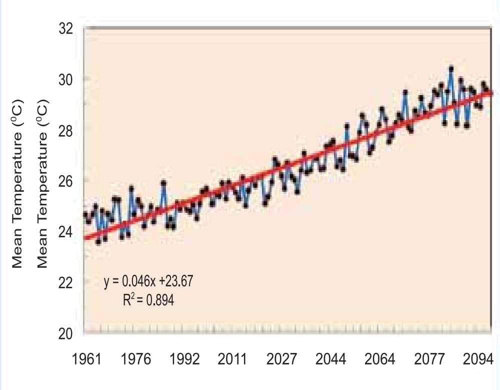

Development of Four Decade Long Climate Scenario & Trend

TEMPERATURE, RAINFALL, SUNSHINE & HUMIDITY

June 2013

STUDY REPORT

Comprehensive Disaster Management Programme (CDMP II)
Ministry of Disaster Management and Relief

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Conducted By

Institute of Water and Flood Management
Bangladesh University of Engineering & Technology

Supported by

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Development of Four Decade Long
Climate Scenario & Trend

Temperature, Rainfall, Sunshine & Humidity

FOREWORD

Bangladesh is a hotspot for geophysical and climatic hazards. The country is relatively ranked very high in terms of vulnerability to natural calamities. Since years, geographical location and geophysical configuration combined with its topography and dense population made the country prone to various disasters including climate change which often resulting in high loss of life and economic damage. The economic impact of disasters usually consists of direct damage e.g. infrastructure, crops, housing, loss of lives and livelihoods, and indirect damage e.g. loss of revenues, unemployment and enduring poverty. It is therefore increasingly becoming a major concern for the government, development partners, researchers and communities as well.

The country frequently experiences multiple natural hazards including floods, cyclones, droughts, salinity, water-logging, river and coastal erosion, hailstorms, tornados, tidal surge and landslides etc. Impact of climate change is increasing the threat of natural disaster and effecting the lives and livelihood of millions. In this scenario, the underpinning needs for detail technical study in relations to disaster risk reduction and various options for climate change adaptation issues have been long due. I am very happy that the Comprehensive Disaster Management Programme (CDMP II), Ministry of Disaster Management and Relief has taken initiatives for conducting some technical research on various critically concerning areas of DRR and CCA from the country perspectives.

I hope the study report on ‘Development of Four Decade Long Climate Scenario & Trend: Temperature, Rainfall, Sunshine & Humidity’ will serve as a resource for understanding, analyzing and addressing the risks and vulnerability associated with disaster and climate change for the relevant stakeholders.

I encourage not only relevant researchers or development professionals but all concerned citizens to make use of the study, utilize the recommendations part and take pro-active effort to pursue the research benefits to bring positive impacts in the life of the vulnerable communities. I congratulate and convey my sincere thanks to the study team and fellow colleagues who were involved in thorough editing and publishing of the document.

Mohammad Abdul Qayyum
National Project Director
Comprehensive Disaster Management Programme (CDMP II)

ACKNOWLEDGEMENT

The study 'Development of Four Decade Long Climate Scenario & Trend: Temperature, Rainfall, Sunshine & Humidity' became possible due to the contribution made by a considerable number of people and organizations. CDMP expresses deepest indebtedness and profound gratitude to all of those who were involved in the whole study, from inception to the completion of the study and preparation of the report.

CDMP wishes to extend heartfelt thanks and acknowledges the hard work and sincere efforts of the study team of Institute of Water and Flood Management (IWFM), BUET.

Special thanks and gratitude are due to the team of reviewers especially Professor Ainun Nishat, Vice Chancellor, BRAC University; Dr. Mohammod Aktarul Islam Chowdhury, Professor and Head, Department of Civil and Environmental Engineering, Shahjalal University of Science and Technology; Dr. Nasreen Ahmed, Professor and Chairperson, Department of Geography and Environment and Dean, Faculty of Earth and Environmental Sciences, University of Dhaka; Mr. Sardar Mohammad Shah-Newaz, Director, Flood Management Division, Institute of Water Modeling; Dr. Sultan Ahmmed, Chief Scientific Officer, Bangladesh Agricultural Research Council; Dr. K.M. Nabiul Islam, Senior Research Fellow, Bangladesh Institute of Development Studies; and Dr. M. Aminul Islam, Assistant Country Director, UNDP, Bangladesh for their review and valuable inputs for the improvement of the results, discussion and the final report.

The comments and suggestions received from the workshop participated by development professionals, research scientists, government officials and others have contributed a lot to improve the report.

Finally, the support from the Department of Disaster Management, Ministry of Disaster Management and Relief and financial contribution from the development partners, UNDP in particular, are gratefully acknowledged.

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ACRONYMS

AEZ	Agro-ecological Zone
BMD	Bangladesh Meteorological Department
BRRI	Bangladesh Rice Research Institute
BUET	Bangladesh University of Engineering and Technology
BWDB	Bangladesh Water Development Board
^0C	Degree Celcius
CCC	Climate Change Cell
CDMP	Comprehensive Disaster Management Programme
CEC	Cation Exchange Capacity
CEGIS	Center for Environmental and Geographic Information Services
CNRS	Center for Natural Resource Studies
CO_2	Carbon dioxide
CSM	Cropping System Model
DoE	Department of Environment
DSSAT	Decision Support System for Agrotechnology Transfer
FAO	Food and Agriculture Organization
FGD	Focus Group Discussion
GCM	General Circulation Model
GNP	Gross National Product
HADCM3	Hadley Centre Coupled Model, version 3
ICASA	International Consortium for Agricultural Systems Applications
IDW	Inverse Distance Weight
IPCC	Intergovernmental Panel on Climate Change
IWFM	Institute of Water and Flood Management
KII	Key Informant Interview
OC	Organic Carbon
PRECIS	Providing Regional Climates for Impacts Studies
RCM	Regional Climate Model
RMSE	Root Mean Square Error
SMRC	SAARC Meteorological Research Centre
SRES	Special Report on Emissions Scenario
TN	Total Nitrogen
USDA	United States Department of Agriculture
WB	World Bank

EXECUTIVE SUMMARY

Long-term temporal and spatial changes including trends in climatic variables, such as temperature, rainfall, sunshine duration and humidity, have been investigated in this study through both statistical analyses and climate modeling. The data used are the BMD (Bangladesh Meteorological Department) data for temperature, rainfall, sunshine duration and humidity, and the BWDB (Bangladesh Water Development Board) data for rainfall. BWDB rainfall data are used due to its extensive coverage. BMD data were available for 34 stations of Bangladesh. Daily maximum and minimum temperatures (1948-2010), rainfall (1948-2010), sunshine duration (1961-2010) and humidity (1948-2010) data available at all these BMD stations were analyzed. BWDB rainfall data (1957-2010) were available for 284 stations. The data for this study were available from BWDB, Climate Change Cell, Center for Environmental and Geographic Information Services, Institute of Water and Flood Management, and also some recent data directly from BMD. A parametric method of trend analysis was used in this study for its wide use and simplicity. Comparative analysis, particularly with rainfall data, indicated that the parametric results were similar to that of non-parametric counterparts. Data screening, consistency checking and filling in missing values (where possible) were also done before the analyses. A regional climate model called PRECIS (Providing Regional Climates for Impact Studies) was run for this study at the Institute of Water and Flood Management (IWFM) to generate future climates (temperature, rainfall and cloud coverage) over the domain of Bangladesh. The projected climates were bias and corrected using the observed data and were used for evaluation of the potential impact of climate change on selected agricultural crops using a crop growth model called DSSAT (Decision Support System for Agro-technology Transfer).

The analysis of measured temperature (1948-2010) at 34 locations indicates that the overall trend in all-Bangladesh annual temperatures is rising at a rate of about 1.2^{0}C per century. More importantly, this trend has become stronger in recent years. The trend in recent mean annual temperatures (1980-2010) is almost the double (2.4^{0}C per century) of the longer-term trend. The PRECIS projected future temperature has even a much higher trend (4.6^{0}C per century). The rise in mean annual temperatures projected by IPCC (2007) for South Asia is 3.3^{0}C with a range of 2.0-4.7^{0}C. Thus, the current trend is found to be at the lower end of the IPCC projection. However, it is clear that the use of the recent data, rather than the long-term data, provide results which are closer to the IPCC and PRECIS projections. Also, the IPCC projection is not unrealistic in that the recent trends are higher than the past and it may further strengthen in the future as indicated by the PRECIS output.

The spatial distribution of the current trends indicates that the temperature in the northern part of the country is increasing at a higher rate compared to the mid-western and eastern hilly regions. However, the PRECIS outputs indicate that the western and central parts of the country could experience more warming in future than the eastern part. The winter (Dec-Feb), pre-monsoon (Mar-May), monsoon (Jun-Sep) and post-monsoon (Oct-Nov) trends in recent temperatures are found to be 1.2, 3.2, 2.7 and 1.5^{0}C per century, respectively. The pre-monsoon, monsoon and winter trends have become stronger and the post-monsoon trend weaker in recent times. The recent trends are also higher for all months except for November-January. The trend in the month of May in the recent period is found to be a staggering 4^{0}C per century and in the month of January to be negative. Other than the mean temperature, the maximum and minimum temperatures were also analyzed and the results are reported in the main text. Both the maximum and minimum temperatures, and hence the mean temperature, has decreasing trends in the month of January, which is the peak winter month. This indicates that the peak winter is becoming cooler day by day.

The analysis of measured rainfalls reveals that the annual rainfall at country level is essentially free of any significant change and trend. The PRECIS outputs also indicate similar result. However, some significant changes in regional annual rainfalls have been identified. The annual rainfalls in the far north-west (Rangpur-Dinajpur) and south-west (Jessore-Khulna-Satkhira) regions are found to be increasing at 90% level of confidence. The rainfalls in south-central and south-east regions (Faridpur-Comilla-Barisal) are decreasing significantly. The seasonal rainfalls at country level are also found to

Season	Trend in all-Bangladesh mean temperatures (^{0}C per century) for data period of	
	1948-2010	1980-2010
Winter (Dec-Feb)	+1.2	+1.2
Pre-monsoon (Mar-May)	+0.7	+3.2
Monsoon (Jun-Sep)	+1.2	+2.7
Post-monsoon (Oct-Nov)	+2.0	+1.5
Annual (Jan-Dec)	+1.2	+2.4

be free of trend except for the pre-monsoon season, when it has significant increasing trend. Rainfall in the post-monsoon season has also increased though not statistically significant. At a monthly scale, rainfalls in the months of May and September are found to be increasing significantly. Rainfalls in the months of June and August are decreasing, though the decreases are not statistically significant.

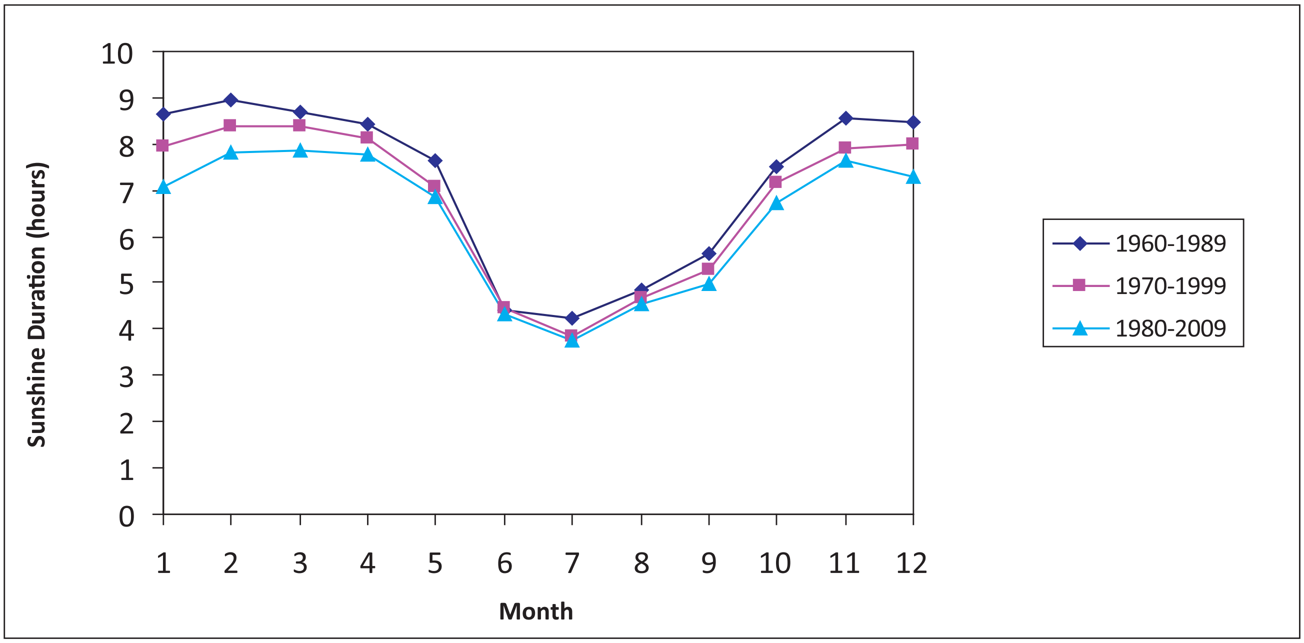
An assessment of the probability of increase in rainfall in a month using an empirical probability plotting by Weibull formula revealed that there is a good chance of increase in monthly rainfall in the months of May, September and October (66%, 73% and 71%, respectively). The chances of increase in June and August rainfalls are found to be relatively low (34.5% and 29.4%, respectively). It thus appears that the rainfalls have in general increasing trends except for the months of June and August of the monsoon season. There are some regional variations in the monthly rainfall trends as well and the inter-annual variability in rainfalls for most months are found to be increasing.

The analysis of rainy days indicates that there is an increasing trend in the number of rainy days in a year. In conformity, the longest consecutive non-rainy days in a year shows a general decreasing trend. The 7-days and 3-days consecutive maximum rainfalls in a year show increasing trend in Rangpur-Dinajpur region. The annual maximum rainfalls also show increasing trend in this region. The number of days with high rainfall (greater than 50 mm and 100 mm) in a year further shows increasing trends in this region.

The analysis of sunshine duration data reveals that the winter, pre-monsoon, monsoon and post-monsoon sunshine are declining at a rate of 8.1%, 4.1%, 3.4% and 5.3%, respectively, in every 10 years for the entire Bangladesh. The overall

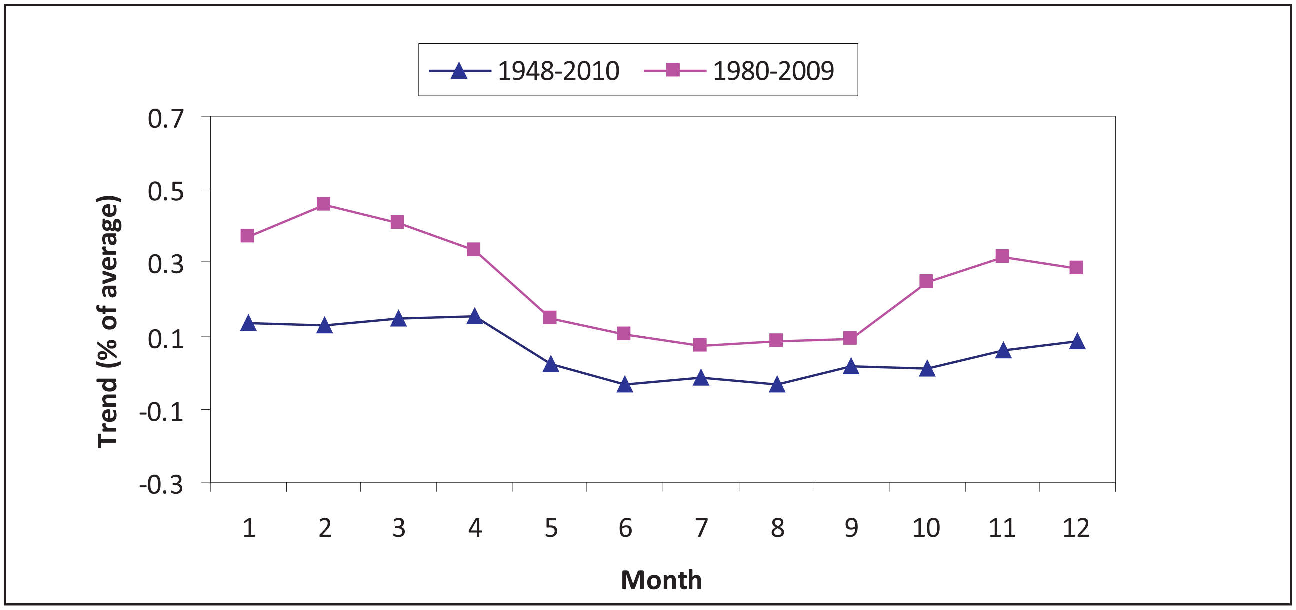
Month	Trend per decade (%)	Chance of increase (%)	Areas of increase	Areas of decrease
May	2.2	65.5	Eastern hilly and south-west coast	Kurigram-Lalmonirhat-Bogra
Jun	- 2.9	34.5	North-west	South-east and eastern hilly
Jul	- 0.7	44.5	South-west and far north-west	Rajshahi, eastern hilly and south-east
Aug	- 3.8	29.4	North-west and eastern hilly	South-east and upper south-west
Sep	3.2	73.1	South-west and eastern hilly	South-east and Bogra Jamalpur
Oct	4.2	71.4	Far north-west	South-east and eastern hilly

annual decrease for the entire Bangladesh is about 5.3% a decade. There are some spatial patterns in the declining rates - the rates increases from south to north and east to west. The sunshine in all the months has decreasing trends. The trend is the highest during the month of January which is the peak period of winter. The trends are lower during June and August of the monsoon season and they are not significant at a level of confidence of 90%. The rainfalls in these two months are found to be decreasing. For July, the trend is significant at 90% level of confidence. For the remaining months of September-May, the trends are significant even at 99% level of confidence. The rainfalls in these latter months, particularly in May, September and October, are found to be increasing. The declining rate of sunshine is very high and is really a matter of great concern for agriculture and health sectors in particular.



The humidity has increasing trends of 1.0%, 0.4% and 1.1% per decade in the pre-monsoon, post-monsoon and winter seasons, respectively, and decreasing trend of 0.2% in the monsoon season. The winter and pre-monsoon trends are statistically significant at a confidence level of 99%. It is noted that the pre-monsoon season has a statistically significant rainfall trend. The country has in general increasing trend in humidity with higher trends over the mid-western and coastal regions in the winter season, the central-west part in the pre-monsoon season, and the coastal and central-west parts in the post-monsoon season. The increase in humidity could be due to the rise in temperature and availability of water for evaporation from irrigation. In a monthly scale, the humidity has increasing trends in all the months except for June-August. Again, this is the period when general decreases in rainfall are found. The humidity trend is the highest in April, which is the warmest month of the year. The recent (1980-2010) trend is much higher than the long-term (1948-2010) trend. The trends in the months of October-April have increased a lot in recent years. Furthermore, the decreasing trends in the months of June-August have been increasing in recent years.

The simulations carried out with the crop growth model (DSSAT) using PRECIS projected and bias corrected climatic data, analyzed soil quality data, field information on cultivation practices, field measurements, etc., indicate that the wheat production in Bangladesh would be highly vulnerable to climate change. The wheat yield may decrease by 26% on an average by the end of this century due to the projected warming and dimming. Among the two irrigated rice crops, the *boro* rice may be more vulnerable to climate change than the *aman* rice. The average yield of *boro* rice may reduce by 12%. The effect on aman rice may be mixed - the yield may decrease in a medium term (2050) and remain unchanged in a longer term (2100). However, the above negative effect on selected crops would be compensated, to some extent, by the positive effect of projected CO_2 increase in the atmosphere. The coastal region and the haor basin might be more



vulnerable to change climate compared to the central floodplain and the high Barind area. These resulted from the combined effects and complex interactions of climate, soil, crop and management practices. The sensitivity analyses of wheat yield to different parameters indicated that the yield may be reduced significantly due to increase in temperature, decrease in solar radiation, delay in sowing after 15 November, application of fewer than three irrigations, increase in soil pH and decrease in organic carbon content. *Boro* rice is also found to be negatively affected by increased temperature and decreased radiation.

The perceptions of local people and officials at four selected sites gathered through focus group discussions, key informant interviews and informal interviews reveal that foggy weather, increased temperature, shortening of winter and erratic pattern of rainfall are being increasingly experienced by the local people. Wheat, mustard, onion, lentil, mango, potato, chili, winter vegetables and different peas have become vulnerable to above climatic hazards. The susceptibility of *boro* seedlings to cold injury, and *aman* rice to low temperature during flowering, has also increased. The above hazards and their effects are more generic in nature, and there are also local peculiarities - flash flood, delayed drainage and hail storms in haor areas; salinity, cyclone, storm surge and tidal flooding in coastal areas; extreme weather and shortage of irrigation water in Barind areas - which affect the crop agriculture.

