The magnitude of increase in yield of early crop is about 9% over the base yield. The rainy-days and mean temperature during winter season were the two main climate variables for the predicted yield increase. Sensitivity analysis showed that increase in winter mean temperature by 0.5°C, increased yield by 29% over the base yield. Yield of early crop is likely to decrease by 10% for every one day decrease in number of rainy-days during winter season from baseline. Likewise, for the over-all climate change scenario considered for 2030s, the yield of main crop is also projected to increase by 13% over the base yield. Under the scenario of 5% increase in rainfall and 10% decrease in number of rainy-days during monsoon, yield of main crop increased by 5% over base yield. In the case of late crop, mean temperature during monsoon, sunshine duration during post-

monsoon and non-climatic factors (management, technology, CO_2 etc) were the most important variables for the projected yield increase of 19% in 2030s. Yield of late crop increased by 12% for an increase of monsoon temperature by 0.5°C over the baseline.

From an analysis of results as summarized above one can arrive at the following conclusions.

7.2 Conclusions

- Climate change is a reality in the study area and impacts have been observed both in short and long term with respect to key identified variables like temperature, rainfall and sunshine hours. The trends and variability are however not necessarily always identical with global and national averages although they are broadly in agreement with generic observations.
- Monsoon rainfall in the Brahmaputra valley exhibited a decreasing trend during the 110 years of assessment primarily due to significant decrease of rainfall in the eastern part of the valley. During the recent 30-year period, monsoon rainfall decreased significantly due to corresponding decrease in July and September rainfall. The valley exhibited spatially coherent tendencies towards relatively drier conditions during monsoon particularly in the last three decades. The last decade was the driest decade since 1901 due to three rain deficient years and absence of excess rainfall year.
- The intensity of monsoon rainfall decreased in the Brahmaputra valley due to decrease of extreme fractions of rainfall, marked by extremely wet, very wet and moderately wet days during the last three decades. Decrease of rainfall fraction due to moderately wet days was particularly significant in the eastern and western parts of the valley.
- Pre-monsoon and post-monsoon seasons showed tendency toward wetter conditions during the most recent 30 years period due to increasing tendency of extreme rainfall events over the entire valley. Increase of rainfall during pre-monsoon was mainly contributed by significant increase of April rainfall only in the western part of the valley. During post-monsoon, October rainfall showed a spatially coherent increasing tendency in the Brahmaputra valley.

- Mean temperature in the Brahmaputra valley increased significantly between 1951 and 2010, especially in post-monsoon and winter seasons, due to increase in both maximum and minimum temperatures. The warming trend in the valley was particularly pronounced in the most recent 30 years period and was 1.6 times higher than the all-India average. During this period, minimum temperature increased at higher rate than that of maximum temperature due to significant decreasing tendency in the annual occurrence of cold nights and a significant increasing tendency in annual occurrence of warm nights. Changes in daily extremes related to minimum temperature (TNx, TNn, TN90p and TN10p) were larger than those related to maximum temperature (TXx, TXn, TX90p and TX10p) over the valley during 1971–2010. This caused a significant decrease in the diurnal temperature range. Significant fall in coldest day temperature during pre-monsoon was due to increasing tendency of rainfall during that season.
- Sunshine duration in the Brahmaputra valley has been decreasing during the last 40 years with an accelerated trend since 1990 affecting the radiation balance. The observed trend of sunshine duration with corresponding increase of aerosol may be responsible in causing the asymmetrical trends in daytime and nighttime temperature indices. Highest decrease of sunshine duration during pre-monsoon season was found to be due to observed increasing trend of rainfall whereas its lowest decrease during post-monsoon might be due to the role of monsoon rainfall in washing away the aerosols.
- Rice yield in the study area was affected by intra-seasonal variability of climate besides the impact of changes in mean climate. The responses of climate variables were different at different growth phases of rice. Estimated impact due to increased minimum temperature during vegetative phase on observed yield trend was positive while its impact during reproductive phase was negative. Rice yield was negatively affected by intra-seasonal variability of both minimum temperature and rainfall distribution during vegetative phase. The yield response due to decrease of rainfall amount during reproductive phase was negative but decrease of number of rainy days during this phase was positive which indicated the positive role of sunshine duration during reproductive phase of rice in the study area.