It is worth to mention that the findings of this study are subject to modeling uncertainty, climate change scenario uncertainty, crop varietals uncertainty, field data limitation, etc., and thus should be considered in light of these constraints.

CHAPTER 1

1.1 Background

Community risk from natural hazards and climate change depends largely on physical and climatic settings of an area, socio-economic condition of a community, and the magnitude, duration and consecutiveness of the hazard or change itself. Assessment of such risk must require credible information on existing climate and its trend, and the future climate and its variability. The information on future climate and its variability is usually obtained from general circulation and regional climate model projection. However, the information on existing climate and its trend is derived either from the analysis of the observed historical data or from the community perception and experiences. The former being instrumental in nature is more reliable than the latter. Such information on base climate and its trend when conveyed to the community people, risk analysts, policy and decision-makers, they can better assess the level of community risk and devise better mitigation and adaptation strategies and plans. Such information can also be useful for checking the reliability of climate model projections.

However, the information on long-term climatic trends is scarce and inadequate in Bangladesh. The spatial coverage in terms of the number of stations, the parameter coverage in terms of the number of climatic variables, the temporal coverage in terms of annual, seasonal, monthly, 10-days, etc., and the analytical soundness are often inadequate and not representative for the entire country. Furthermore, no information is available at community level which is at union or lower level. It is necessary to fill in this information and knowledge gap in order to devise appropriate policy and strategic measures and plan of action.

The generation of regional and local climate settings and trends is a difficult task and should give due consideration to the consistency, homogeneity and continuity of data, unequal length of available data, outliers and extreme values in available records, and appropriate statistical and mapping tools. Moreover, all available data sets including temperature, rainfall, sunshine, humidity, evaporation, wind, etc., should be analyzed. Previous studies (Climate Change Cell, 2009a) suggest that the evaporation data of BWDB is not very reliable and thus BMD data should be considered. The analysis of the data and subsequent generation of climate and trend maps would provide important information on geographical areas and time periods of concerns due to climate change. This can further be linked with economic and livelihood activities and productivities such as crop agriculture.

Crop agriculture is the mainstay of Bangladesh and will continue to be so in the foreseeable future. About 60.1% of the area is presently under agriculture and the sector contributes about 22% to the GNP. Any unfavorable change in future climate could have a devastating impact on agriculture and the economy of the country. It is needed to know the socio-economic settings of the rural community, their agricultural practices, anticipated changes in climatic parameters and the link between the climatic variables and crop growth and productivity. The cropping practices again vary according to geographical locations - the practices are different in haors, coasts, central floodplains and uplands. Field-level information is necessary to identify the vulnerability of different crops in different locations at different times.

1.2 Present State of Knowledge

Predictions of future climate of Bangladesh are available based on atmospheric and coupled atmospheric-oceanic general circulation models and from regional climate models. Both the resolution and the accuracy of these models are improving; however, there are a number of uncertainties in predicted climates, especially in regional climates. There are large differences among inter-model forecasts. To overcome the uncertainties as well as to apprehend the magnitude and direction of future changes, it is necessary to evaluate the spatial and temporal changes that have already occurred in our past climate of Bangladesh. However, relatively few studies have been done in this respect though a vast body of literature is available on future climates from model predictions.

Ahmed *et. al.* (1992) studied the trends in annual rainfalls of Bangladesh. They concluded that there was no significant trend in the annual rainfall over the country. Ahmad *et. al.* (1996) reported an increase of 0.5 ^{0}C in temperature over Bangladesh during past 100 years. Rahman *et. al.* (1997) studied the long-term monsoonal rainfall pattern at 12 stations of Bangladesh. Though they found no overall trend in seasonal total rainfall, they detected some trends in monthly rainfalls of the two highly urbanized stations (Dhaka and Chittagong). Mondal and Wasimi (2004) analyzed the temperatures and rainfalls of the Ganges Delta within Bangladesh and found an increasing trend of 0.5 ^{0}C and 1.1 ^{0}C per century in day-time maximum and night-time minimum temperatures, respectively. They also analyzed seasonal rainfalls of the delta. Though their results show increasing trends in winter, pre-monsoon and summer rainfalls, there is no appreciable overall trend in critical period rainfall. Based on regional trends in temperatures and rainfalls, they concluded that the water scarcity in the dry season might increase and the critical period could become more critical in future.

SAARC Meteorological Research Centre (SMRC, 2003) studied surface climatological data on monthly and annual mean maximum and minimum temperatures, and monthly and annual rainfalls for the period of 1961-90. The study shows an increasing trend of mean maximum and minimum temperatures in some seasons and decreasing trend in some others. Overall, the trend of the annual mean maximum temperature has shown a significant increase over the period of 1961-90. Rahman and Alam (2003) found that the temperature is generally increasing in the June-August period. Average maximum and minimum temperatures show an increasing trend of 5 ^{0}C and 3 ^{0}C per century, respectively. On the other hand, average maximum and minimum temperatures of December-February period show, respectively, a decreasing and an increasing trend of 0.1 ^{0}C and 1.6 ^{0}C per century. Regional variations have also been observed around the average trend (SMRC, 2003).

In a recent study, Climate Change Cell (2009a) has analyzed the temperature and sunshine duration at all BMD stations of Bangladesh. It has also analyzed rainfall trend at eight stations. Rainfall data at other stations could not be analyzed due to time and budgetary limitations and also, the rainfall data after the year of 2001 were not available for the study. Islam and Neelim (2010) analyzed the maximum and minimum temperatures of four months (January, April, May and December) and two seasons only. The two months of April-May were considered as the summer season and the two months of December-January as the winter season in the study. The study found in general an increasing trend in both summer and winter temperatures. The rainfall data of some selected locations were also studied by Islam and Neelim (2010). However, they did not make any complete assessment of trend in rainfall in different time scales. Most of their analyses are on simple distribution of rainfall in a form of bar graphs. The spatial distribution of trends is not available. More importantly, the statistical significance of the trends, in either rainfall or temperature, was not reported. We have reasons to doubt whether a proper statistical technique was followed in the study. It is noted that in none of the above studies, characterization of climatic variables at local (union) level was done though such information is vital for community risk assessment including identification and assessment of crop vulnerability.

In a study at the International Rice Research Institute, Peng *et. al.* (2004) found a 10% decrease in rice yield per 1 ^{0}C increase in growing season night temperature. Increased surface temperature tends to release more carbon from the top soils which in turn reduces fertility of lands. Wheat production is very vulnerable to temperature rise (WB, 2000).

Any increase in crop water requirement, particularly during critical period when available surface and groundwater are at the minimum, would adversely affect the *boro* rice production. Irrigation cost could rise. Increasing stress on resources induced by climate change could result in a substantial decrease in cereal production potential in Bangladesh. All these will negatively impact agriculture and hence food security, livelihood, poverty and migration. Climate Change Cell (2009a) stipulated that the rice yield could decrease by 15-20% due to a reduction in day length of 25%. Zaman (2009) also indicated a similar decrease in *boro* rice yield.

The studies that have been done so far on long-term changes in observed climates are not comprehensive enough in spatial coverage, temporal resolution and number of variables. In most studies, appropriate statistical techniques and tools were not used. None of these studies provides collective information for the country as a whole at a glance. The only exception could be the study by the Climate Change Cell (2009a) on temperature and sunshine. The current study is an extension of our previous study for Climate Change Cell incorporating more climatic variables, recent climatic data, field data and crop growth simulation. It will generate base maps of local climatic trends and evaluate the impacts of climate change and variability on agricultural crops both from crop growth model and community perception.

1.3 Objective

This study was undertaken on the following key objectives:

- To characterize the spatial and temporal changes and trends in long-term climate of Bangladesh using the data available with the BMD and BWDB at different locations of Bangladesh.
- To evaluate the potential vulnerability of agricultural crops from climatic change and variability at different geographical regions based on community perception as well as crop model.

It was expected that those information will be very useful for the community risk assessment which would eventually be served as baseline information for calibration and validation of regional climate models.

1.4 Scope of Work

The scope of the study was:

i. To evaluate long-term changes and trends in air temperatures (maximum, minimum, average) at different stations of the BMD. Annual, seasonal (monsoon, pre-monsoon, post-monsoon, winter, dry season and critical period) and monthly trends were assessed. Trends in annual maximum and minimum temperatures were also evaluated.

ii. To evaluate long-term changes and trends in rainfalls at different stations of the BWDB. Annual, seasonal (monsoon, pre-monsoon, post-monsoon, winter, dry season and critical period) and monthly trends were assessed. Trends in annual maximum rainfall and number of rainy days were evaluated.

iii. To evaluate long-term changes and trends in sunshine and humidity at different stations of the BMD. Annual, seasonal (monsoon, pre-monsoon, post-monsoon, winter, dry season and critical period) and monthly trends were assessed.

iv. To characterize regional and all-Bangladesh changes in air temperature patterns at different temporal resolutions.

v. To characterize regional and all-Bangladesh changes in rainfall patterns at different temporal resolutions.

vi. To characterize regional and all-Bangladesh changes in sunshine and humidity patterns at different temporal resolutions.

vii. To develop base map of changes and trends in air temperatures at different temporal resolutions for community risk assessment and identify the geographical regions where the likelihood of changes in temperatures is high.

viii. To develop base map of changes and trends in rainfalls at different temporal resolutions for community risk assessment and identify the geographical regions where the likelihood of changes in rainfalls is high.

ix. To develop base map of changes and trends in sunshine and humidity at different temporal resolutions for community risk assessment and identify the geographical regions where the likelihood of changes in these parameters is high.

x. To identify the potential climatic vulnerability of each crop in each region from community perception.

xi. To evaluate vulnerability of crop agriculture (mainly rice and wheat) in each region using a standard crop growth model.

CHAPTER 2

Methodology and Data

2.1 Temporal Trend Analysis

Temporal trend is the gradual change in a variable at a specific location with time. Such change can be linear or non-linear, and monotonic or non-monotonic. Linear monotonic change is expressed in the following form:

$$y = a + bt + \varepsilon$$

where, y is the dependent variable such as temperature, rainfall, sunshine duration or humidity; t is the independent variable which is time (year) in this case; ε is the random variation (noise) in the dependent variable; a and b are, respectively, the intercept and slope of the linear trend line. The estimate of b is the change in the variable per unit time, and is the linear trend.

The two parameters (a and b) can be estimated by the parametric or non-parametric method. Parametric method is commonly used and is robust in case of normally distributed residuals (noise) and in absence of outliers and extremes in the data set. Otherwise, a non-parametric method becomes more suitable. In parametric method, the parameters are estimated by an ordinary least-squares regression (OLS) technique. It is required in such estimation that the residuals be normally, independently and identically distributed. It is to be noted that the above requirements are for the residuals, and no assumptions are made concerning the distribution of either the explanatory or the response variable. The trends in different climatic and hydrologic variables, reported in IPCC (2007), are mostly based on this method. In non-parametric method, the parameters are estimated by comparing each data pair to all others in a pair-wise fashion. The fitted line passes through the median point. It has been found that when the departures from the true linear relationship (true residuals) are normally distributed, OLS is more efficient than the non-parametric line. However, when residuals depart from normality (are skewed or prone to outliers and extremes), then the non-parametric trend is more efficient than the OLS trend. Thus, the appropriateness of a technique depends on the given set of data to be analyzed.

For testing the statistical significance of trend, the most commonly used statistic in parametric method is Pearson's r. Pearson's r measures the linear monotonic association between two variables and most widely used. Kendall's τ and Spearman's ρ are usually used to measure both linear and non-linear monotonic associations between two variables. Both τ and ρ are rank-based procedures - the latter being dependent on the actual magnitudes of the two variables, while the former being not dependent on them. The values of these three correlation coefficients indicate the presence or absence of the trend and its direction (increasing or decreasing). However, the coefficient in itself does not indicate whether the trend is statistically significant or not at a given confidence level. For that purpose, a t -test for Pearson's r and a z -test for Kendall's τ can be used (Helsel and Hirsch, 2002). Bhattacharyya and Johnson (1977) present the exact and large sample approximation versions of the significance testing for Spearman's ρ. By this way, one can know whether there is any significant increasing or decreasing trend in a data set.

In this study, the temporal trend in a variable at a place is estimated using a parametric technique. Our previous experiences of working with the climatic data of Bangladesh (Climate Change Cell, 2009a; Mondal and Wasimi, 2004; Mondal *et. al.*, 2009; Nasrin and Mondal, 2011; Zaman and Mondal, 2011) as well as testing both the methods in a number of cases in this study indicated that there would not be any significant gain in using a non-parametric technique. For example, both the parametric method and the non-parametric method involving Spearman's ρ indicated the same direction and similar confidence level in the trends of June rainfalls at 17 BMD locations for which long-term data are available. Only in two occasions, the trends were found to be different between the parametric method and the non-parametric method involving Kendall's τ. For the number of days in a year with rainfall greater than or equal to 100 mm, which is an extreme series, both the techniques produced similar results for the 17 stations. Similar conclusions were also reached with the sunshine duration data of eight stations for which long-term data are available.

The analyses of trends for temperature, rainfall, sunshine duration and humidity were carried out using the Statistical Package for Social Sciences (SPSS) software. Before carrying out any analysis, the box-and-whisker plot and the stem-and-leaf plot (Tukey, 1977) were made to identify outliers and extremes in the data. If an outlier or an extreme value was identified by these plots, the original data set was looked back to see if it is a real data or a coding mistake, and corrected accordingly. It is to be noted here that the simple errors in the data, such as negative values, absurd values, maximum temperature lower than minimum temperature, etc., were identified by a visual C++ computer program, written by us and well tested even before this work. The normality of the errors after fitting a regression line was tested with normal probability plot, Kolmogorov-Smirnov's test with Lilliefors significance correction (Lilliefors, 1967) and Shapira-Wilk's test (Shapira and Wilk, 1965). Residual autocorrelation function was plotted and tested for whiteness of residuals through *t*-test (Bartlet.t, 1946) and χ^2-test (Box and Pierce, 1970; Ljung and Box, 1978). Scatter plot of residuals against fitted values was produced to check for violation of equality of variance assumption.

The study made use of the BMD data on temperature, sunshine duration and humidity, and BWDB data on rainfall. It incorporated all the available stations of these two organizations. The BWDB stations for which data are reliable were identified by checking the length of available periods of records, continuity and consistency of data. Continuity of data was checked by calculating the percentage of available records within the period of records. Consistency of data was checked by a double mass analysis (see IFCDR, 2001, for details). The homogeneity of measuring stations was checked by standard procedure and the missing data were filled in based on the available data in surrounding homogeneous regions. These processes led to discard rainfall data of 50 BWDB stations, out of 284 stations, from further analyses. BMD data of a few stations were dropped mainly because of inadequate length of available records.

2.2 Generation of Spatial Trend at Local Level

The main purpose of this study was to generate information about the change of climate at local level. As mentioned in the preceding section, temporal trends were generated for each meteorological station using time series data. To obtain spatial distribution of such trends, the value of such trend for each station was plotted in a point shape map. An interpolation surface was generated using the interpolation techniques. Inverse Distance Weight (IDW), Thin Plate Spline and Kriging are the three commonly used interpolation techniques for the geo-spatial data. Kriging (van Beers and Kleijnen, 2004) is the geo-statistical interpolation technique which has been widely used because it can provide error prediction maps. The results from each of the interpolation techniques were compared and the technique which produced the least root mean square error (RMSE) was selected.

2.3 Prediction of Future Climate

Global climate models are used to predict plausible future climate based on various SRES Scenarios proposed by IPCC. General circulation models (GCMs) are typically run with horizontal scales of 300 km which is not often adequate to produce fine scale information. A regional climate model (RCM) is a downscaling tool that adds fine scale (high resolution) information to the large-scale projections of a global GCM. Regional models can resolve the GCM features down to 50 km or less. This makes for a more accurate representation of many surface features, such as complex mountain topographies and coastlines. It also allows small islands and peninsulas to be represented realistically, whereas in a global model their size (relative to the model grid-box) would mean their climate would be that of the surrounding ocean.

A Regional Climate Model, PRECIS (Providing Regional Climates for Impact Studies), was run at the IWFM simulation laboratory from which the primary climate prediction data were collected. Simulation with a regional model, such as PRECIS, is computationally expensive and requires lateral boundary data from a GCM. It was, therefore, not possible to carry out simulations with a number of regional climate models. The PRECIS model is a physically-based model which helped generate high-resolution climate change information for Bangladesh. It is a mathematical model of the atmosphere and land surface and sometimes the ocean. It contains representations of most of the important physical processes within the climate system including cloud, radiation, rainfall, atmospheric aerosols and soil hydrology. Figure 2.1 shows the typical schematizations of a global climate model.

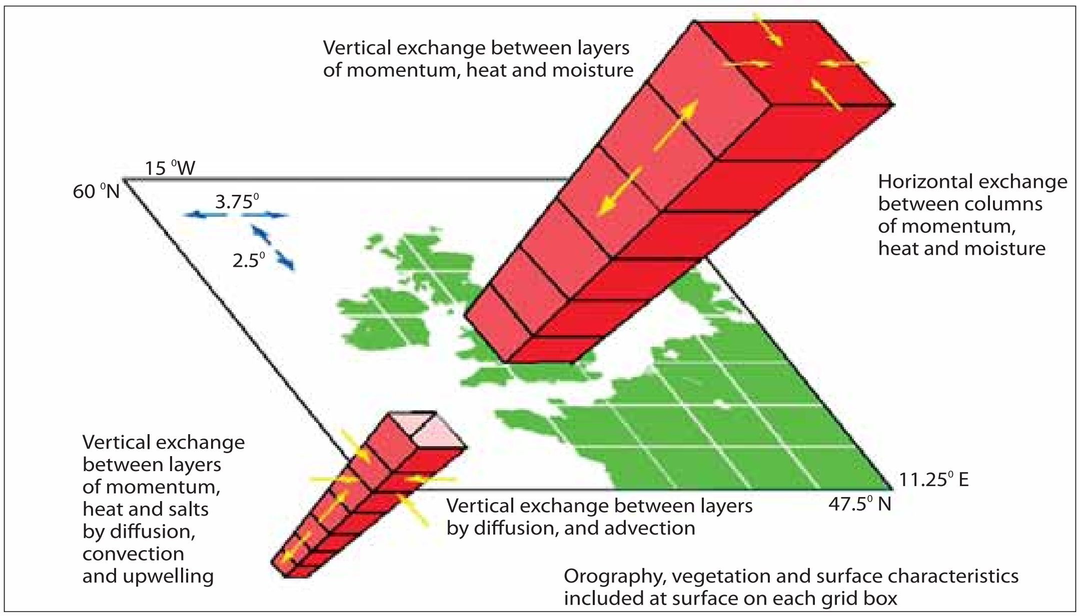


Figure 2.1: Typical schematization of a global climate model

The climate of a region is always strongly influenced by the global situation. PRECIS requires lateral boundary condition, as a limited area regional model requires meteorological information at their edges. These data provide the interface between the regional model's domain and the rest of the world. These data are necessarily provided by GCMs or from observed data sets with global coverage. In this study, the lateral boundary condition data used is from HadCM3Q which is a GCM developed in the Hadley Center, UK. SRES A1B scenarios used to predict future climate change which is balanced in terms of energy used. The processes that are parameterized in the PRECIS regional climate modeling systems are listed in Table 2.1. Figure 2.2(a) shows the simulation domain that includes Bangladesh and South Asia and Figure 2.2(b) shows the grid points of the domain over Bangladesh. The domain has 88×88 grid points with a 50 km horizontal resolution. The SRES A1B scenario of IPCC was used to derive the lateral boundary conditions of the simulation using three dimensional ocean-atmospheric coupled model (HadCM3Q) to generate prognostic variables over the simulated domains. A1B scenario was used for predicting the future climate as it is the most balanced scenario in terms of energy used. The above information was used to generate diagnostic variables, such as temperature and rainfall, using the PRECIS model all over the domain. The regional climate model was used to dynamically down-scale the data of the GCM with a resolution of 50 km from 250 km from 1951 to 2100 over the study area.

Table 2.1: Climate processes parameterized in the PRECIS model

Components of climatic system	Processes
Large-scale cloud	● Ice fall speed ● Critical relative humidity for formation ● Cloud droplet to rain: conversion rate and threshold ● Cloud fraction calculation
Convection	● Entrainment rate ● Intensity of mass flux ● Shape of cloud (anvils) ● Cloud water seen by radiation
Radiation	● Ice particle size/shape ● Cloud overlap assumptions ● Water vapor continuum absorption
Boundary layer	● Turbulent mixing coefficients: stability-dependence, neutral mixing length ● Roughness length over sea: Charnock constant, free convective value
Dynamics	● Diffusion: order and e-folding time ● Gravity wave drag: surface and trapped lee wave constants ● Gravity wave drag start level
Land surface processes	● Root depths ● Forest roughness lengths ● Surface-canopy coupling ● CO_2 dependence of stomatal conductance
Sea ice	● Albedo dependence on temperature ● Ocean-ice heat transfer

2.4 Assessment of Crop Vulnerability

Vulnerability of an agricultural crop is the expected loss in production due to climate change induced hazards. It depends on the timing, duration and magnitude of a hazard, type and growing stage of a crop, physical settings of an area, and different types of capacities available to respond. Crop agriculture in Bangladesh is vulnerable to different climate change induced hazards, such as floods, untimely rainfall, fog, increased temperature, cold injury, heat stress, salinity, drought, pest outbreaks, etc. In this study, quantitative assessment of vulnerability of a few selected crops, such as wheat, *boro* rice and *aman* rice, was made using a crop growth model. For other crops, qualitative assessment of vulnerability was made using a participatory approach

In the participatory approach, group discussions with farmers, interviews of key informants and informal discussions with local people at selected sites were held. Information on the major crops cultivated their growing periods, climatic environment required, fertilizer and irrigation applications, possible climatic shocks, crop damage due to such shocks, crop yield, etc., were gathered. Special care was undertaken so that the information gathered becomes representative for the selected geographical areas.

In the modeling approach, a crop growth and yield simulation model called Decision Support System for Agrotechnology Transfer (DSSAT) was used to simulate the effects of climate change on yields of rice (both *boro* and *aman*) and wheat. The DSSAT model simulates crop growth, development and yield taking into account the integrated effects of weather, management, genetics, irrigation, and carbon and nitrogen processes. It has been widely used almost all over the world.

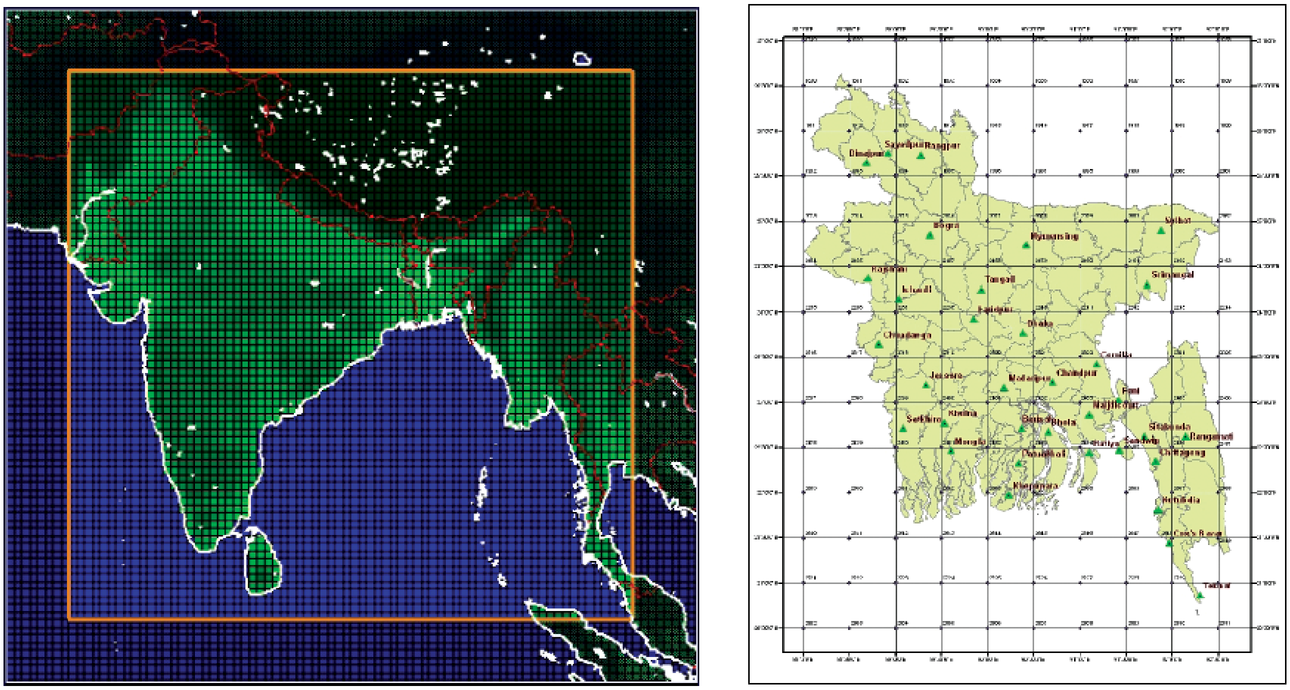


Figure 2.2: (a) Domains of the PRECIS experiments over South Asia including Bangladesh (b) Grids over the simulation domain of Bangladesh

Basak (2009), Rahman (2009) and Rahman (2010) used it for evaluation of the effects of climate change on *boro* rice, transplanted *aman* rice and wheat cultivation, respectively, in Bangladesh. It is a licensed software package from the International Consortium for Agricultural Systems Applications (ICASA), USA.

The DSSAT Cropping System Model (CSM) simulates growth and development of a crop over time. The model includes the following units:

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

2.4.1 Tools of DSSAT model

The tools of DSSAT model include the crop management data editor, the soil data editor, the experimental data editor, the weather data editor and the graphical display tools. A brief description of each of these tools is given below:

2.4.1.1 Crop management data editor

The crop management data editor, which is called XBuild in DSSAT, is designed to help the users to create experimental data files so that some major errors like format errors, error with dates, etc., can easily be avoided. An important role of the XBuild program is to make it easy to select default information values and retrieve information from DSSAT files. The XBuild contains the Environment, Management, Treatments and Simulation sub-menus which contain management information of crop.

The Environment sub-menu option allows users to make changes to field information, soil initial, soil analysis and environmental modification.

In the Management sub-menu option, the user can use the following options: (1) cultivar, (2) planting details including the planting date, plant density, row spacing and planting depth, (3) irrigation and water management practices including the dates and amounts of irrigation applications, (4) fertilizer application including the dates, amounts and types of fertilizers used, (5) organic amendments, (6) tillage operations, (7) harvest, and (8) chemical applications.

The importance of the above sub-menu options depends on the treatment factor levels that one defines for an experiment. The Treatments sub-menu allows one to select combination of the factors on option entries for each treatment.

The Simulation sub-menu provides the various options available for simulation, such as water balance, nitrogen balance and crop management options. It also defines the output files and output frequency.

2.4.1.2 Soil data editor

The soil data editor, which is called SBuild in DSSAT, is designed to help the users to create or edit soil files easily. The soil file (Soil.sol) contains data on the soil profile properties. These data are used in the soil water, nitrogen, phosphorus and root sections of the crop models. The purpose of SBuild is to provide an effective tool for creating and modifying the soil files. SBuild is a key-mouse driven windows program that allows the user to enter data into tables, freeing the user from possible formatting errors associated with entering data directly into an ASCII file. The program also calculates missing data before saving.

2.4.1.3 Weather data editor

The weather data editor, which is called WeatherMan in DSSAT, is an object-oriented tool for importing, analyzing and exporting climatic data for use in crop simulation modeling and other activities. The WeatherMan program is designed to simplify or automate many of the tasks associated with handling, analyzing and preparing weather data for use with crop models or other simulation softwares. The WeatherMan has the ability to translate both the format and units of daily weather data files, check for errors on import, and fill-in missing or suspicious values on export. The WeatherMan can also generate complete sets of weather data comprising solar radiation, maximum and minimum temperature, rainfall, and photo-synthetically active radiation. Summary statistics can be computed and reported in tables. The summary statistics and daily data can be viewed graphically.

2.4.1.4 Graphical display tool

The graphical display tool, which is known as GBuild in DSSAT, is a mouse-menu-key-driven plotting tool for data visualization. It provides users with the capability to easily plot graphs which are routinely used during the development and validation of crop models. Different graphical options provide different views of the research results. The GBuild lets one compare the data from an experimental measurement with result of the simulation model. Additionally, GBuild calculates statistics based on experimental and simulated data. The output can be seen on the screen, printed, and saved in a file. It also provides the possibility of exporting the data into an excel spread sheet., or to a text file. The program is user-friendly and leads through the consequences steps for the desired results.

2.4.2 Data requirement for DSSAT model

The minimum set of data required to run the DSSAT model and validate its outputs are the site weather data for the duration of the growing season, site soil data, and crop management data and observed data from an experiment. The required minimum weather data includes latitude and longitude of the weather station, daily values of incoming solar radiation, maximum and minimum air temperature, and rainfall. Available weather data up to the year of 2010 were collected from Bangladesh Meteorological Department. Predicted weather data up to the year of 2100 were available from the PRECIS outputs for the four locations. Soil information is contained in a soil data file (Soil.sol). The file contains information collected for soil profile at a specific site along with supplementary information extracted from soil tests. The file needs to be created by maintaining the format required by DSSAT crop models. Desired soil data includes soil classification (USDA/NRCS), surface slope, soil color, permeability, and drainage class. Soil profile data by soil horizons include upper and lower horizon depths, percentage of sand, silt and clay contents, bulk density, organic carbon, pH in water, aluminum saturation, and information on abundance of roots. For collecting the soil data, soil samples were taken from four locations - Shyamnagar of Satkhira, Nachole of Nawabganj, Pangsha of Rajbari and Jamalganj of Sunamganj. A total of 16 samples were collected from the four sites - four samples from each site. The soil samples were collected following the nine-point standard soil sample collection method described in BARC (2005). The soil samples were analyzed in the laboratories of Soil Resources Development Institute (SRDI) and the Department of Soil, Water and Environment of the University of Dhaka. The methods of analysis of different soil parameters are given in Table 2.2.

Table 2.2: Methods of analyses of different soil parameters

Parameter	Method	Unit
pH	pH was determined by Jenway and Hanna glass electrode pH meter from a soil suspension, where soil and water ratio was 1:2.5.	_
Organic Carbon (OC)	OC was determined by dry combustion method through LECO C-200 analyzer as well as wet oxidation method.	%
Total Nitrogen (TN)	TN was determined by following a three-step (digestion, distillation and titration) Kjedahl method.	%
Cation Exchange Capacity (CEC)	CEC was determined by Barium-chloride method.	meq/100gm

The required crop data on development and growth characteristics and cultivation practices for selected rice and wheat varieties were collected during the field visits through focus group discussions (FGDs) with the farmers and field measurements. The information on cultivation practices were used in different simulation experiments. The cultivation practices are the planting date, plant density, row spacing, planting depth, irrigation and fertilizer applications, crop growing period, soil water and fertility management.

The DSSAT model uses genetic coefficients as input parameters to account for the differences in growth and development among cultivars. These coefficients allow the model to simulate performance of different varieties under diverse weather and management conditions. Therefore, to obtain reasonable outputs from the model simulation, it is necessary to have the appropriate genetic coefficients for selected cultivators. The genetic coefficients required in DSSAT model for each cultivar of rice and wheat are the vernalization sensitivity coefficient (P1V), photoperiod sensitivity coefficient (P1D), thermal time from the onset of linear fill to maturity (P5), kernel number per unit stem/spike weight at anthesis (G1), potential kernel growth rate (G2), tiller death coefficient expressed as the weight of standard stem and spike when elongation ceases (G3), and thermal time between the appearance of leaf tips (PHINT).

In addition to the site weather and soil data, experimental data on crop growth, soil water and fertility are also needed. All these data are needed for both model validation and strategy evaluation. With these data, assessment of economic risks and environmental impacts associated with irrigation, fertilizer and nutrient management, climate change, soil carbon sequestration, climate variability and precision management can be done.

The model was run once for a base climate and again for a changed climate. Monthly average climatic data on temperature, rainfall and solar radiation for the period of 1961-1990, which is presented as data of 1975 in Chapter eight, were taken as base condition in crop growth and yield simulation. Similarly, the average data of 2011-2040, 2041-2070 and 2071-2100, presented as data of 2025, 2055 and 2085, respectively, were used for future year simulations.

2.5 Collection of Field Data

Field data were required to assess the impact of climate change on crop agriculture. Field data were collected from four field sites (Figure 2.3). The field sites were selected in consultation with CDMP depending on the available budgets, time and other resources. One site each from the central, upland, coastal and haor regions was selected. The sites differ in hydrologic, climatic and agricultural peculiarities. A total of eight field visits were made to the selected sites for field data collection purposes. Table 2.3 shows the details of the field visits made. Field data were collected mainly through focus group discussions (FGDs) with farmers, interviews of key informants (KIIs) and informal interviews of local people. A total of 8 FGDs, 21 KIIs and 40 informal interviews were conducted during the field visits. Moreover, 16 soil samples were collected for chemical analyses required in the DSSAT model.

From the central part of the country, Modapur union of pangsha upazila in Rajbari district was selected. The area is flood-free due to the presence of the Ganges right embankment, is moderately to well drained, and has soils of loamy texture. Rice, jute, wheat, sugarcane, oil seeds, pulses, etc., are the major agricultural crops in the area. Two field visits - one during 1-4 December 2010 and the other during 30 March-1 April 2011 - were made to the area for data collection purpose.

Table 2.3: Details of the field visits made to the selected locations

Site	Dates of visits	No. of FGDs	No. of KIIs	No. of informal interviews
Rajbari	1-4 Dec 2010 30 Mar– 1 Apr 2011	2	5	10
Sunamganj	22-24 Dec 2010 17-19 Jun 2011	3	5	10
Chapai Nawabganj	16-18 Feb 2011 5-7 Apr 2011	2	5	10
Satkhira	21-23 Jan 2011 15-17 May 2011	1	6	10
Total	**8 visits**	**8 FGDs**	**21 KIIs**	**40 interviews**

During the field visits, two focus group discussions (FGDs) with the local farmers, five key informant interviews (KIIs) - one with a Block Supervisor, one with the Upazila Agriculture Officer of Pangsha upazila, one with a local farmer- cum-businessman and two with educated local farmers - and some informal interviews were made to collect the information. Photo 2.1 shows a view of an FGD conducted in Rajbari during December 2010. Four soil samples from different soil depths were also collected for chemical analyses. Erratic rainfall, foggy weather, shortening of winter and increased temperature were identified to be the main threats to agricultural crops in the area. Photo 2.2 shows a view of a field measurement for obtaining plant density in a wheat field in Rajbari during December 2010.

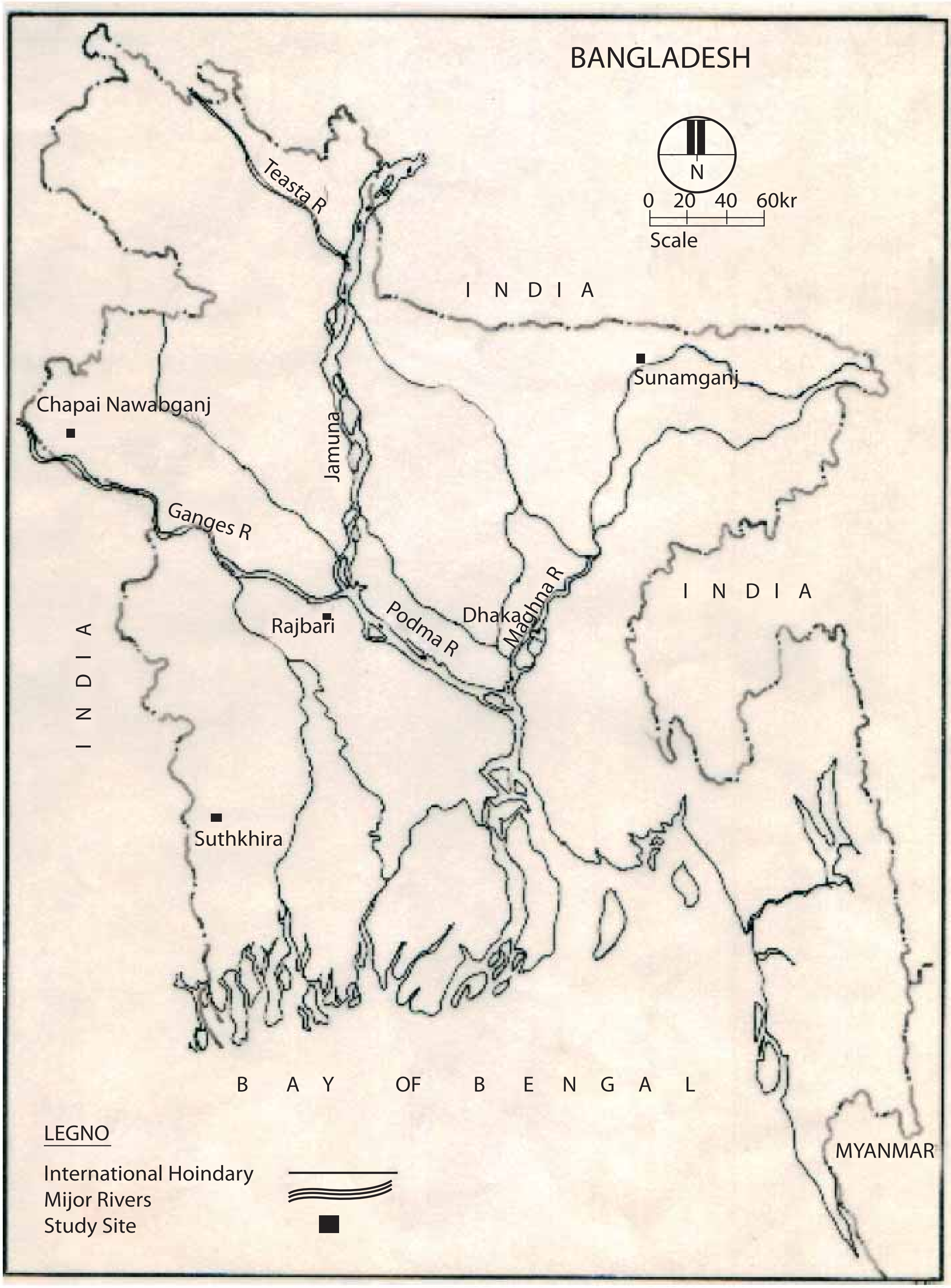


Figure 2.3: Locations of field sites

Photo 2.1: Focus group discussion at Durgapur village of Pangsha upazila in Rajbari district

From the haor basin, Pagner haor in Jamalganj upazila under Sunamganj district was selected. CNRS conducted a study for DoE in this haor and as such secondary data and information were available (Climate Change Cell, 2009b). The land type of the area is Eastern Surma-Kushiyara Floodplain and falls under AEZ 20. Two field visits - one during 22-24 December 2010 and the other during 17-19 June 2011 - were made to the area for data collection purpose. The main crop of the area is *boro* rice, which is cultivated during December-May. About 75% of the net cropped area is under *boro* cultivation. About 15-20% of the area is under other crops. *Aman* rice is cultivated on high lands near the roads. But its coverage is low compared to the total haor area. Besides these, small amount of winter crops such as potato, wheat, chili, egg plant, mustard, ladies finger, etc., are cultivated on the *kandas*. Flash flood, hail-storm, haze, cold injury, delayed drainage and irrigation water scarcity are the main threats to agricultural crops in the area. From high land area, Hajidanga and Nejampur villages of Nachole upazila in Chapai Nawabganj district were selected. This area comprises mainly of the Barind Tract which falls under AEZ 26. The Barind Tract has some unique characteristics and is made up of the Pleistocene alluvium, also known as the older alluvium. Two field visits - one during 16-18 February 2011 and the other during 5-7 April 2011 - were made to the area for data collection purpose. During the field visits, two FGDs with the local farmers, 5 KIIs (with different Agriculture Officers in the upazila, local farmers, school teacher, etc.) and some informal interviews with the local farmers were held. The main crops of the area are *boro* rice, T. *aman* rice and wheat. This area experiences extreme hot weather during summer and is highly drought-prone.

Photo 2.2: Field measurement for obtaining plant density in a wheat field at Pangsha upazila of Rajbari district

From the coastal region, Badoghata and Kathalbaria villages of Shyamnagar upazila in Satkhira district was selected. CEGIS conducted a study in the area for DoE (Climate Change Cell, 2009c) and as such secondary data and information were available. The land type of the area is the Ganges Tidal Floodplain and falls under AEZ 13. Two field visits - one during 21-23 January 2011 and the other during 15-17 May 2011 - were made to the area for data collection purpose. One FGD with the local farmers, six KIIs (with different Agriculture Officers in the upazila, local farmers, etc.), and some informal interviews with the local farmers were held. The main crop of the area is T. *aman* rice. *Boro* rice is the second important crop in the area. Other crops of the area are wheat, potato, chili, maize, beans and vegetables. Soil and water salinity, cyclone, storm surge, tidal flooding, haze, cold injury, irrigation water scarcity, increased temperature, shorter winter and erratic rainfalls are the main threats to agricultural crops in the area.

CHAPTER 3

Analysis of Observed Temperatures

3.1 Trend in Mean Temperature

Daily maximum and minimum temperatures were available at 34 locations for a period of 63 years (1948-2010). From these two temperatures, mean temperatures were calculated. In this study, the data available at all these stations were analyzed. The estimated trends in mean annual temperatures for some selected stations are given in Table 3.1.