- At prevailing ambient temperature, relative increase in yield due to changes in rainfall amount, CO_2 concentration and solar radiation during the crop season was small. At current level of CO_2 concentration, with enhancement of ambient temperature up to +3.0°C, rice yield increases linearly over base yield. The CO_2 fertilization effect on rice yield in the study area is reflected only at elevated temperatures. The positive effect of 450 ppm of CO_2 on rice yield is cancelled out at a temperature +4°C over baseline, whereas the positive effect 550 ppm to 750 ppm CO_2 concentration is wiped out at +5°C temperature in the study area – a higher margin compared to other parts of India. Over-all, rice yield is likely to be impacted positively under the projected climate change scenario considered under the sub-tropical humid climate of upper Brahmaputra valley mainly due to the interaction of CO_2 and temperature in the near future.
- Empirical assessment of impact of climate change and variability on observed yield trend of tea indicated that the yield of early crop is most sensitive to rainfall distribution and to mean temperature during winter – the increase in number of rainy days and mean temperature has influenced the increase in yield during the study period. The positive influence of winter warming on yield of early crop was negated by decreased number of rainy-days in winter along with increased mean temperature during pre-monsoon season, causing a net decrease in yield.
- Tea yield during main crop season was highly sensitive to rainfall amount, number of rainy days as well as temperature during monsoon season in addition to the pre-monsoon rainfall. The negative yield trend observed during the study period was caused mainly by negative influences of decreasing trend of monsoon rainfall as well as its distribution, in spite of the positive impact of higher monsoon temperature and pre-monsoon rainfall on main crop yield.
- Tea yield during the late season was controlled by temperature during monsoon, total rainfall and its distribution during post-monsoon and duration of sunshine during monsoon and post-monsoon seasons during the study period. The net gain in yield was determined by the positive impact of increased temperature and decreased sunshine duration during monsoon and decreased rainfall amount as well as sunshine duration during post-monsoon season.

- Empirical assessment of projected impact of climate change scenarios on tea yield is likely to be positive in the coming three decades. Tea yield during early, main and late crop seasons are likely to increase by 9%, 13% and 19% respectively for the combined climate change scenarios considered for the study area. Use of statistical modeling, based on observed relationship between current climate and yields can easily be extrapolated out to the future with different climate change projections in other tea growing areas of the Brahmaputra valley.
- Although the crop models developed for tea in this study can generally be assumed to be robust, uncertainties about future scenarios do exist. Development of climate change scenarios at finer scale may modify the predicted yield levels in the study area. The sensitivity analysis for the possible scenarios of climate change using empirical crop model should be undertaken for assessing the impact of future climate in different tea growing areas of the valley for developing adaptation strategies.
- Impact of climate change on yield of rice and tea in the study area is likely to be consequential to degree of changes in the variables and the scale of adaptation undertaken. While an overall positive implication for both rice and tea productivity is predicted, careful and precise adjustment of timing of transplantation (rice) and selection of appropriate varieties (rice and tea) can lead to enhancement of positive outcomes and neutralization of several potential negative impacts.

7.3 Scope for future research

- Future research interest can be to establish the linkage of weather systems, aerosol, soil moisture feedbacks and other land-use changes when analyzing trends and fluctuations of rainfall and temperature regimes which was not within the scope of this study. Changes or fluctuations in weather pattern and weather system in terms of their area of formation, intensity and life span and area of decay will better address the recent fluctuations in climate regime in the study area.
- Modeling climate change impact on crop productivity involves climate forecasts, crop responses, technological developments and adaptation strategies. Assessment of climate change on rice by CERES-Rice model in the present study considered

only one major rice variety. In order to investigate response of a composite of varieties including more cultivars representing early and medium duration varieties and varieties which farmer actually prefer can be useful. Long-term field experiments, conducted at different locations of the valley with a selected range of cultivars will support modeling with primary data. The genetic coefficients established in this study can be used to examine the sensitivity of the cultivar to future climates in different agro-climatic zones of the Brahmaputra valley. This would facilitate the breeder to prepare for future by tailoring breeding programmes to anticipated changes.

- Some weaknesses in the CERES-rice model simulation in this study were the non-inclusion of effects of pest, diseases and catastrophic events like flooding. Potential impacts of climate change on pest and diseases that will impact rice productivity needs investigation. In order to arrive at realistic assessments of climate-yield interactions, knowledge from several disciplines such as agronomy, soil science, plant physiology, plant protection, agrometeorology and meteorology can be integrated in the CERES-Rice model simulations for a balanced representation of different natural processes.
- Tea estates at different agro-climatic zones having different climatic conditions may yield varied results when the regression models developed in this study is applied. Results obtained for specific clonal, seedling, or mixed plants may respond differently to different climatic parameters. Future research should focus on exploring the phenology of different tea cultivars and their behavior to different climatic conditions based on designed experiments.

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APPENDIX A

Table A.1 Bartlett's test (short-cut) of homogeneity of variance for rainfall

Sl. No.	Station	Bartlett's test (k = 5, n = 22)	
		S^2max/S^2min	α = 0.05
1	Dibrugarh	1.80	3.53
2	Jorhat	1.93	3.53
3	Golaghat	1.83	3.53
4	North Lakhimpur	3.30	3.53
5	Sibsagar	1.86	3.53
6	Tezpur	2.28	3.53
7	Kampur	1.58	3.53
8	Lumding	2.63	3.53
9	Mazbat	1.72	3.53
10	Guwahati	1.69	3.53
11	Dhubri	3.12	3.53
12	Goalpara	2.35	3.53

Table A.2 Bartlett's test (short-cut) of homogeneity of variance for temperature

Sl. No.	Station	Bartlett's test (k = 3, n = 20)		α = 0.05
		S^2max/S^2min		
		Tmax	Tmin	
1	Dibrugarh	2.23	2.71	2.95
2	Jorhat	2.41	1.14	2.95
3	North Lakhimpur	2.81	1.69	2.95
4	Tezpur	2.19	2.44	2.95
5	Guwahati	2.89	2.06	2.95
6	Dhubri	2.25	1.52	2.95

Table A.3 Basic statistics of climatic parameters at different growth phases of rice (*kharif*) in Jorhat during 1985–2010

Period	Tmax (°C)		Tmin (°C)		Tmean (°C)		Total rainfall (mm)		Rainy days (nos)		Sunshine duration (hr)	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Jun	31.7	2.6	24.9	1.5	28.3	1.9	270	31	15	19	4.4	25.8
Jul	31.9	2.2	25.4	1.5	28.7	1.7	379	25	18	14	4.4	23.3
Aug	32.3	2.0	25.5	1.5	28.9	1.5	307	23	15	18	5.0	20.7
Sep	31.4	2.0	24.7	1.8	28.0	2.0	241	38	13	30	4.8	21.0
JJAS	31.8	1.3	25.1	1.2	28.5	1.0	1196	14	62	11	4.7	12.7
Oct	29.8	2.5	21.8	3.8	25.8	2.6	121	69	7	39	5.8	13.1
Nov	27.2	2.5	16.2	4.7	21.7	2.9	20	17	2	72	6.7	12.6

(The period from June to September (JJAS), Oct and Nov correspond to vegetative phase, reproductive and maturity phase respectively, CV= Coefficient of variation in %)

APPENDIX B

RICE GROWTH SIMULATION MODEL (CERES-Rice)

CERES-Rice, a computer model designed at Michigan State University, is one of the models being developed through the International Benchmark Sites for Agrotechnology Transfer (INSBAT) project. The model consists of a series of subroutines with a separate subroutine for each major process (Fig. B.1). Beside this, there are subroutines associated with input and output and for the user-friendly interface. The model uses a standardized system for model inputs and outputs. The input system enables the user to select crop genotypic, weather, soil, and management data appropriate to experiment being simulated. After selection of the appropriate input, the model initializes the necessary variable for growth, water balance, and soil nitrogen dynamics simulation, and displays these parameters for checking before starting simulation. After initializations a daily simulation loop is entered in which first day's weather data is read and then all calculations on water and N balance, crop growth, and development are performed. The model ultimately will estimate yields for rainfed and irrigated rice. It is relatively simple, user-oriented, yet comprehensive, rice model that will be able to predict the growth of different varieties under all agroclimatic condition.

The CERES-Rice model primarily handles

1. Phasic development or duration of growth stages as influenced by plant genetics, weather, and other environmental factors ;
2. Biomass production and partitioning;
3. Root system dynamics; and
4. Effect of soil water deficit and N deficiency on photosynthesis and photosynthate partitioning in the plant system.

1.0 Model inputs

The CERES-Rice model requires these inputs

- Daily weather, at least for the duration of the cropping seasons, including solar radiation, a and minimum air temperatures, and precipitation;

- Soil properties, including single values of drainage, runoff, evaporation and radiation reflection coefficients; values of several depth increments of rooting preference factors; soil water contents at the drained upper limit, lower limit, and saturation; N and organic matter details;
- Initial conditions of soil water content, NO_3 and NH_4 at several depth increments;
- Management practices, such as variety, plant density, sowing depth; planting date, irrigation (frequency and amount) and N fertilization (frequency, type, and amount);
- Latitude of the production area to evaluate day length during the cropping season; and
- Genetic coefficients; thermal time required for the plant to develop from after emergence to end of juvenile stage (P1), rate of photo induction (P2R), optimum photoperiod (P2O), thermal time for grain filling (P5), conversion efficiency from sunlight to assimilates (G1), tillering rate (TR) and grain size (G2).