Table 3.1 Trends in mean annual temperatures at some selected stations of Bangladesh

Station	Available period of data	Number of available years	Trend (^{0}C/century)	Significance
Cox's Bazar	1948-2010	63	2.7	**
Jessore	1948-2010	62	2.2	**
Chittagong	1949-2010	62	1.5	**
Srimangal	1948-2010	61	1.3	**
Satkhira	1948-2010	61	0.9	**
Faridpur	1948-2010	60	3.0	**
Khulna	1948-2010	60	0.1	NS
Bogra	1948-2010	59	2.7	**
Comilla	1948-2010	59	0.4	NS
Dhaka	1953-2010	58	2.3	**
Barisal	1949-2010	58	-0.1	NS
Maijdee Court	1951-2010	57	2.1	**
Mymensingh	1948-2010	59	0.3	NS
Dinajpur	1948-2010	55	-0.2	NS
Sylhet	1956-2010	54	1.5	NS
Rangamati	1957-2010	54	-0.8	*
Ishwardi	1961-2010	49	0.6	NS
Rangpur	1957-2010	48	0.3	NS
Rajshahi	1964-2010	46	1.4	*
Bhola	1966-2010	44	2.3	**

*Note: **Significant at the 95% level of confidence;*
**Significant at the 90% level of confidence; NS - Not significant at the 90% level of confidence*

It is seen from the table that almost all the stations in Bangladesh exhibit increasing trends in mean annual temperatures. In fact, our analysis including all the 34 stations suggests that the trend is 1.2^{0}C per century (100 years) (Figure 3.1). The corresponding winter (December-February), pre-monsoon (March-May), monsoon (June-September) and post-monsoon (October-November) trends are 1.2, 0.7, 1.2 and 2.0^{0}C per century (Figures 3.2-3.5).

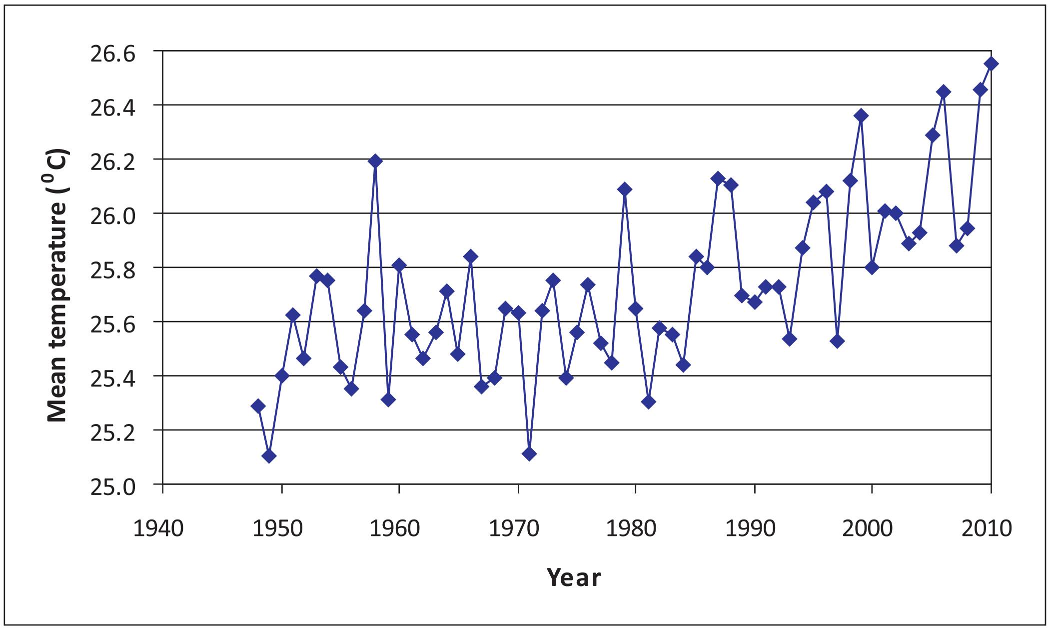


Figure 3.1: Time series of all-Bangladesh annual mean temperatures [Data period: 1948-2010]

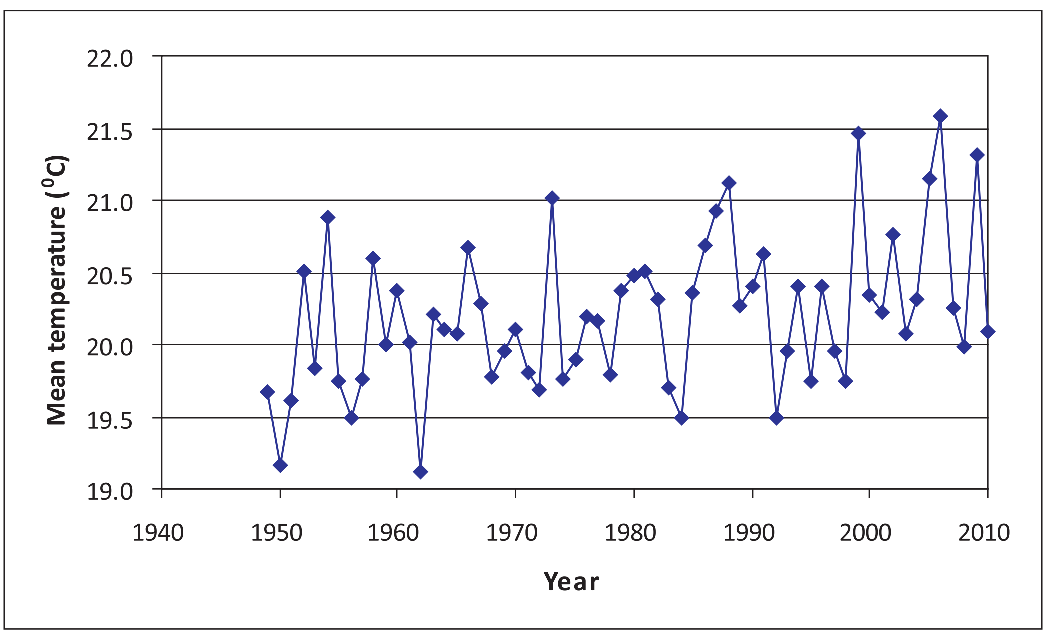


Figure 3.2: Time series of all-Bangladesh winter mean temperatures [Data period: 1948-2010]

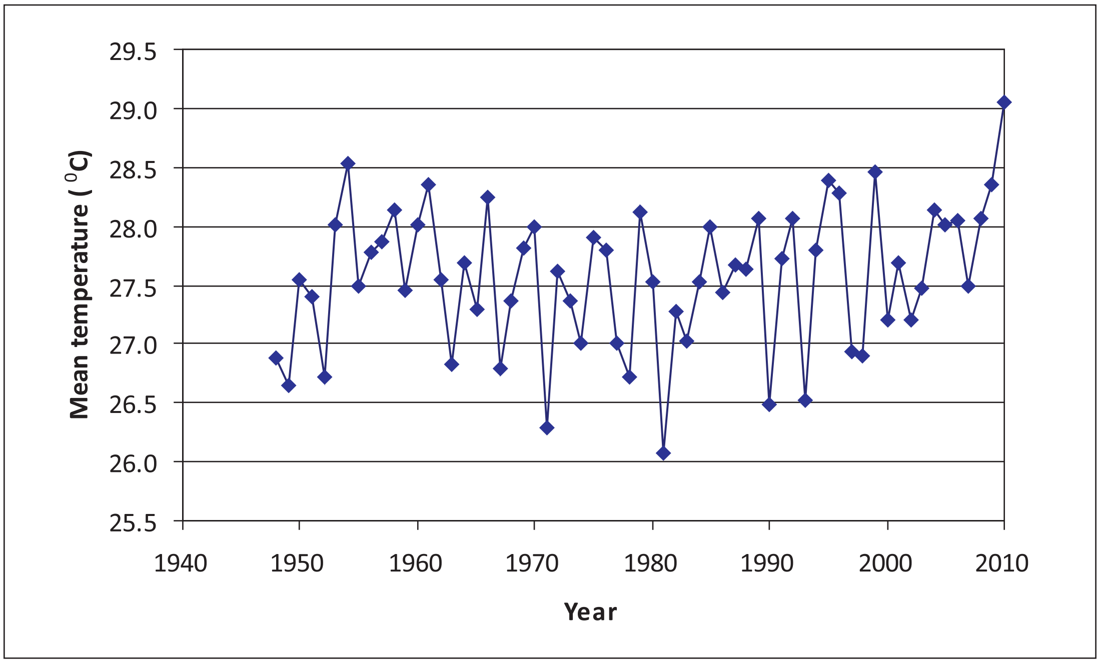


Figure 3.3: Time series of all-Bangladesh pre-monsoon mean temperatures [Data period: 1948-2010]

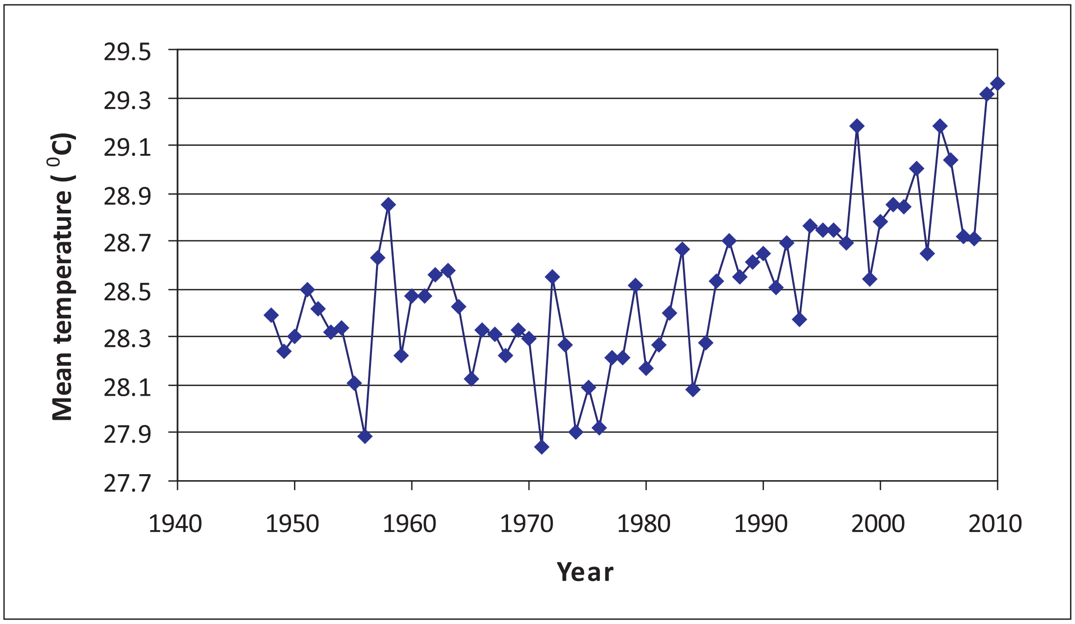


Figure 3.4: Time series of all-Bangladesh monsoon mean temperatures [Data period: 1948-2010]

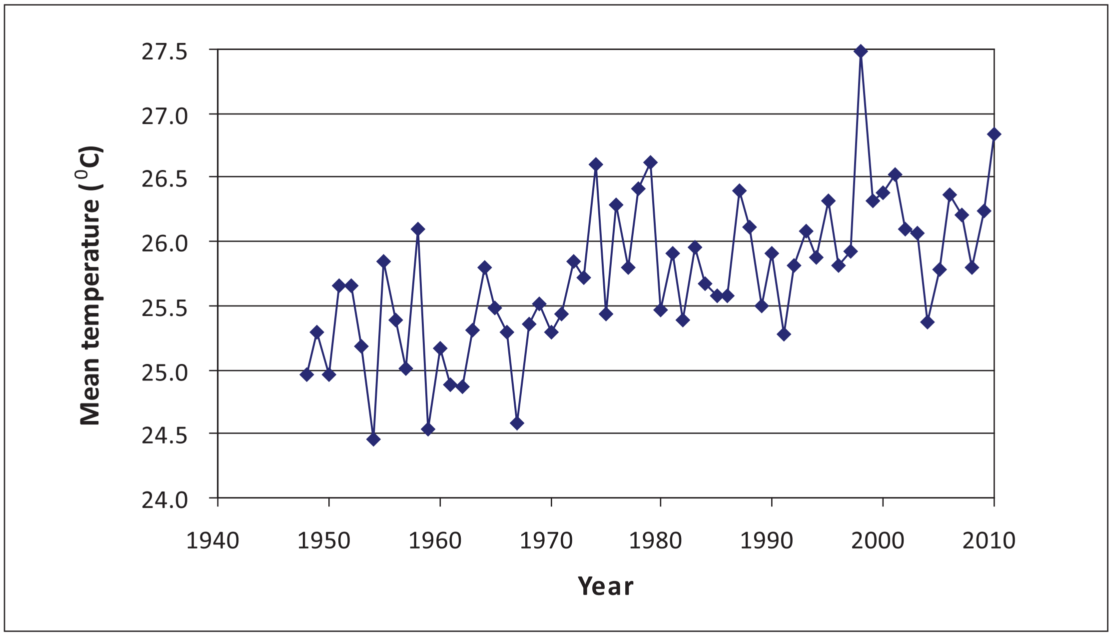


Figure 3.5: Time series of all-Bangladesh post-monsoon mean temperatures [Data period: 1948-2010]

It is seen from the figures that the trends would be quite different during the period of 1980-2010 than that in the entire time period (1948-2010). This is particularly evident in the pre-monsoon and monsoon temperatures. Therefore, the all-Bangladesh trends in seasonal and annual mean temperatures are also calculated using the data since 1980 and are reported in Table 3.2. The trends in annual mean temperatures at different stations using recent data (1980-2010) were also evaluated. The trends were found to be increasing at all the 34 stations. The magnitude at individual stations varied between 0 to 0.26% of normal annual temperature per year. This was equivalent to 0 to 6.4^{0}C increase in mean annual temperature per century. The median trend was 0.09% per year or 2.25^{0}C per century. The spatial distribution of trends, expressed as % of normal annual temperature, is shown in Figure 3.6. It is seen from the figure that the northern part of the country has a higher rate of increase in mean temperatures compared to the mid-western and eastern hilly regions.

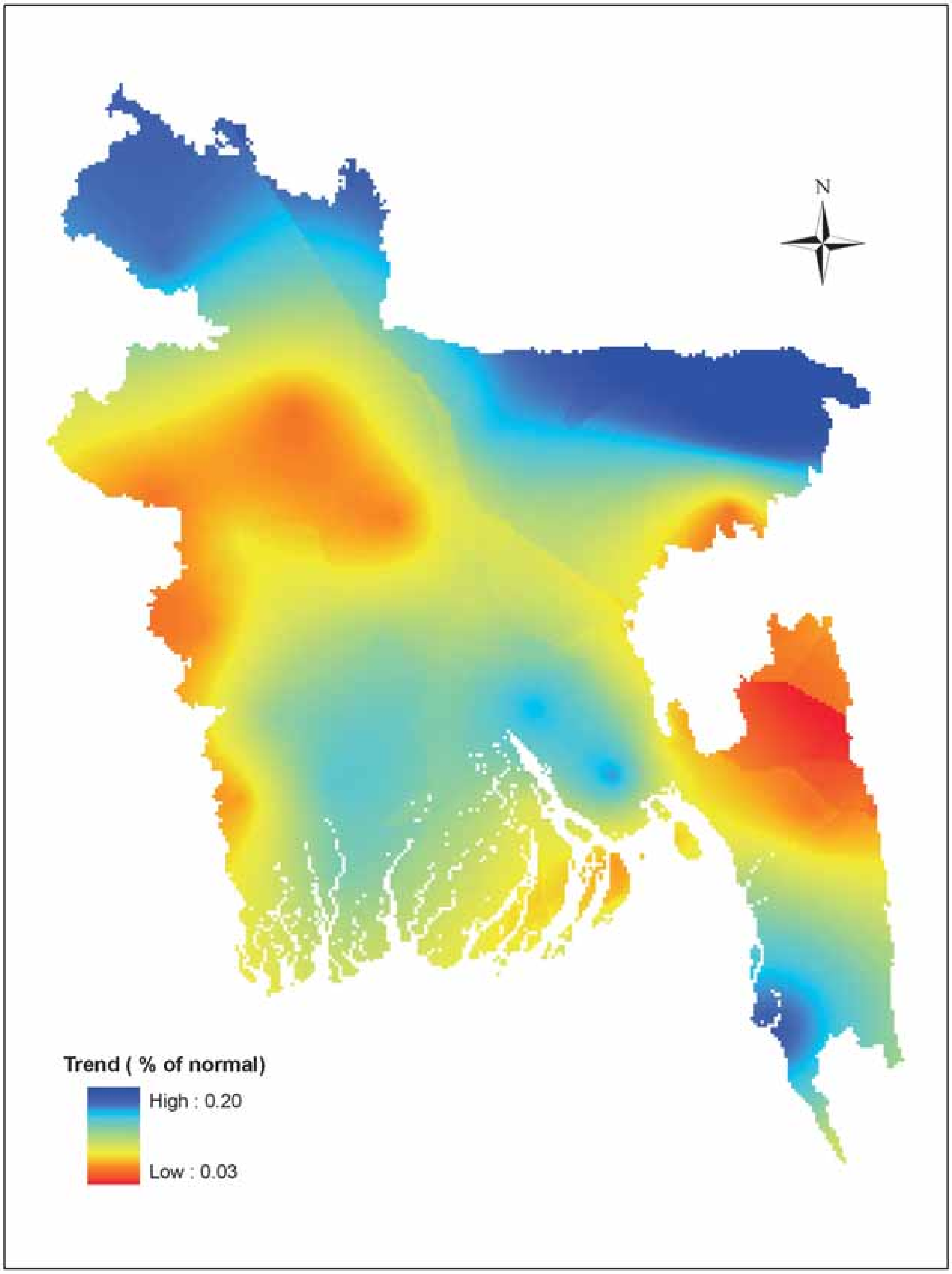


Figure 3.6: Spatial pattern of trends in annual mean temperatures (% of normal) [based on data from 1980 to 2010 for all 34 stations]

Table 3.2: All-Bangladesh trends in seasonal and annual mean temperatures [data used from 1980 to 2010 for all 34 stations]

Season	Trend (^{0}C/century)
Winter (Dec-Feb)	1.2
Pre-monsoon (Mar-May)	3.2
Monsoon (Jun-Sep)	2.7
Post-monsoon (Oct-Nov)	1.5
Annual (Jan-Dec)	2.4

It is seen from the table that the increasing trend in annual mean temperatures during the 1980-2010 period is about 2.4^{0}C per century. This value is about the double of the value computed using the data for the entire time period (1948-2010). The rise in mean annual temperatures projected by IPCC (2007) for South Asia is 3.3^{0}C with a range of 2.0-4.7^{0}C. Thus, the current trend is at the lower end of the IPCC projection. However, it is clear that the use of the recent data, rather than the historical data, provide results which are closer to the IPCC projection. The pre-monsoon, monsoon and winter trends have become stronger and the post-monsoon trend has become weaker in the recent time period. The IPCC (2007) median projections for quarterly temperatures are increases of 3.6, 3.5, 2.7 and 3.1^{0}C in December-February, March-May, June-August, and September-November, respectively, by the end of the 21st century. The IPCC projections of seasonal temperatures are also higher than the present seasonal trends. However, the projection is not unrealistic in that the recent trends are higher than the past and it may further strengthen in the future.

Trends in all-Bangladesh mean monthly temperatures are given in Table 3.3. Two values are reported in the table - one using the data since 1948 and the other using the recent data since 1980. If we compare the values reported in Columns 2 and 4, we find that the recent trends are higher for all months except November, December and January. The trend in recent temperatures in the month of January, which is the coldest month, is negative. This indicates that the peak winter is becoming cooler day by day. The recent increasing trend in the month of May is a staggering 4.0^{0}C per century.

Table 3.3 All-Bangladesh trends (^{0}C/century) in monthly mean temperatures

Month	Trend [1]	Significance [1]	Trend [2]	Significance [2]
Jan	-0.1	NS	-1.5	NS
Feb	1.5	**	3.2	*
Mar	0.9	NS	2.8	NS
Apr	0.5	NS	2.9	*
May	0.6	NS	4.0	**
Jun	1.4	**	2.6	*
Jul	1.1	**	3.0	**
Aug	1.4	**	2.9	**
Sep	0.7	**	2.3	**
Oct	1.2	**	1.9	*
Nov	2.7	**	2.6	**
Dec	2.0	**	1.8	NS

Note: [1]using data of all stations from 1948 to 2010; [2]using data of all stations from 1980 to 2010

3.2 Trend in Maximum Temperature

The time series of annual mean maximum temperatures for all-Bangladesh is shown in Figure 3.7. It is seen from the figure that the maximum temperature has started rising since 1970s or 1980s. The rising trend is 0.82^{0}C per century since 1948 and 2.84^{0}C per century since 1980. So the recent trend since 1980 is much higher than the historical trend since 1948. The seasonal trends are 0, -0.3, 1.5 and 2.3^{0}C per century for winter, pre-monsoon, monsoon and post-monsoon seasons, respectively, since 1948. The corresponding trends from 1980 are 1.6, 3.6, 3.7 and 2.2^{0}C per century. It is noted that even the sign of the trend for the pre-monsoon season changes with the consideration of the recent data.