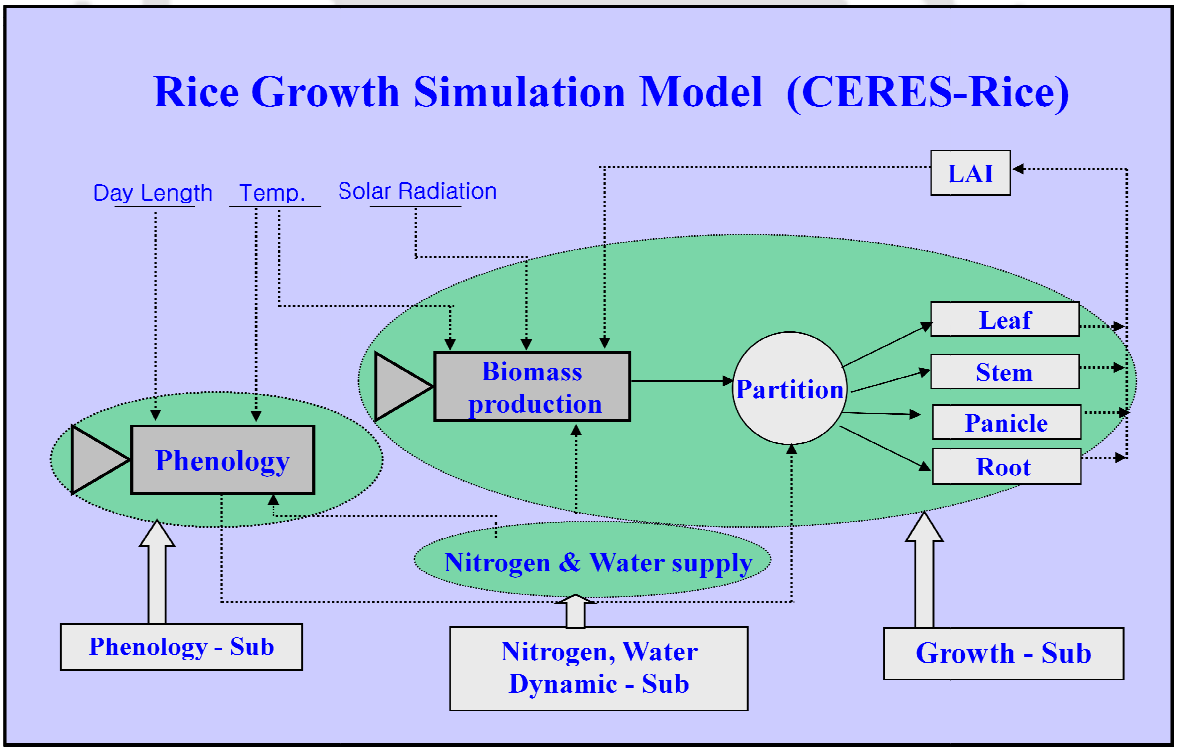

Fig. B.1 Schematic diagram of rice growth simulation model (CERES-Rice) (Cheyglinted et al. 2001)

2.0 Growth and development

2.1 Phasic development

Phasic development in the CERES-Rice model is based on the duration of different growth stages, and is affected primarily by genetic and environmental factors. Growth duration is extremely important in determining potential crop yield (Ritchie and NeSmith 1991). In general, the longer the growth duration period the higher is the yield potential. Prior to germination the primary variable influencing the development rate is soil-water environment, and temperature becomes the primary variable of influence after germination.

The growth stages are numbered 1 through 9: 1 through 5 represent the active aboveground growing stages, 6 through 9 describe other events in the crop cycle. Growth stages and their corresponding descriptions are summarized in Table 1.

Table B.1 Phenological stages of CERES-Rice

Stage No	Event	Plant parts growing
7	Fallow or pre-sowing	
8	Sowing to germination	
9	Germination to emergence	Roots, coleoptiles
1	Juvenile	Roots, leaves
2	Floral induction	Roots, leaves, stems
3	End of leaf growth and heading	Roots, leaves, stems, panicle
4	Anthesis or flowering	Roots, stems, panicle
5	Grain filling	Grain
6	Physiological maturity to harvest	

The duration of each phonological stage makes use of the concept of thermal time or degree day at time k (DDT(k)). DDT(k) is a function of minimum (TEMPMN(k)) and maximum (TEMPMX(k)) air temperatures and temperature threshold (TBASE). The CERES-Rice model assumes that development rates are directly proportional to temperatures between 8 and 32°C. From a series of phytotron studies, the threshold temperature of rice is estimated to be 8°C. When TEMPMN(k) is greater than TBASE and TEMPMX(k) is less than 33°C, DTT(k) is the difference between daily mean temperature (TEMPM(k)) and TBASE. TEMPM(k) is calculated as the average between TEMPMX(k) and TEMPMN(k). That is,

$$TEMPM(k) = ½(TEMPMX(k) + TEMPMN(k)$$

DTT(k)=TEMPM(k)-TBASE, TEMPM>TBASE

If the maximum and minimum temperatures are outside the given range, thermal time is calculated using a different set of relationships. The CERES-Rice model separately calculates phasic development to drive the model through time. Thermal time requirements for each growth stage vary with stage and variety. Photosensitivity of a variety directly affects the thermal time requirement during the induction stage (stage 2). A photoperiod-sensitive variety has a longer thermal time requirement when day length is longer than the optimum photoperiod.

2.2 Biomass production and partitioning

2.2.1 Germination: The germination factor used in the model was derived from the 90% germination curve proposed by Livingston and Haasis (1933). They showed that complete germination of healthy rice seeds occurred between 15 and 37°C. Using a base temperature of 8°C, seed germination requires 45 degree days.

2.2.2 Leaf area and dry matter production: The total leaf area of a rice population is closely related to grain production; physiologically active leaves contribute to the photosynthesis of the plant. As in many models of photosynthesis, the CERES-Rice model adapts Beer's Law to quantify light absorption by the plant community (Yoshida 1981).

$I/I_0=\exp(-K*LAI)$

Where,

I/I_0 = light transmission ratio

LAI = average cumulative total green leaf area per unit of ground area, and

K = foliar absorption coefficient or extinction coefficient (dimensionless)

The photosynthetic rate is expressed as a function of the photosynthetically active radiation (PAR). The percentage of incoming PAR intercepted by the canopy then becomes an exponential function of the leaf area index (LAI). The value of PAR above canopy is assumed to be equal to 50% of the incoming solar radiation. Photosynthesis is expressed mathematically in the model as:

$PCARB = G1 * PAR * (1-e^{(-k*LAI)})$

Where,

PCARB = potential dry matter production in g/m^2 per day;
PAR = photosynthetically active solar radiation in MJ/m^2 per day; and
GI = conversion factor of PAR to dry matter in grams per MJ of intercepted PAR

The actual daily biomass production (CARBO) is usually less than the potential rate (PCARB) because of non-optimal temperature or deficits of water or nitrogen. The equation to calculate CARBO uses the law of limiting concept to reduce PCARB.

CARBO=PCARB* PRFT *MIN (SWDF1, NDEF1)

Where PRFT, SWDF1 and NDEF1 are the temperature, water deficit, and nitrogen deficit factors, respectively, varying between 0 and 1, and min indicates the minimum value of the parenthesis is used.

The temperature reduction effect (PRFT) is dependent on a weighted daytime temperature (T) calculated from maximum and minimum temperatures with optimum value at 26°C and expressed as

$$PRFT = 1 - 0.0025 * (T-16)^2$$

$$T = 0.25 * T_n + 0.75 * T_x$$

Where, PRFT varies between 0 and 1

The water stress reduction factor (SWDF1) is calculated whenever the crop extraction of soil water falls below the potential transpiration rate calculated for the crop. The actual biomass production (CARBO) is then a function of the smallest of the two reduction factors and PCARB. Dry matter accumulation is represented by following equations

$$\delta W_L/\delta t = X_L W^+ - S_L - M_L$$

$$\delta W_S/\delta t = X_S W^+ - S_S - M_S$$

$$\delta W_R/\delta t = X_R W^+ - S_R$$

Where,

W_L = Dry weight of leaf per unit ground area (g/m^2), W_S = Dry weight of stem per unit ground area (g/m^2), W_R = Dry weight of root per unit ground area (g/m^2), t = Time in day, X_L = Fraction of photosynthate partitioned to leaves, M_L= Rate of protein remobilization to seeds from leaves, X_S = Fraction of photosynthate partitioned to stems, S_S = Petiole dry weight senesced per unit time (g/m^2/day), M_S = Rate of protein remobilization to seeds from stems (g/m^2/day), X_R = Fraction of photosynthate partitioned to roots, S_R = Root dry weight senesced per unit time (g/m^2/day), S_L = Leaf dry weight senesced per unit time (g/m^2/day), W^+ = Growth rate of new plant tissues which is a function of photosynthesis.