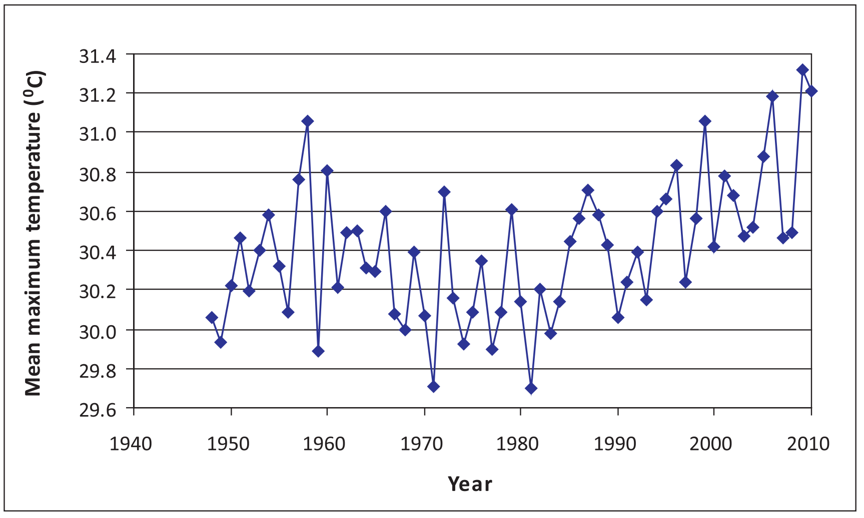


Figure 3.7: Time series of all-Bangladesh mean maximum temperatures [Data period: 1948-2010]

The monthly trends in mean maximum temperatures are given in Table 3.4. The table shows that the trends have become steeper since 1980 for all months except November. During June-October, the trends are statistically significant for both periods (1948-2010 and 1980-2010).

Table 3.4: All-Bangladesh trends (^{0}C/century) in mean monthly maximum temperatures

Month	Trend [1]	Significance [1]	Trend [2]	Significance [2]
Jan	-1.3	**	-0.1	NS
Feb	0.1	NS	4.0	*
Mar	-0.7	NS	3.1	*
Apr	-0.7	NS	2.8	NS
May	0.6	NS	4.9	NS
Jun	1.7	**	3.6	**
Jul	1.3	**	3.7	**
Aug	2.0	**	4.0	**
Sep	1.0	*	3.4	**
Oct	1.9	**	2.1	*
Nov	2.8	**	2.3	**
Dec	1.3	**	1.8	NS

Note: [1]using data of all stations from 1948 to 2010; [2]using data of all stations from 1980 to 2010

3.3 Trend in Minimum Temperature

The time series of mean annual minimum temperatures for all-Bangladesh is shown in Figure 3.8. It is seen from the figure that unlike the mean and maximum temperatures, the minimum temperatures show an increasing trend from the very beginning. The trend is 1.50^{0}C per century since 1948 and 1.91^{0}C per century since 1980; the difference is not much. The trends in winter, pre-monsoon, monsoon and post-monsoon temperatures are 2.3, 1.6, 0.8 and 1.6^{0}C per century, respectively, since 1948 and 0.8, 2.9, 1.7 and 2.3^{0}C per century since 1980. It is noted from the values that the winter trend has substantially decreased and the monsoon trend has substantially increased in recent years.

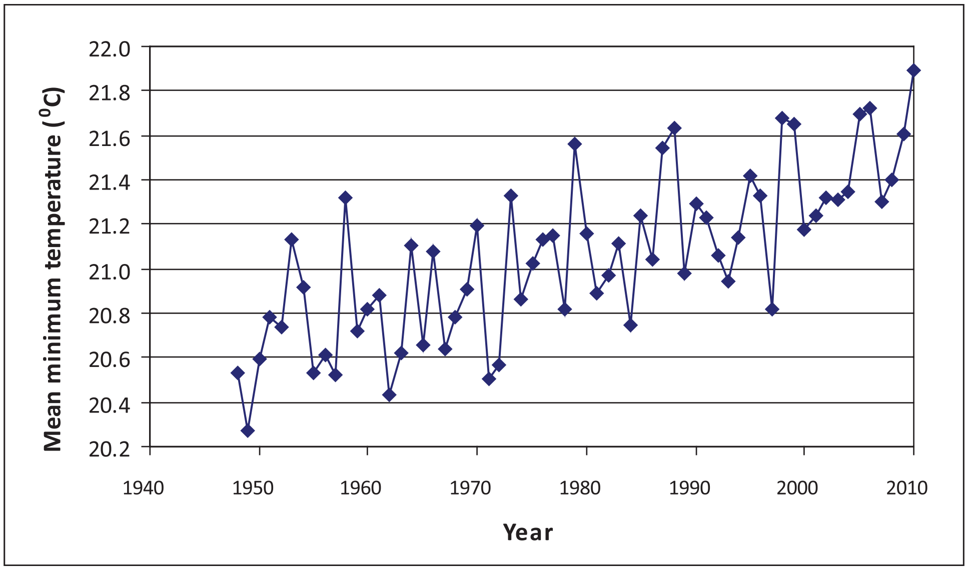


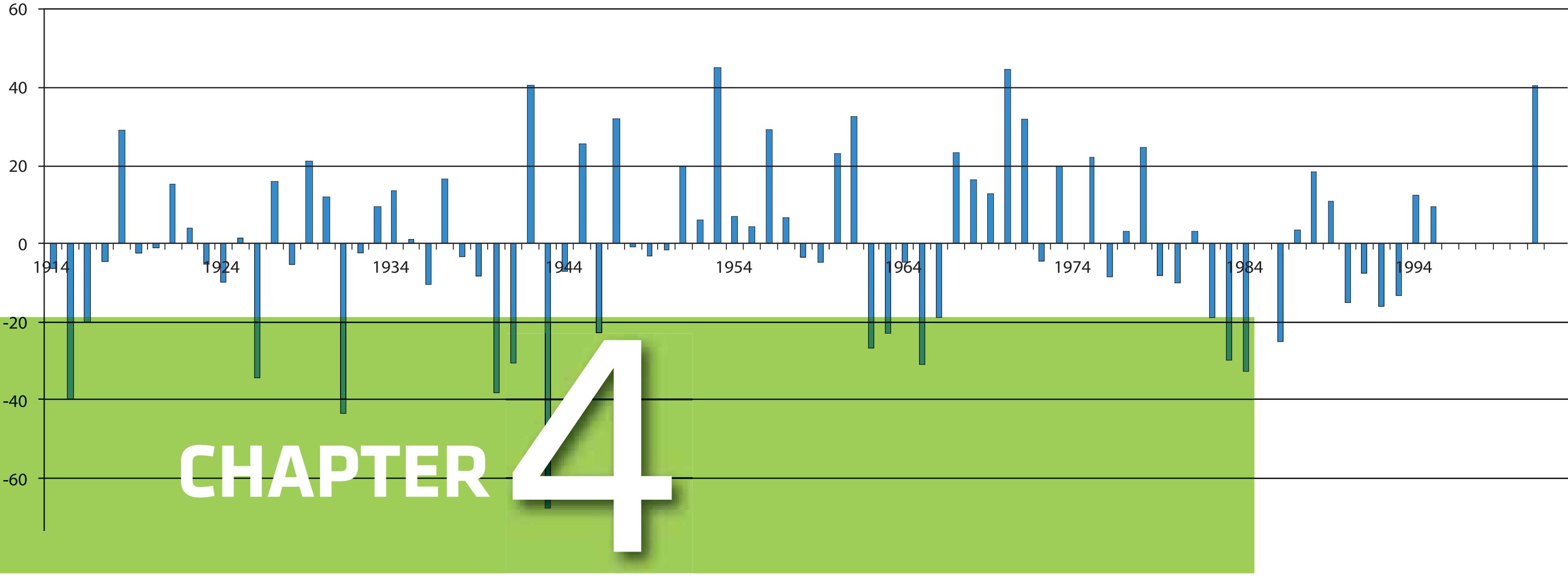
Figure 3.8: Time series of all-Bangladesh annual mean minimum temperatures [Data period: 1948-2010]

Trends in monthly mean minimum temperatures for all-Bangladesh are given in Table 3.5. It is seen from the table that the trends have increased for April-November, and decreased for December-March in recent times. It is also apparent that, though the trends have in general increased the statistical significance has decreased; this implies that the variability has increased except for the month of May.

Table 3.5: All-Bangladesh trends (^{0}C/century) in monthly mean minimum temperatures

Month	Trend [1]	Significance [1]	Trend [2]	Significance [2]
Jan	1.1	**	-1.4	NS
Feb	2.9	**	2.5	NS
Mar	2.6	**	2.5	NS
Apr	1.7	**	3.0	NS
May	0.7	NS	3.2	**
Jun	1.1	**	1.5	*
Jul	0.9	**	2.3	**
Aug	0.9	**	1.8	**
Sep	0.4	*	1.1	*
Oct	0.6	NS	1.8	NS
Nov	2.7	**	2.8	NS
Dec	2.6	**	1.8	NS

Note: [1]using data of all stations from 1948 to 2010; [2]using data of all stations from 1980 to 2010



CHAPTER 4

Analysis of Observed Rainfall

4.1 Introduction

Daily rainfall data at different stations were collected from BWDB for this study. The data were available for 284 stations. Data scrutiny and consistency and continuity checking suggested that the data of 50 stations could not be used in trend analysis and they were dropped. A list of the stations along with the length of available records that were used in this study is given in Annexure A. Missing data were filled in (whenever possible) from the nearest gage station. However, if the nearest gage station also had missing values for the same period, the average values of the surrounding stations were used to fill in the missing values. The data for this study were available for a maximum period of 54 years (1957-2010). However, most stations had available record lengths of 43-47 years. Thus, to avoid bias in the results, the data from 1961 were used. A map showing the locations of the stations is given in Figure 4.1 From the daily values, monthly total rainfall was calculated for each month, for station and for each year. Seasonal and annual rainfalls were calculated from the monthly values. Critical period rainfall was calculated by summing the daily values from 11 March to 10 May. The all-Bangladesh rainfall series for a given month, season or year was calculated from the average rainfall of different stations. Since the stations spread all-over the country, and the available periods of record and the missing values at different stations do not follow any particular spatial pattern, the averaging from all available stations is justified. We also created all-Bangladesh rainfall series from 17 selected BMD stations for which a relatively longer data set. is available to further verify the averaging process.

4.2 Annual Rainfall

All-Bangladesh annual normal rainfall for a period of 30 years (1980-2009) is found to be 2,306 mm. Such rainfalls were 2,298 and 2,314 mm during 1960-1989 and 1970-1999, respectively. It thus appears that the annual normal rainfalls have not changed much in Bangladesh.

All-Bangladesh decadal (10 years) rainfalls are shown in Figure 4.2 It is seen from the figure that the rainfalls increased gradually over the first three decades and then decreased. The highest rainfall was observed during the 1980s. There is no overall trend in decadal annual rainfalls.

A time series plot of all-Bangladesh annual rainfalls is given in Figure 4.3 It is seen from the figure that the annual rainfall series is essentially trend free. The annual rainfall series created from the 17 selected BMD stations also revealed that the series is trend free. It is to be noted that the same 17 stations were used by Shahid (2010). He found an increasing trend of 5.5 mm/year for an analysis period of 1958-2007 at a confidence level of 90%. Our analysis with the same data set and for the same period but with parametric technique indicated an increasing trend of 4.9 mm/year and significant at 90% confidence level. It thus appears that the use of two methods provides comparable results. Interestingly, inclusion of the last three years data in the series (1958-2010) provided an increasing trend of 3.0 mm/year, which is not significant even at 80% level of confidence irrespective of the choice of significance testing method (parametric or non-parametric).

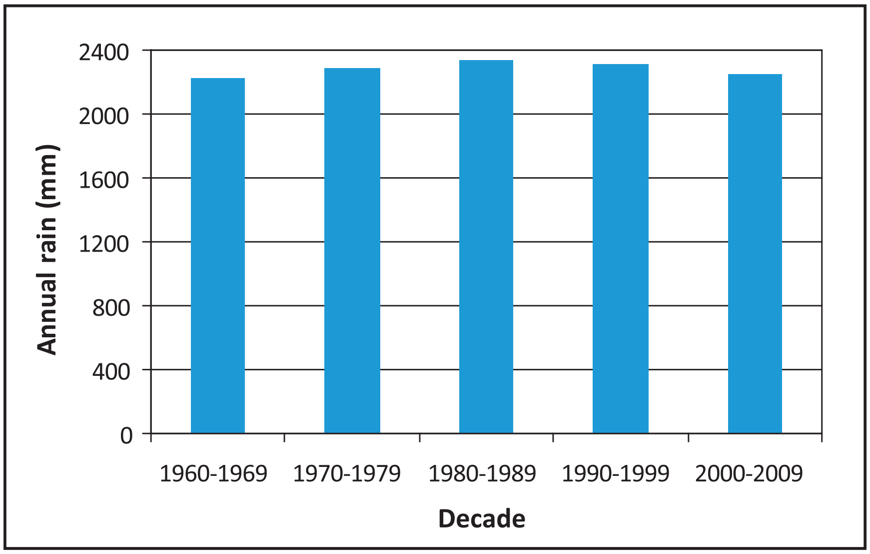


Figure 4.1: All-Bangladesh annual rainfalls during different decades

The inclusion of the earlier 10 years of data in the series (1948-2010) produced further milder trend of 2.7 mm/year, significant at 80% level of confidence (again irrespective of the choice of significance testing method). All these indicate that the rainfall trend is not very stable and is dependent on the period of analysis. Shahid's finding of a significant trend was due to the period of analysis. There is no evidence so far of any significant change in over-all annual rainfall in Bangladesh. This, however, does not mean that there is no trend at individual station level or regional level. In fact our analysis suggests that Rangpur, Dinajpur, Khulna, Jessore and Satkhira have increasing trends at 90% level of confidence. In contrast, Comilla, Faridpur and Barisal have significant decreasing trends. The areas of increase are in the far north-west and south-west parts of the country. The areas of decrease are in the south-central and south-east parts of the country.

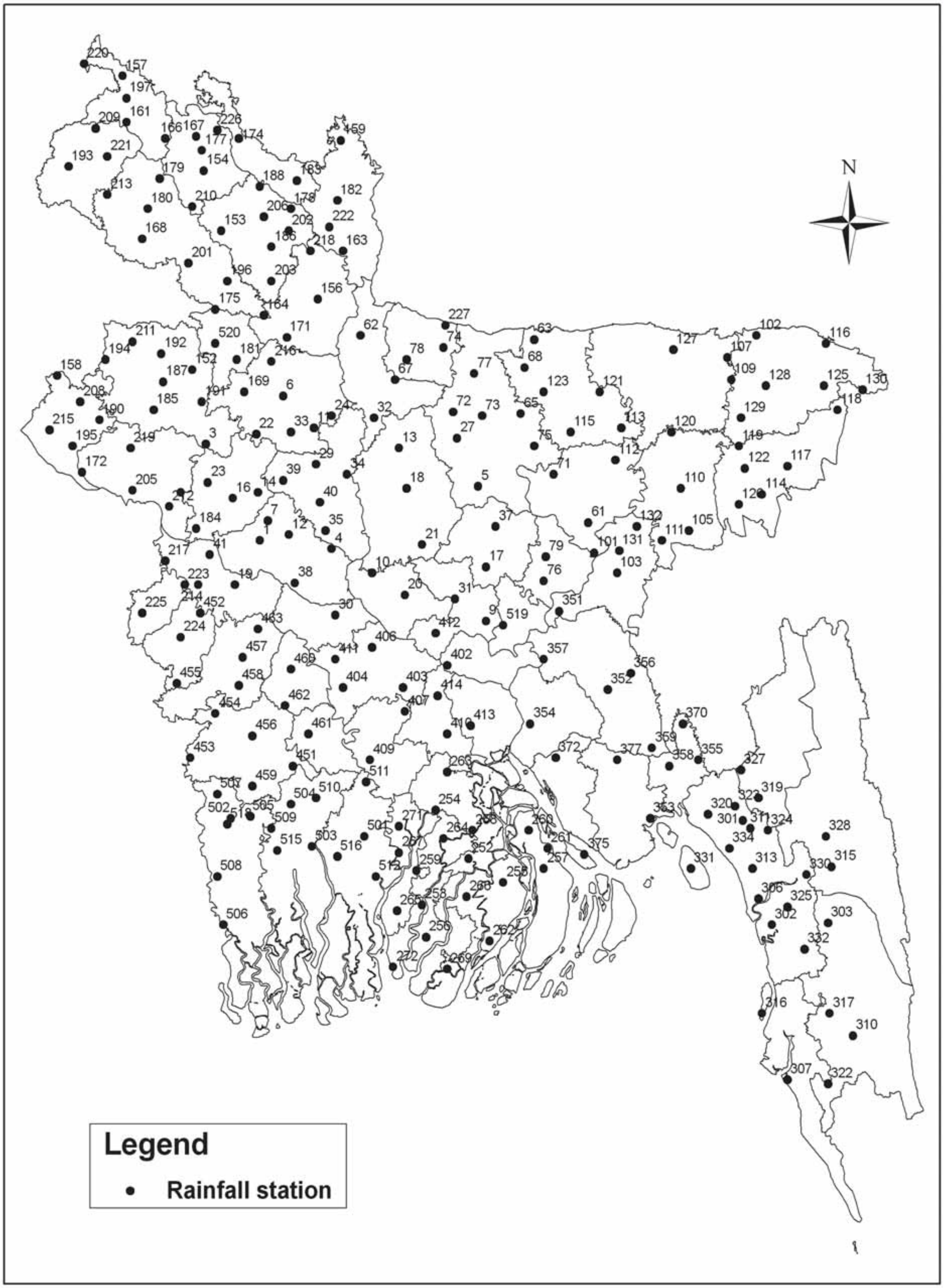


Figure 4.2: Locations of the BWDB rainfall stations used in the study

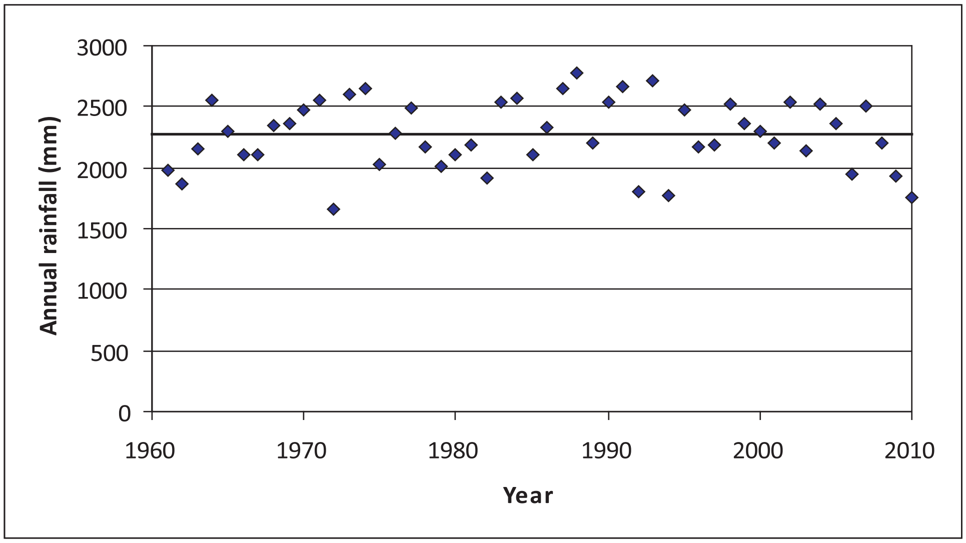


Figure 4.3: All-Bangladesh annual rainfall time series [1961-2010]

4.3 Seasonal Rainfall

All-Bangladesh normal rainfalls in different seasons are given in Table 4.1. It is seen from the table that the pre-monsoon (March-May) and post-monsoonal (October-November) normal rainfalls have increased and the monsoonal (June-September) normal rainfall has decreased over the three time periods. The critical period (11 March-10 May) normal rainfalls have increased. The winter (December-February) normal rainfall has increased in the last two periods compared to the first period. However, these changes in rainfalls in different seasons would not be statistically significant except for the pre-monsoon season.

Table 4.1: All-Bangladesh normal rainfalls in different seasons

Season	Normal rainfall (mm)		
	1960-1989	1970-1999	1980-2009
Pre-monsoon	428	449	452
Monsoon	1657	1639	1617
Post-monsoon	181	186	197
Winter	32	41	40
Critical period	233	241	244

The decadal rainfalls in different seasons are given in Figure 4.4. It is seen from the figure that the rainfalls in the pre-monsoon and post-monsoon seasons have increased and that in the monsoon season have decreased.