2.2.3 Genetic coefficients

Crop genetic input data, which explains how the life cycle of a rice cultivar responds to its environment, are not usually available. The genetic coefficients are crucial because they strongly influence the simulation of growth and development of the crop and therefore, these are derived iteratively following Hunt's method (Hunt et al. 1993). This involves describing growth and grain development. Minimum crop data sets are required for these calculation included dates of transplanting, panicle initiation, anthesis, physiological maturity, grain yield, aboveground biomass, grain density and weight, number of grains per spike and maximum leaf area index. The CERES-Rice model uses eight genetic coefficients viz., P1, P2O, P2R, P5, G1, G2, G3, and G4. The first four coefficients are related to phonological development aspects and the last four are related to growth and development aspects of the rice crop. The details of these coefficients are described in Chapter 5 (Table 5.3).

2.3 Root system dynamics

Biomass is partitioned into shoots and roots. The proportion partitioned to roots affects root density and thus the ability of the root system to supply water and nutrients to the shoot. The fraction of assimilates portioned to the roots depends primarily on the growth stage of the crop, declining as the plant matures. However, at all growth stages except stage 5, the fraction partitioned to the roots increases with water deficits or N deficiency.

Total root growth in a day is calculated by the amount of biomass partitioned to the roots. To determine the distribution of roots in the soil, a rooting preference factor that decreases with depth is input for each layer. The preference factor of a layer is reduced when soil water content is below a threshold value.

The potential rate of downward root growth is assumed to be proportionate to the rate of plant development, which is influenced by temperature. The water content of each depth is used to determine the distribution of root growth in the profile. The mass of assimilate portioned to the roots is converted to a root length, assuming a constant proportionality to the root mass and length, to provide estimates of root length density.

2.4 Soil water balance

The effect of soil and plant water deficits on plant growth and yield reduction is calculated by the soil water balance. The soil water balance in CERES-Rice is based on Ritchie's model where the concept of drained upper limit (DUL) and drained lower limit (LL) of the soil is used as the basis of the available soil water (Ritchie 1972, Ritchie 1981a, Ritchie 1981b). The approach is simple water accounting in each layer considered in the soil profile (Ritchie 1998). The water in the upper layer cascades to the lower layers mimicking the process of a series of linear reservoirs. This one-dimensional model computes the daily changes in soil water content by soil layer due to infiltration of rainfall and irrigation, vertical drainage, unsaturated flow, soil evaporation, and root water uptake processes. In the new DSSAT-CSM, soil evaporation, and root water uptake processes were separated out into a soil-plant-atmosphere module (SPAM) to create more flexibility for expanding and maintaining the model (Jones et al. 2003).

2.4.1 Infiltration and runoff

Daily precipitation in mm is entered into the model from weather file. Soil water infiltration during a day is computed by subtracting surface runoff from rainfall that occurs on that day. The SCC (Soil Conservation Service, 1972) Curve Number technique is used to partition rainfall into runoff and infiltration, based on a 'curve number' that attempts to account for texture, slope, and tillage. The modification to this method that was developed by Williams et al. (1984) is used in the model; it accounts for layered soils and soil water content at the time when rainfall occurs. When irrigation is applied, the amount applied is

added to the amount of rainfall for the day to compute infiltration and runoff (Jones et al. 2003).

Infiltration is calculated as the difference of the rainfall/irrigation and runoff. Drainage takes place if the infiltration and the soil water present in the layer exceed its water holding capacity (HOLD). The drainage at the bottom of the profile is the drainage flux of the bottom layer. Upward flow can be caused by root water uptake due to transpiration and soil evaporation. The potential root water extraction depends on the available soil water in the soil profile. Runoff is calculated using the modified USDA-SCS curve number method (Williams 1991). The profile is assumed to be well drained and thus having no interaction with the groundwater. Water content in any layer can increase in response to infiltration of rain, irrigation water, or flow from an adjacent layer. Water content can decrease because of soil evaporation, root absorption, or flow to an adjacent layer. The limits to which water content can increase or decrease for each layer are input as the lower limit of plant water availability, the field-drained upper limit, and the field-saturated water content (Jones et al. 2003).

Drainage of liquid water through the profile is first calculated based on an overall soil drainage parameter assumed to be constant with depth. Drainage is calculated as a function of water content above the drained upper limit (DUL). The amount of water passing through any layer is then compared with the saturated hydraulic conductivity of that layer. If the saturated hydraulic conductivity of any layer is less than computed vertical drainage through that layer, actual drainage is limited to the conductivity value, and water accumulates above that layer. This feature allows the model to simulate poorly drained soils and perched water table.