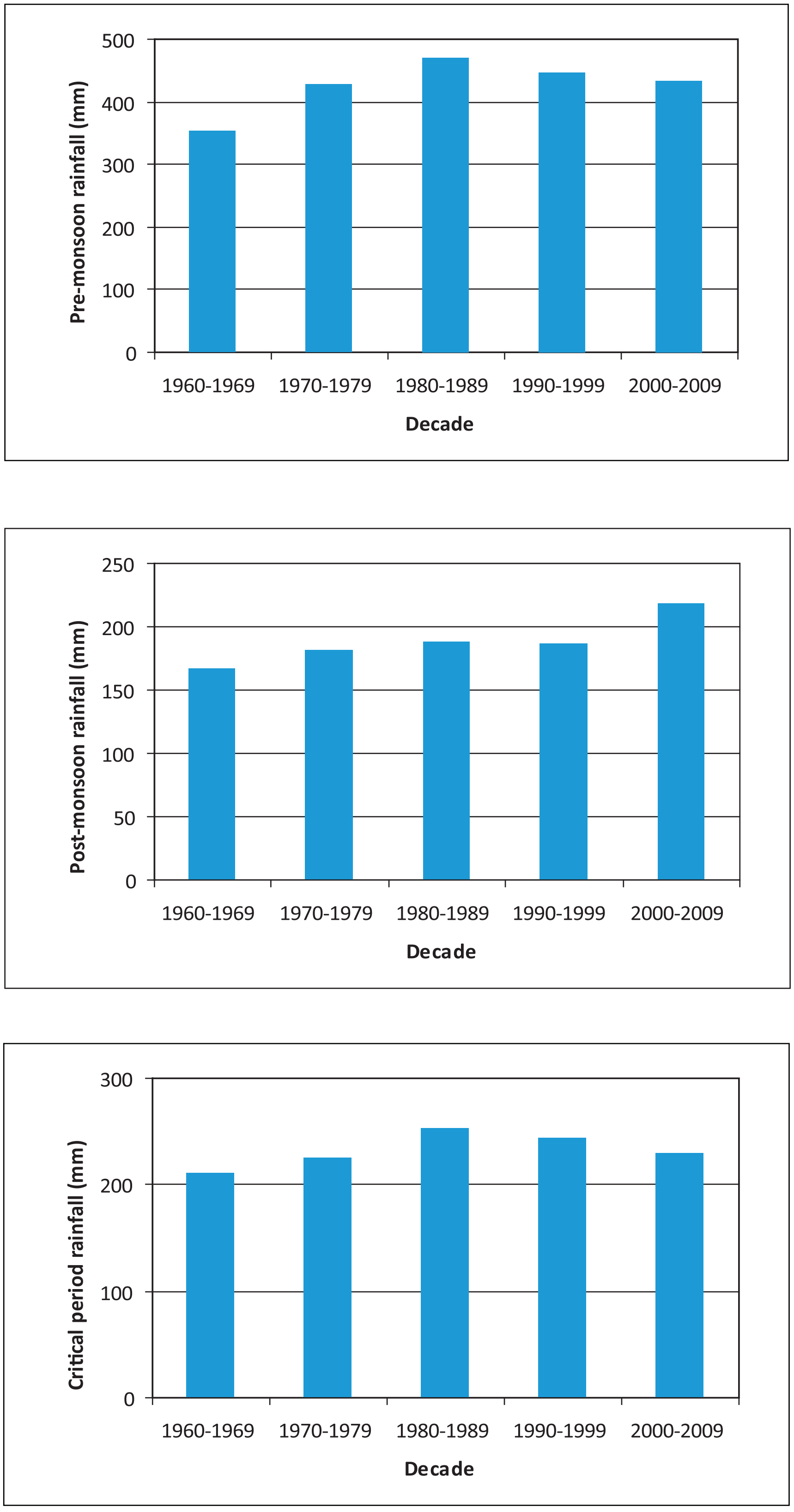
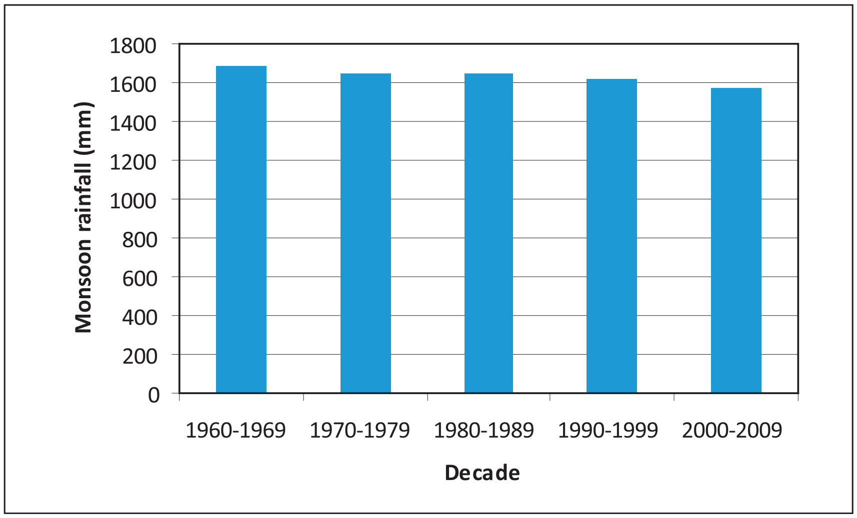


Figure 4.4: All-Bangladesh decadal rainfall variation in different seasons



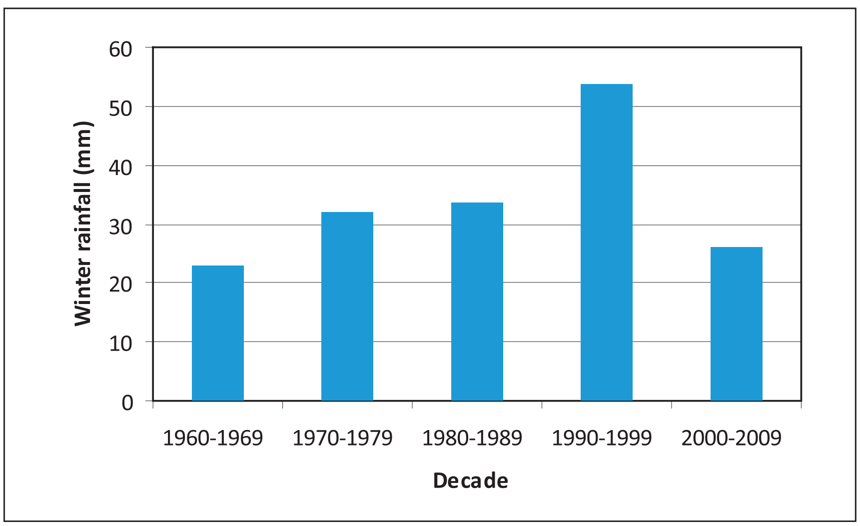


Figure 4.4: (continued)

Time series plots of all-Bangladesh rainfalls for different seasons are shown in Figure 4.5. It is seen from the figure that the rainfalls in the pre-monsoon and post-monsoon seasons have increasing trends, whereas those in the monsoon season have no appreciable trend. The increasing trend in the pre-monsoon was found to be about 2.0 mm/year, significant at 95% level of confidence. South-eastern hilly region (Rangamati, Chittagong, Cox's Bazar), north-western region (Rangpur, Dinajpur), and northern region (Sylhet, Mymensingh) shows significant increasing trends at 90% or higher level of confidence. This is the path of travel of the monsoon wind. The stations are also located at relatively higher altitudes. Shahid (2010) also found an over-all increasing trend in the pre-monsoon rainfall. In the monsoon season, Rangpur and Jessore areas were found to have increasing trends and Comilla and Barisal areas decreasing trends. The pattern was more or less similar to the annual trend. Only the Dinajpur-Rangpur areas show increasing trends in the post-monsoon rainfall at 90% level of confidence. Shahid (2010) also did not find any significant trends in monsoonal and post-monsoonal rainfalls at country level. The winter and critical period rainfalls have also remained essentially unchanged.

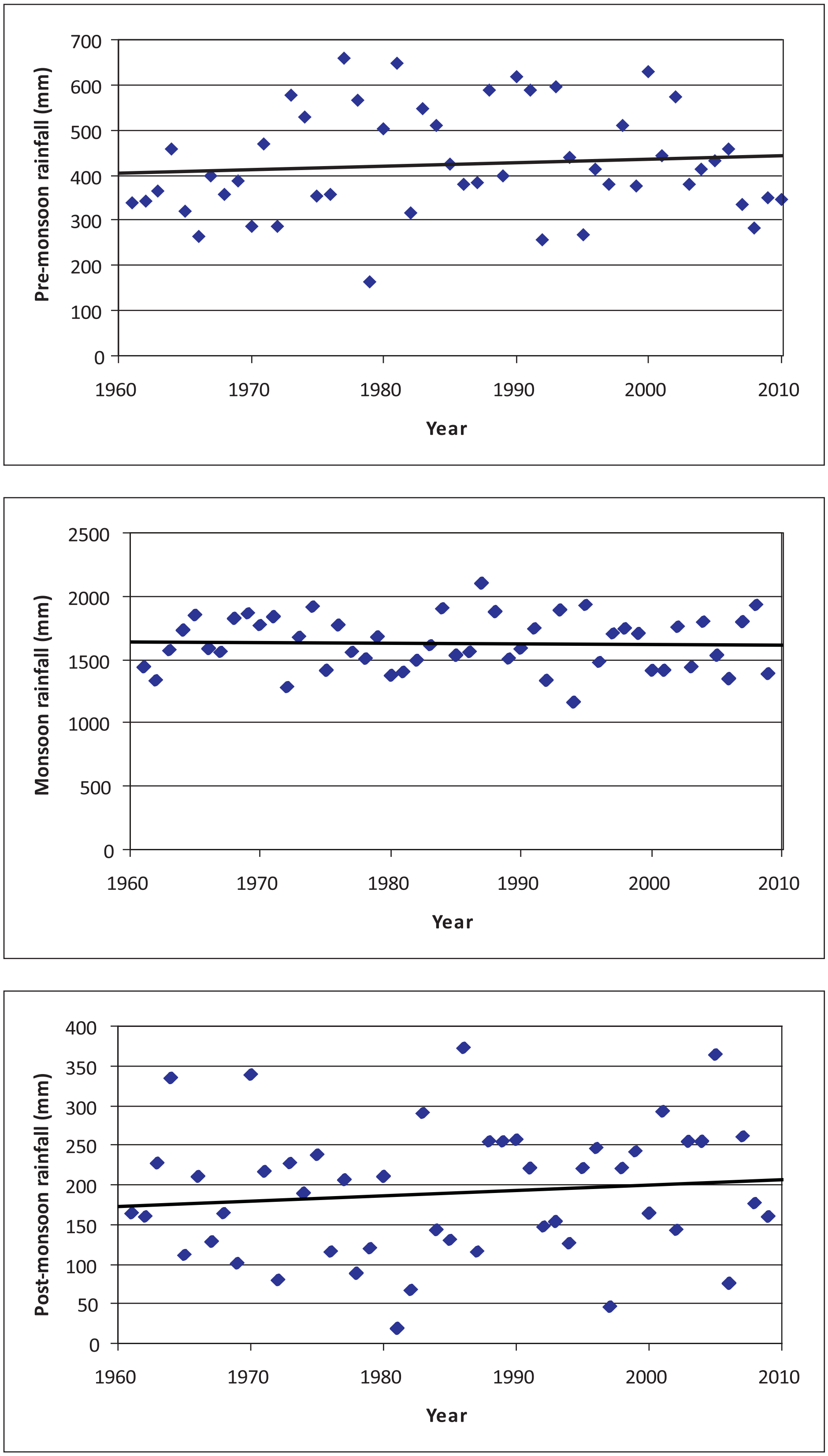
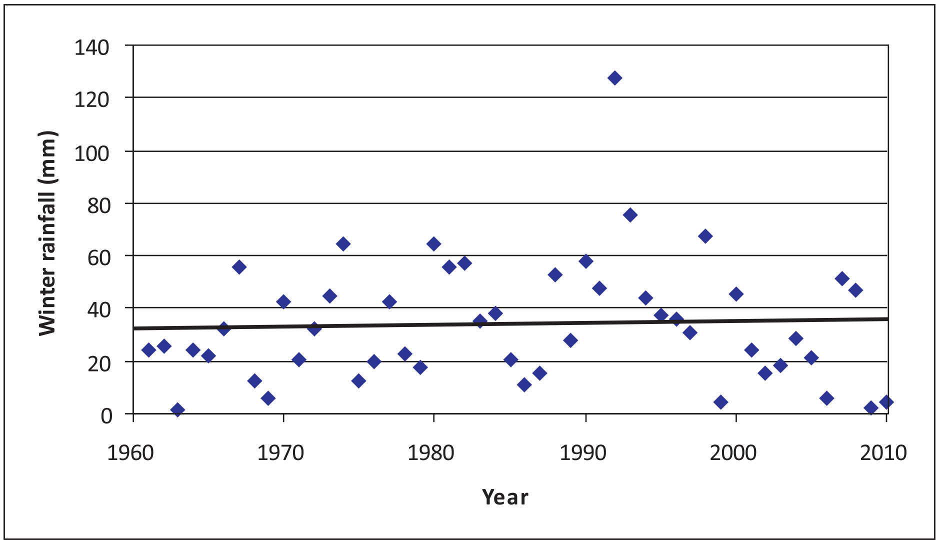


Figure 4.5: Trends in all-Bangladesh seasonal rainfall time series



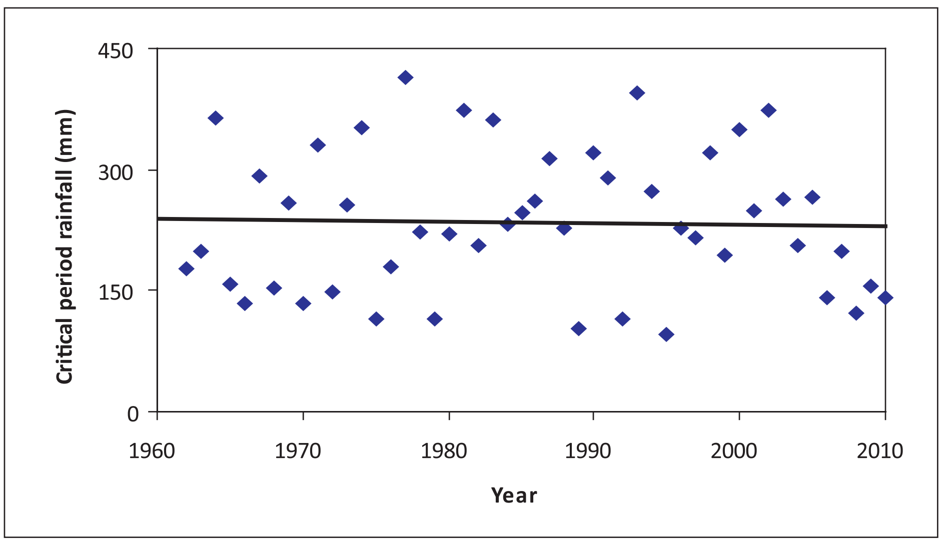


Figure 4.5: (continued)

4.4 Monthly Rainfall

All-Bangladesh monthly normal rainfall variations are given in Figure 4.6 and Table 4.2. It is seen from the figure and table that, the normal rainfalls in the months of March and May of the pre-monsoon season and September of the monsoon season have increased, while the normal rainfalls in the months of June and August of the monsoon season have decreased.

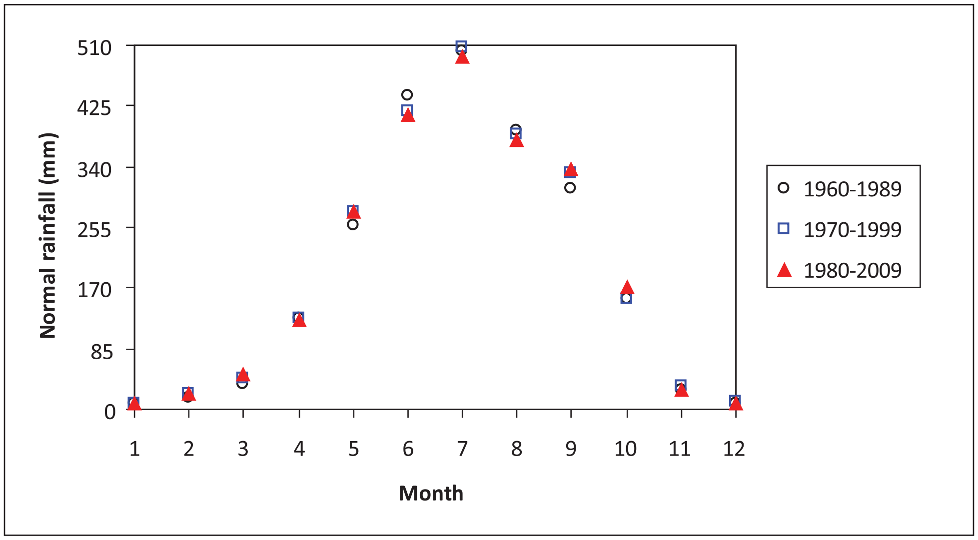


Figure 4.6: All-Bangladesh normal rainfall variation in different months

Table 4.2: All-Bangladesh normal rainfalls in different months

Month	Normal rainfall (mm)		
	1960-1989	1970-1999	1980-2009
Jan	7.1	7.5	8.1
Feb	15.4	22.9	21.8
Mar	36.1	44.1	49.2
Apr	126.3	127.2	124.3
May	258.8	275.8	277.5
Jun	**439.3**	**418.8**	**413.2**
Jul	500.6	506.2	493.3
Aug	**391.3**	**385.7**	**377.1**
Sep	309.3	331.2	336.6
Oct	155.6	153.4	169.9
Nov	26.7	32.2	27.3
Dec	8.6	10.8	8.2

The decadal variation of all-Bangladesh monthly rainfalls is given in Figure 4.7. It is seen from the figures that the rainfalls in the monsoon months, except for September, have decreased in recent decades compared to the past. Rainfalls have significantly increased in October and decreased in November of the post-monsoon season in the last decade compared to the past decades. There is no definite pattern in variations of monthly rainfalls in other seasons.

The trends in all-Bangladesh monthly rainfalls are given in Figure 4.8. It is seen from the figure that the rainfalls in the months of June and August of the monsoon season have decreasing trends. The month of September of the monsoon season and the months of March and May of the pre-monsoon season have increasing trends in rainfalls. The months of October of the post-monsoon season has a slightly increasing trend. However, the trends of May and September were found to be statistically significant at 90% level of confidence. The all-Bangladesh trends of May and September are 13 mm and 11 mm a decade, respectively.

The trends in monthly rainfalls for each individual station were also estimated. For June, 155 stations were found to have negative trends and 82 stations were found to have positive trends. The spatial variation of trends is shown in Figure 4.15. It is seen from the figure that the north-western part of the country has increasing trends while the south-eastern and eastern hilly region has decreasing trends. Since there is no strong correlation among the rainfall trends at different stations, they can be considered as independent observations from a continuous probability distribution. However, the mathematical form of this distribution is not known. In absence of such knowledge, an empirical technique based on probability plotting can be used to estimate the probability of increase or decrease in rainfall. In this study, such probability was estimated by using the Weibull's plotting position formula. For normal and extreme value distributions, Weibull formula provides estimates consistent with experience (Haan, 1977). It is found that the overall chance of increase in rainfall in June is about 34.5%. The expected change, which is expressed by a median change with an exceedence probability of 50%, is found to be decreasing at a rate of 0.29% per year (Figure 4.9). This means that, over a period of 10 years, the rainfall in the month of June has decreased by 2.9%. For July, 131 stations were found to have negative trends and 106 stations were found to have positive trends. The spatial variation of trends is shown in Figure 4.16. It is seen from the figure that the Rajshahi, Nawabganj and Naogaon region of the north-western part of the country along with the south-eastern and eastern hilly region has decreasing trends, while the south-western part particularly Meherpur, Chuadanga, Jhenaidah and Kushtia region has increasing trends in July rainfalls. The chance of increase in rainfall in July is found to be about 44.5%. The expected change, based on observed data, is found to be decreasing at a rate of 0.07% per year (Figure 4.10) or 0.7% per decade.

For August, 167 stations were found to have negative trends and 70 stations were found to have positive trends. The spatial variation of trends is shown in Figure 4.17. It is seen from the figure that the rainfall in the month of August has in general decreasing trend except at the eastern hilly region and north-western part of the country where it has increasing trend. The chance of increase in rainfall in August is found to be about 29.4%. The expected change is found to be decreasing at a rate of 0.38% per year (Figure 4.11) or 3.8% per decade.

For September, 174 stations were found to have positive trends and 63 stations were found to have negative trends. The spatial variation of trends is shown in Figure 4.18. It is seen from the figure that the rainfall in the month of September has in general increasing trend except at the Noakhali-Comilla region and Joypurhat. The chance of increase in rainfall in September is found to be about 73.1%. The expected change is found to be increasing at a rate of 0.32% per year (Figure 4.12) or 3.2% per decade.

For October, 170 stations were found to have positive trends and 67 stations were found to have negative trends. The spatial variation of trends is shown in Figure 4.19. It is seen from the figure that the rainfall in the month of October has in general increasing trend except in the Noakhali-Comilla region and Cox's Bazar. The increasing trend is higher in the Dinajpur-Rangpur region compared to that in other regions. The chance of increase in rainfall in October is found to be about 71.4%. The expected change is found to be increasing at a rate of 0.42% per year (Figure 4.13) or 4.2% per decade.

For May, 156 stations were found to have positive trends and 81 stations were found to have negative trends. The spatial variation of trends is shown in Figure 4.20. It is seen from the figure that the rainfall in the month of May has in general increasing trend particularly in the eastern hilly and the Sundarbans regions. The chance of increase in rainfall in May is found to be about 65.5%. The expected change is found to be increasing at a rate of 0.22% per year (Figure 4.14) or 2.2% per decade.

For other months (November-April), the spatial variation of trends was not determined as there are some zero rainfalls in these months at individual stations. A summary of spatial pattern of rainfall trends for May-October is given in Table 4.3. The findings of this study are consistent with the findings of Mondal and Wasimi (2004) who have analyzed the seasonal rainfall data of the Ganges basin within Bangladesh and Rahman *et. al.* (1997) who have analyzed the monsoon rainfall data at 12 stations of Bangladesh and found no conclusive evidence of any changing pattern of monsoon rainfall. The findings are also consistent with the findings of Singh and Sontakke (2002) who found a decreasing trend (statistically insignificant) in monsoon rainfall over central and eastern Indo-Gangetic plain. However, the findings are not consistent with the IPCC (2007) projections for winter and monsoon rainfalls. The IPCC has projected a decrease in winter rainfall and an increase in monsoon rainfall. Though there is a general increasing trend in rainfall in Bangladesh, the increases in the monsoon are not conclusive, except for Rangpur-Dinajpur and, to some extent, for Jessore-Khulna-Satkhira region. It is to be noted that the IPCC projection is for entire South Asia and not for Bangladesh alone. From the analysis of monthly and 10-day data, it is found that the monsoon may have weakened at the earlier months (June-July) of the season and strengthened during the later months (September).

Table 4.3: Summary of monthly rainfall trends for some selected months

Month	Trend per decade (%)	Chance of increase (%)	Areas of increase	Areas of decrease
May	2.2	65.5	Eastern hilly and south-west coast	Kurigram-Lalmonirhat-Bogra
Jun	-2.9	34.5	North-west	South-east and eastern hilly
Jul	-0.7	44.5	South-west and far north-west	Rajshahi, eastern hilly and south-east
Aug	-3.8	29.4	North-west and eastern hilly	South-east and upper south-west
Sep	3.2	73.1	South-west and eastern hilly	South-east and Bogra-Jamalpur
Oct	4.2	71.4	Far north-west	South-east and eastern hilly

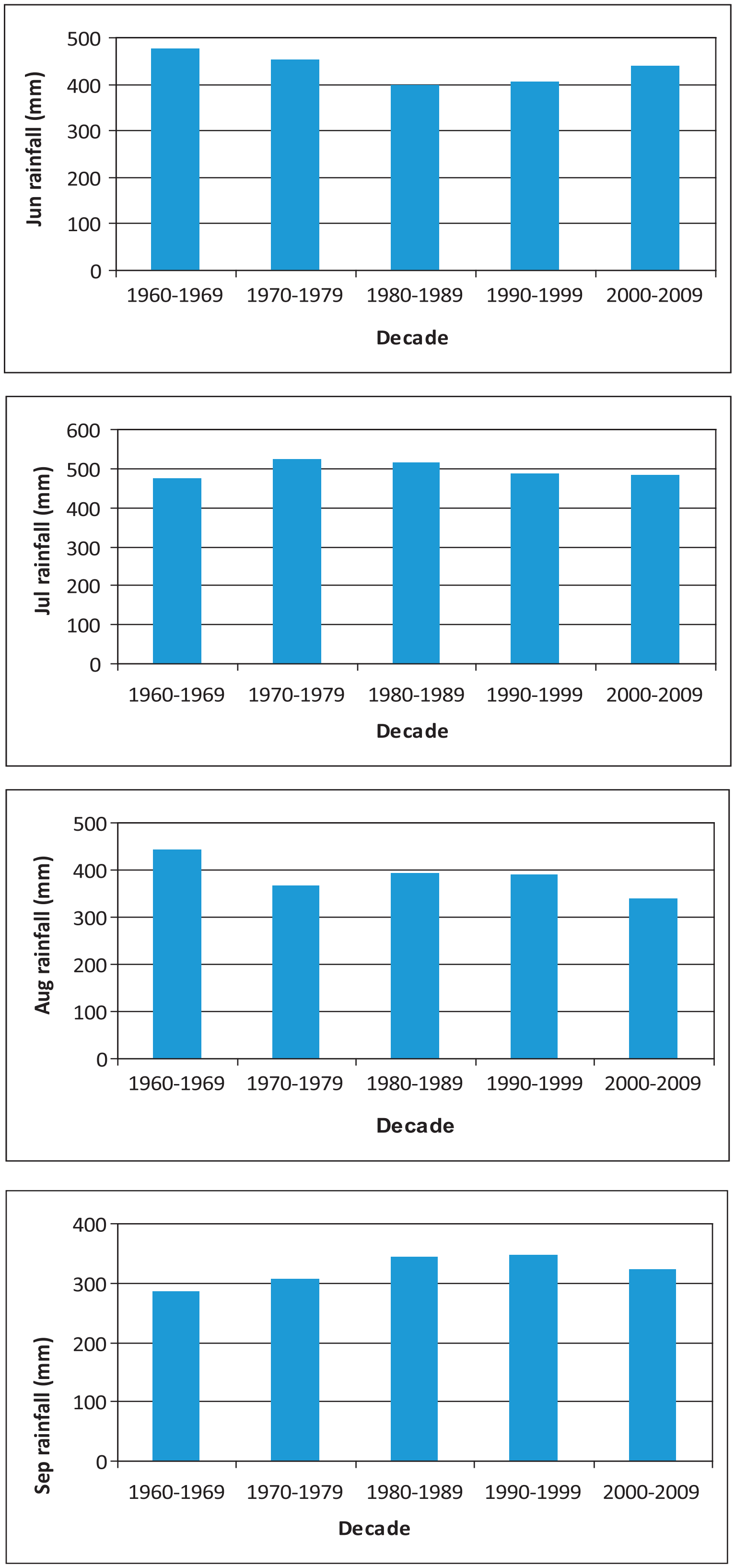


Figure 4.7: Decadal variation in all-Bangladesh monthly rainfalls

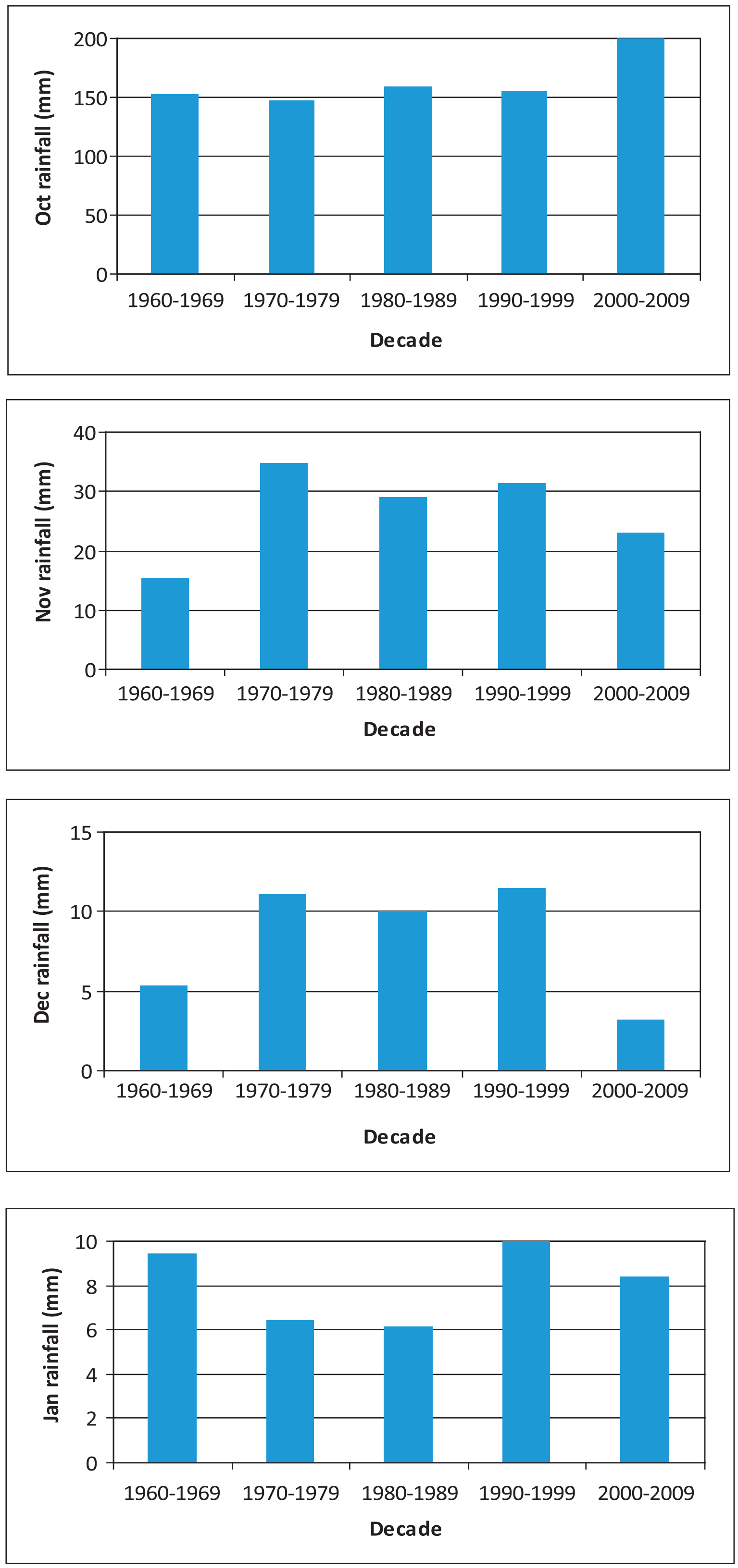
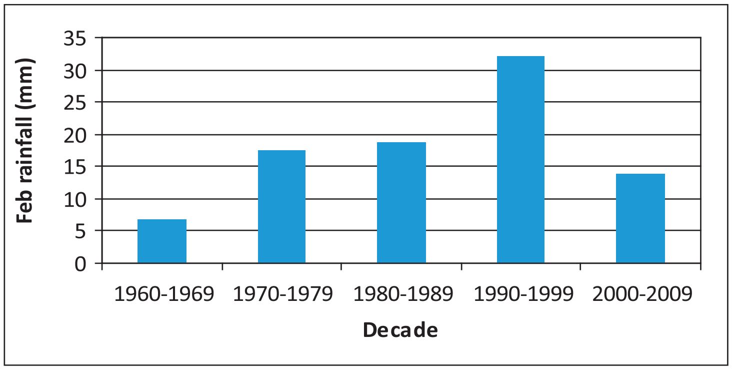
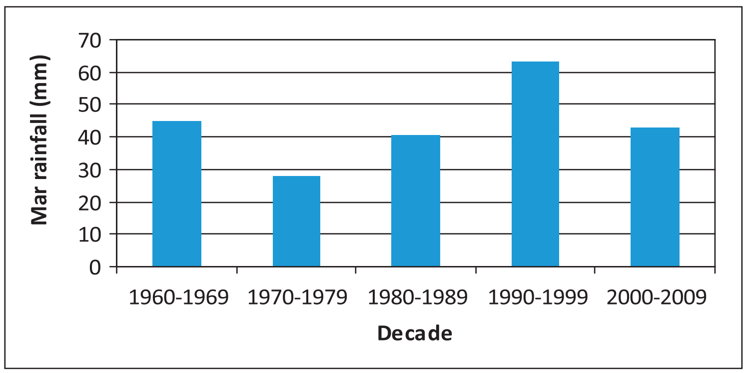
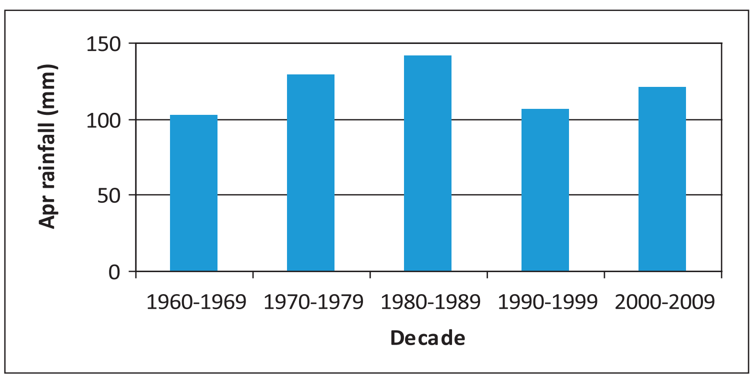


Figure 4.7: (continued)







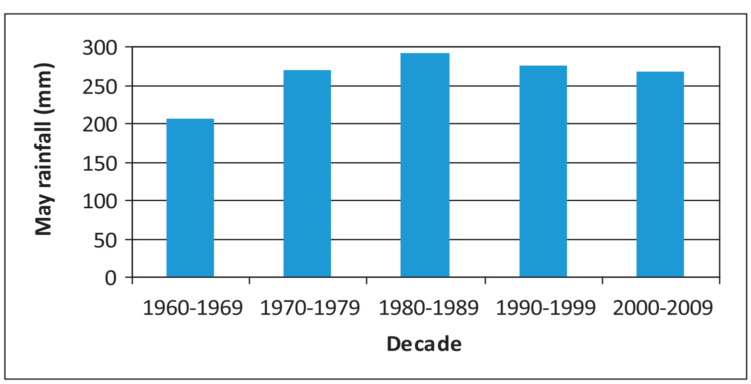


Figure 4.7: (continued)

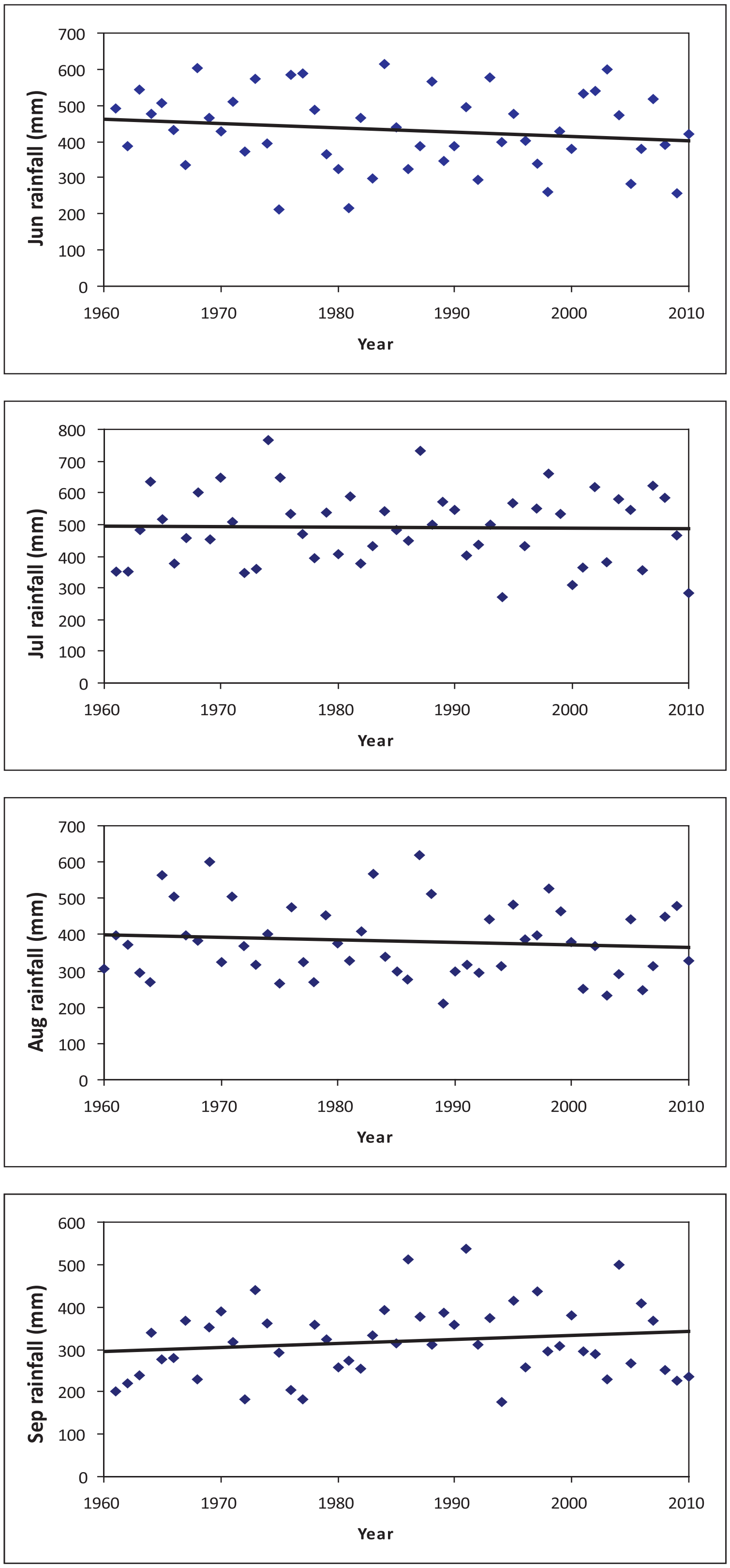
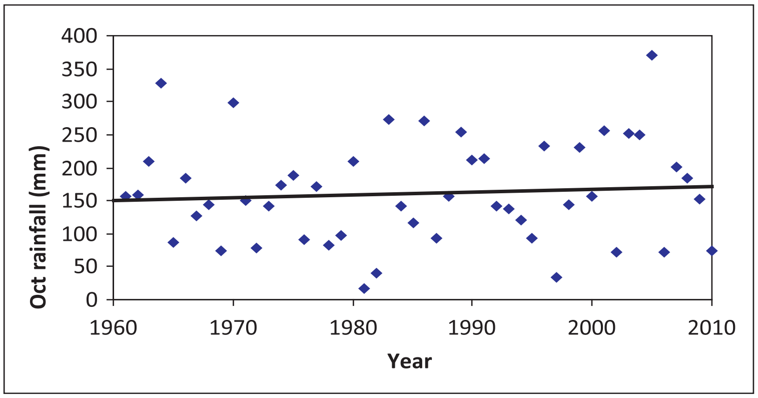
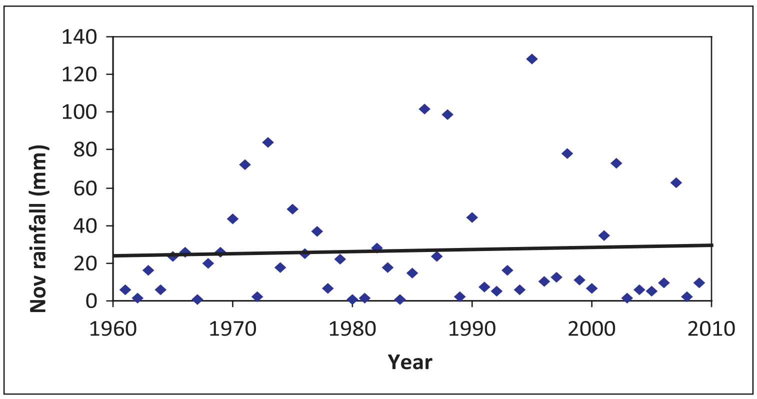
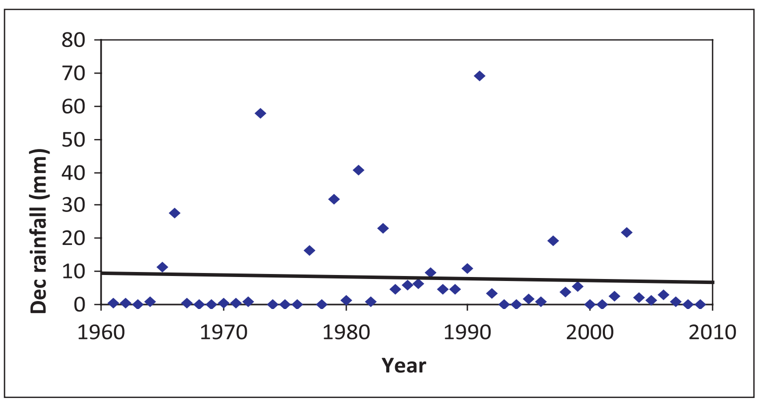


Figure 4.8: Trends in all-Bangladesh monthly rainfalls







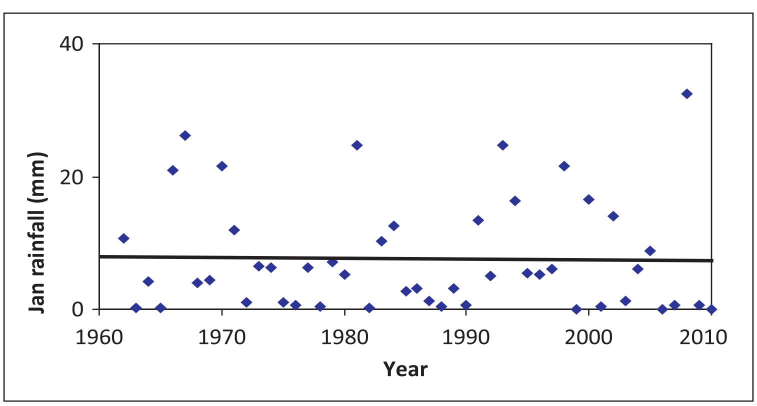


Figure 4.8: (continued)