CERES-Rice adds to this the simulated effect of the presence of a bund. Floodwater depth, runoff (when floodwater depth exceeds bund height) and evaporation from floodwater are simulated. The model also simulates the effect of changes in percolation rate and bulk density associated with puddling and the reversion to a non-puddled state.

Evaporation of water from the soil surface and root water uptake (transpiration) from each layer are computed in the SPAM and communicated to this soil water balance module.

Each day, the soil water content of each layer is updated by adding or subtracting daily flows of water to or from the layer due to each process.

2.5 Soil-plant-atmosphere module

This module computes daily soil evaporation and plant transpiration. This module brings together soil, plant, and atmosphere inputs and computes light interception by the canopy, potential evapotranspiration (ET) as well as actual soil evaporation and plant transpiration (Jones et al. 2003). It also computes the root water uptake of each soil layer. The daily weather values as well as all soil properties and current soil water content, by layer, are required as input. In addition, leaf area index (LAI) and root length density for each layer are needed.

The module first computes daily net solar radiation, taking into account the combined soil and plant canopy albedo. It calculates potential ET using one of the two current options. The default Priestly and Taylor (1972) method require only daily solar radiation and temperature. The Penman-FAO (Doorebos and Pruitt 1977) method for computing potential ET can optionally be used to better account for arid or windy conditions, bur weather data files must include wind and humidity data.

The soil water balance subroutine requires calculations for potential evaporation from the soil and plant surfaces. Calculation of potential evaporation requires an approximation of daytime temperatures (TD) and soil-plant reflection coefficient (ALBEDO) for solar radiation. For the approximation of daytime temperature, a weighted mean of daily maximum (TEMPMX) and minimum (TEMPMN) air temperatures are used:

TD = (0.6 * TEMPMX) + (0.4 * TEMPMN)

The combined crop and soil albedo (ALBEDO) is calculated from the model-calculated leaf area index (LAI) and the input bare soil albedo (SALB). An equilibrium evaporation rate (EEQ) defined in Priestly and Taylor (1972) is calculated from ALBEDO, TD, and the input solar radiation SOLRAD.

$EEQ = SOLRAD * (4.88 \times 10^{-3} - 4.37 \times 10^{-3} * ALBEDO) * (TD + 29)$

This empirical equation is a simplification of one containing long wave radiation approximations needed to calculate net radiation. The potential evaporation (EO) is calculated as the product of EEQ times 1.1. The constant 1.1 increases EEQ to a larger value to account for unsaturated air. The potential plant evaporation (EP) is calculated using simulated LAI values less than or equal to three.

EP = EO * LAI/3,

When LAI is greater than 3,

EP = EO

Potential ET is calculated using an equilibrium evaporation concept as modified by Priestly and Taylor (1972). This was done to eliminate the need for vapor pressure and wind inputs and under many circumstances it provides equal accuracy.

2.6 Nitrogen dynamics

As with the soil water balance, the N component in the CERES-Rice model can be bypassed when N fertilization is considered nonlimiting. Included in the N subroutine are the initial of soil N conditions and fertilizer management, as well as the transformation processes of humus, organic N, soil nitrate, and soil ammonium in to N forms usable by the plant system (Jones et al. 2003). The process involves the mineralization of organic N and the immobilization of mineral N from organic matter decomposition and the nitrification of ammonium in each soil layer.

The N module of CERES Rice simulates hydrolysis of urea, nitrification, ammonia volatilization, nitrate leaching, denitrification, algal activity and floodwater pH changes, plant N uptake and partitioning under continuously flooded, intermittently flooded and non-ponded conditions (Singh 1994). Nitrate movement associated with water movement in both an upward and downward direction is also simulated. Since the rates of transformation of N are influenced by soil water status, the simulation of N dynamics requires that water balance also be simulated. The floodwater N chemistry component of the model (Godwin et al. 1990, Godwin and Singh 1998) uses an hourly time step to calculate rapid N transformations and to update soil-floodwater-atmosphere equilibria.

This component of the model calculates the demand for N by the crop, the supply of N available to the crop, and the N uptake by the crop. N stress is developed when the actual N concentration of the stover (nongrain shoot) is less than the critical N requirement; a severe stress occurs when the actual concentration is equal to the minimum allowable value. N stress affects leaf area expansion, photosynthesis, and grain N concentration in the growth subroutine.

Soil temperature greatly influences many of the N transformation rates. Therefore, a procedure to calculate soil temperature at various depths, based on soil temperature routine of the EPC model (Williams et al. 1989). Soil temperature is computed from air temperature and a deep soil temperature boundary condition that is calculated from the average annual air temperature and the amplitude of monthly mean temperatures (Jones et al. 2003). It also includes a simple approach to calculate the impact of solar radiation and albedo on the soil temperature.

2.7 Initialization

Inputs describing the amount of organic matter and the amount of mineral nitrogen present in the soil are needed to initialize the model. The model requires the organic carbon concentration in each layer as input and, using an assumed soil C:N ratio of 10:1, calculate the amount of organic N in the soil organic matter. To determine the concentration of a recent crop residue to supply of nitrogen in the soil, the model also requires an estimate of the amount of crop residue (straw) which is present. Based on this estimate and depth of incorporation of the crop residue, the fresh organic matter content of each layer is estimated. An estimate of the amount of root residue remaining from the previous crop is required for the calculation of fresh organic matter (Jones et al. 2003).

List of publications

1. Peer reviewed Journal

Deka RL, Mahanta C, Pathak H, Nath KK, Das S (2013) Trends and Fluctuations of Rainfall Regime in the Brahmaputra and Barak basins of Assam, India. Theor Appl Climatol. 114 : 61-71 (DOI 10.1007/s00704-012-0820-x)

Deka RL, Nath KK, Mahanta C, Sharma K (2012) Recent Variability of Solar Radiation in the upper Brahmaputra valley of Assam. J Agrometeorol 14:145–150

2. Conference proceedings

Deka RL, Mahanta C, Nath KK (2009) Trends and Fluctuations of Temperature Regime of North East India. ISPRS Archives XXXVIII-8/W3 Workshop Proceedings: Impact of Climate Change on Agriculture: pp. 376–380

Saikia L, Mahanta C, **Deka RL** (2010) Climate Change in the Brahmaputra Basin of Northeast India and Need of Policy Interventions and Institutional Mechanism. Proceedings of EWRI's 3rd Developing Nations Conference: India 2010 – An International Perspective on Current & Future State of Water Resources & the Environment, IIT Madras, Chennai, India, 5–7 January, 2010.

Mahanta C, Saikia L, **Deka RL** (2011) Water Security-Food Security Linkage vis a vis Climate Change Impact on Rainfed Agriculture in the Eastern Himalayan Watershed. Proceedings of the 4th International Perspective on Water Resources and the Environment, Singapore, 4–6 January, 2011.

Deka RL, Saikia L, Mahanta C, Dutta MK (2012) Increasing Extreme Temperature Events in the Guwahati City during 1971–2010. CD proceedings: Environmentally Sustainable Urban Ecosystem (ENSURE–2012), IIT Guwahati, Guwahati, India, 24–26 February, 2012.

3. Book chapter

Nath KK, **Deka RL** (2010) Climate Change and Agriculture over Assam. In: Climate Change and Agriculture over India. (Eds. Rao et al.). PHI Learning Private Limited, New Delhi. pp 224–243.

4. International Conference/Workshop

Deka RL, Saikia L, Mahanta C, Dutta MK (2012) Increasing Extreme Temperature Events in the Guwahati City during 1971–2010. International Conference "Environmentally Sustainable Urban Ecosystem". IIT Guwahati, Assam, February 24–26, 2012.

Deka RL, Saikia L, Mahanta C (2011) Observed Climate Variability in the Brahmaputra Valley: Implications to Water Security and Food Security. International Conference "Climate Change and Water: Assessing impact, vulnerability and adaptation in the Eastern Himalayan region". IIT Guwahati, Assam, January 3–5, 2011.

Deka RL, Mahanta C (2010) Climate Change Impact and Agricultural System in the Brahmaputra Flood Plains. International Conference "Seeking Sustainable Solutions to the Brahmaputra: Challenges and Opportunities." Guwahati, Assam, December 18–19, 2010.

5. National Seminar/Conference/Symposium

Deka RL, Mahanta C, Dutta MK (2010) An Assessment of Monsoon Rainfall Variability and Rice Productivity in Assam. National Seminar "Climate Change and Sustainable Development," Tezpur University, Assam, India, 1–3 April, 2010.

Deka RL, Mahanta C (2010) Trends in the Rainfall Pattern over North East India. National Seminar "Climate Change and Sustainable Development," Tezpur University, Assam, India, 1–3 April, 2010.

Bora PK, Ray Lala IP, **Deka RL** (2013) Prediction of Consecutive day Rainfall for Lower Brahmaputra Valley Zone. National Symposium "Climate Change and Indian Agriculture: Slicing Down the Uncertainties". CRIDA, Hyderabad, India, 22–23 January, 2013.