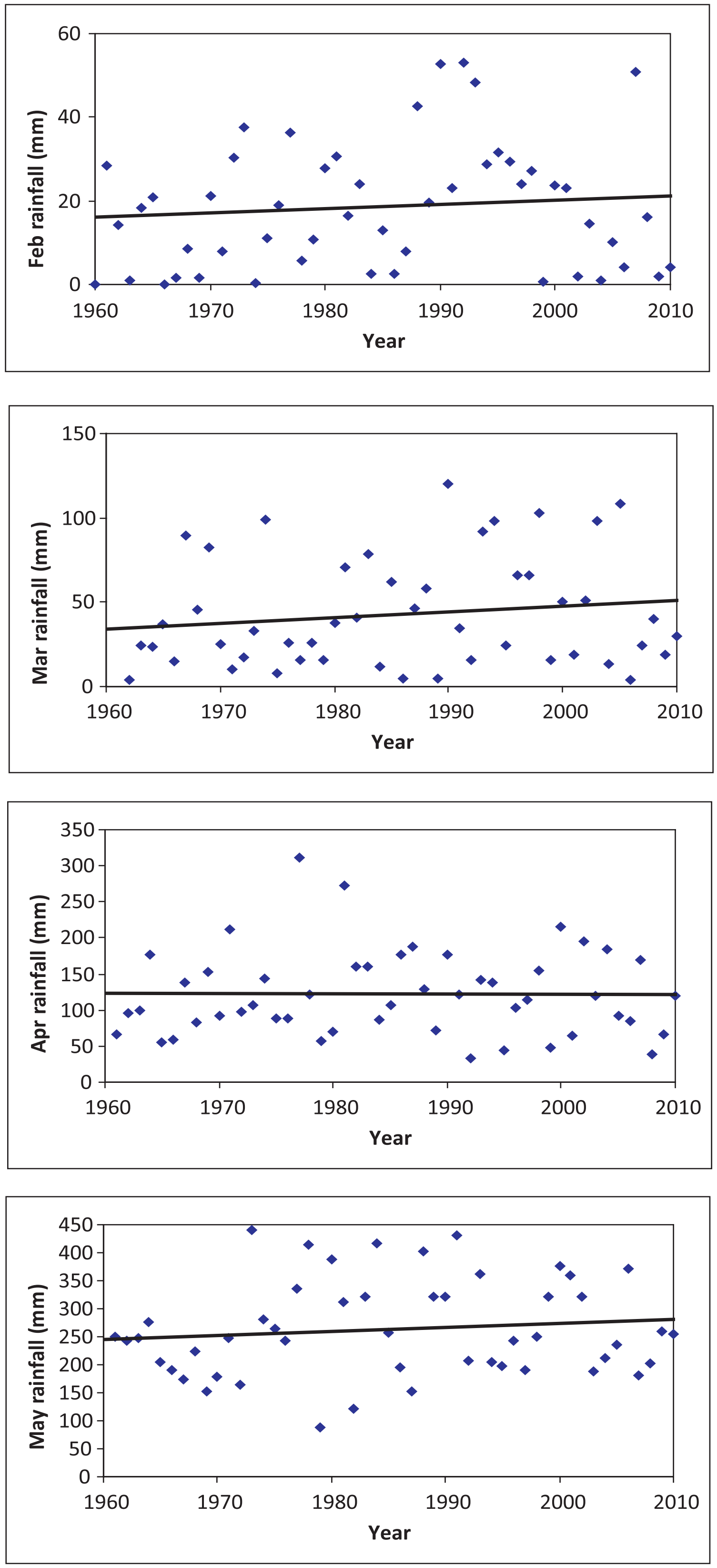


Figure 4.8: (continued)

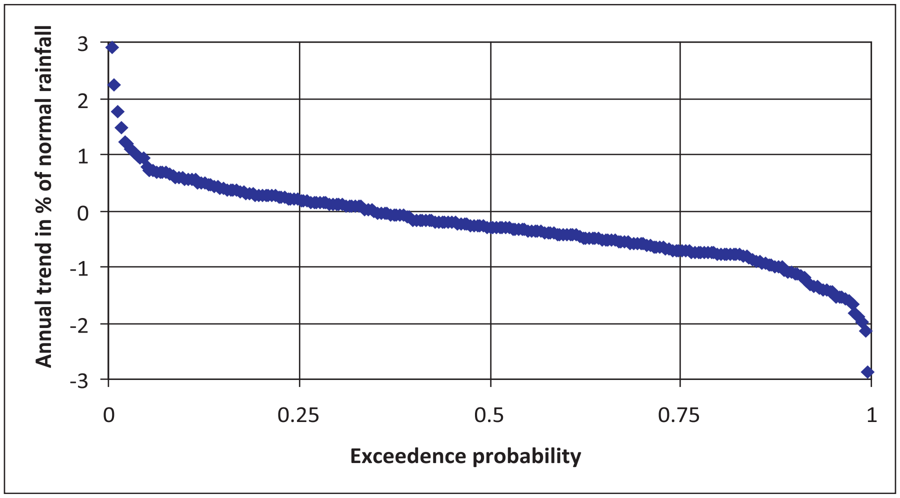


Figure 4.9: Exceedence probability of a rainfall trend in the month of June

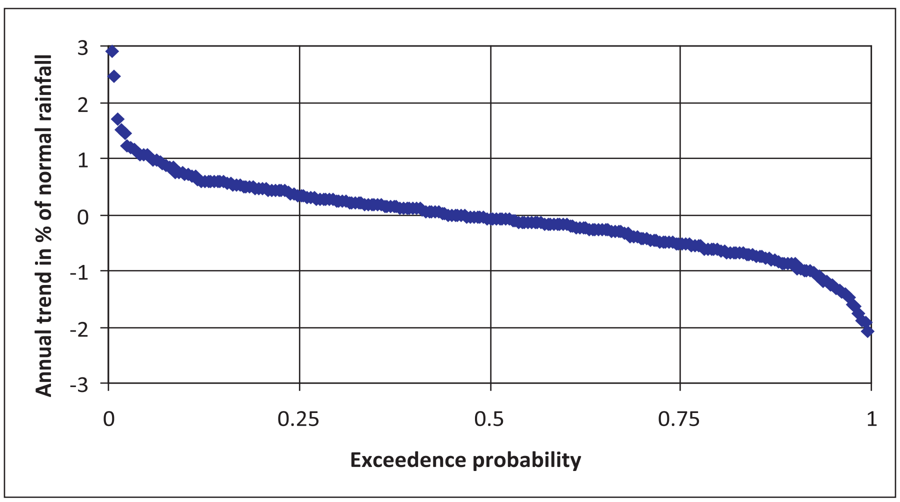


Figure 4.10: Exceedence probability of a rainfall trend in the month of July

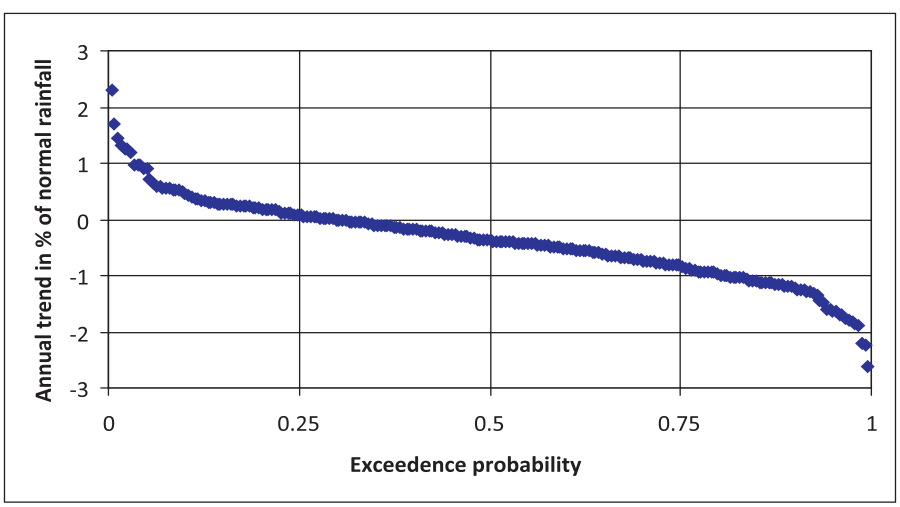


Figure 4.11: Exceedence probability of a rainfall trend in the month of August

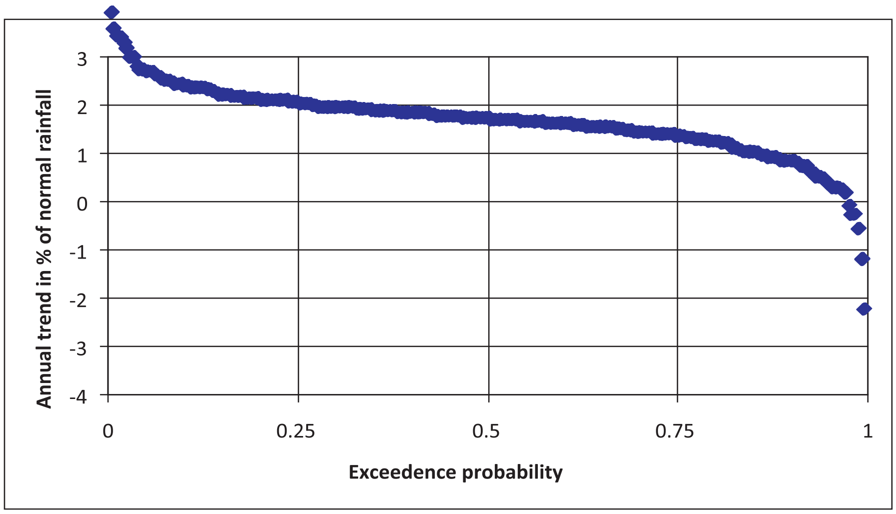


Figure 4.12: Exceedence probability of a rainfall trend in the month of September

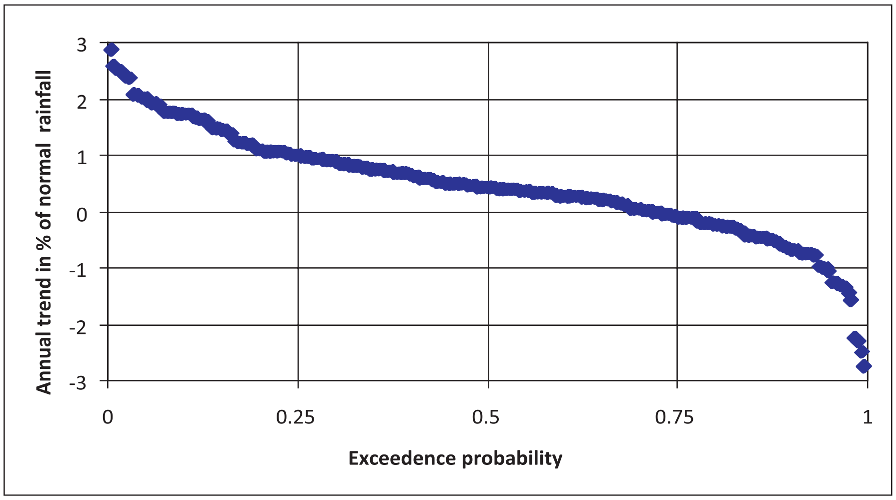


Figure 4.13: Exceedence probability of a rainfall trend in the month of October

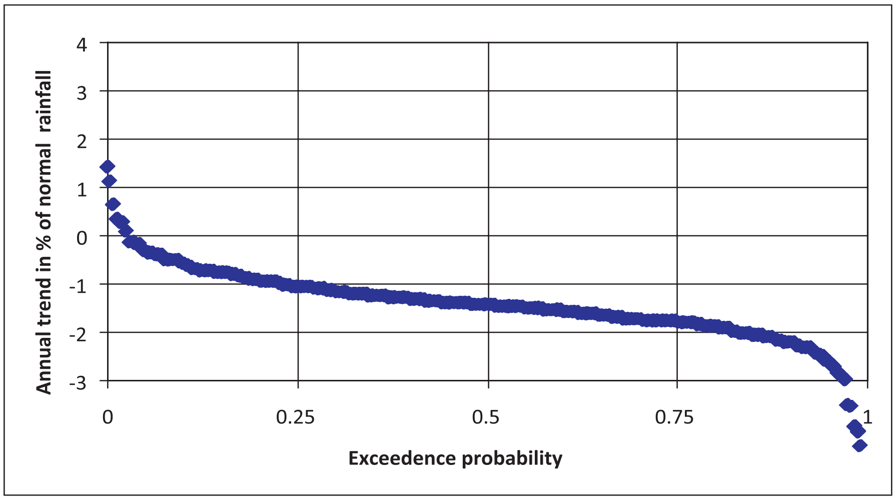


Figure 4.14: Exceedence probability of a rainfall trend in the month of May

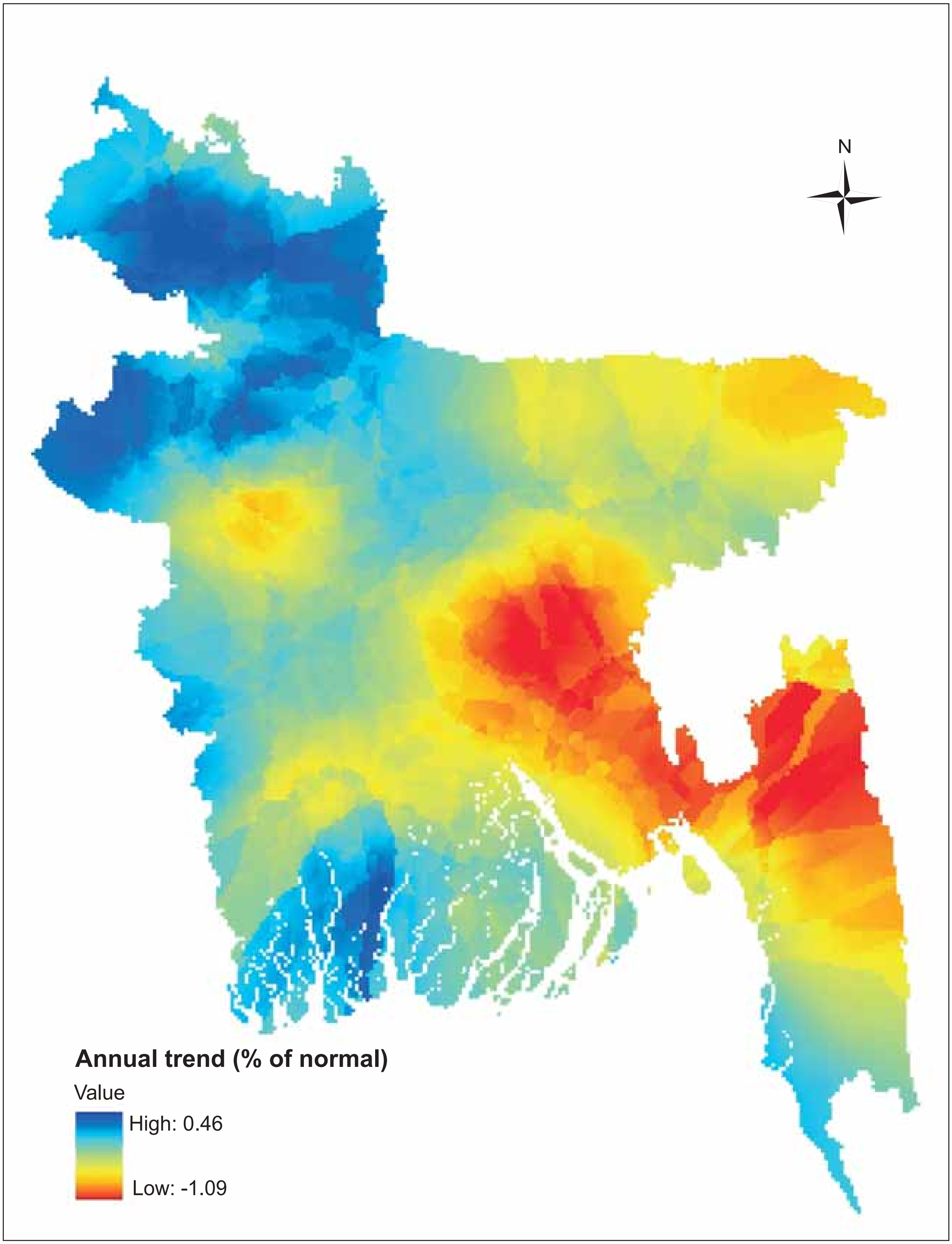


Figure 4.15: Spatial variation of trends in June rainfall (trend per year is expressed as percentage of normal rainfall)

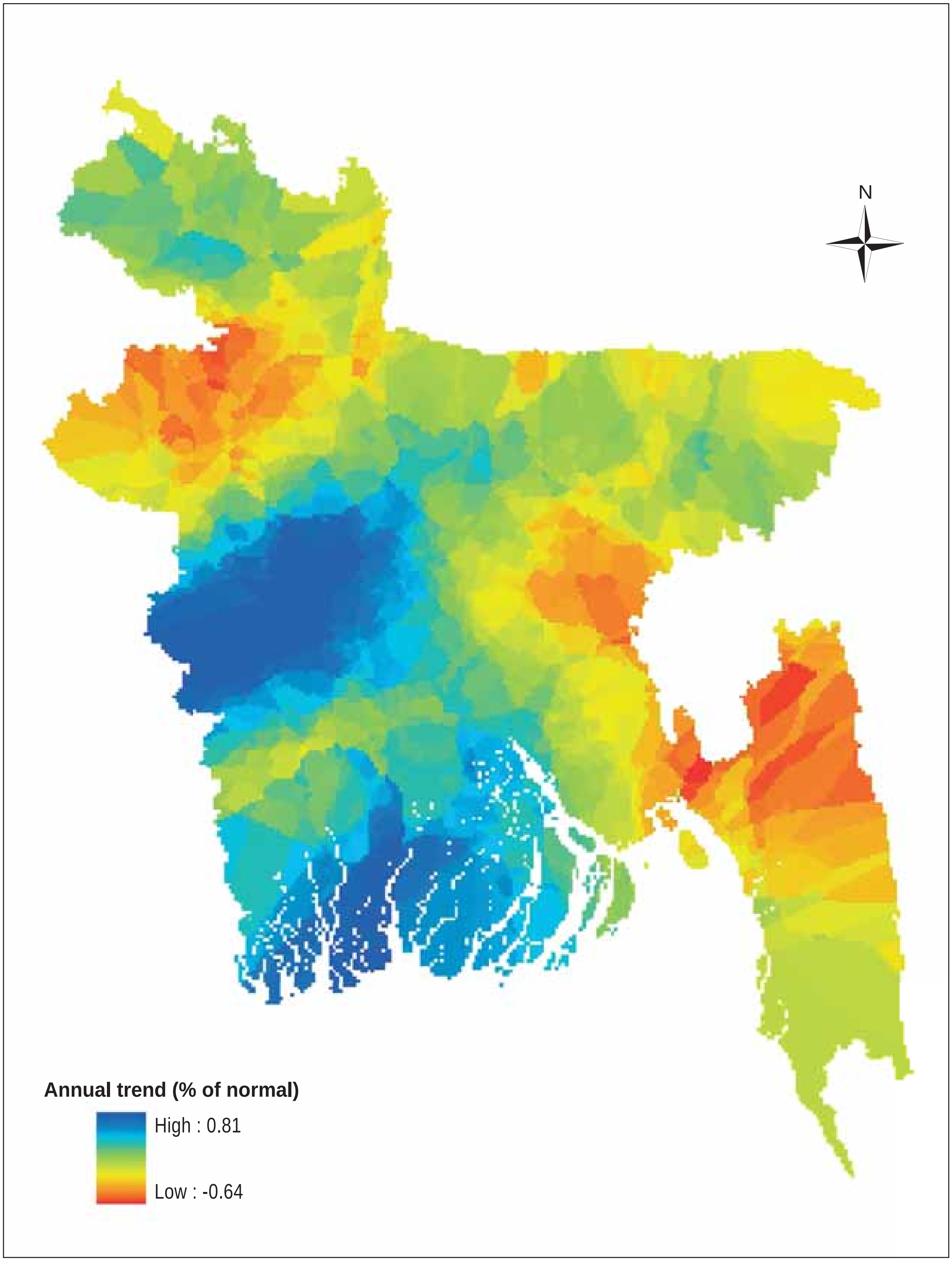


Figure 4.16: Spatial variation of trends in July rainfall (trend per year is expressed as percentage of normal rainfall)

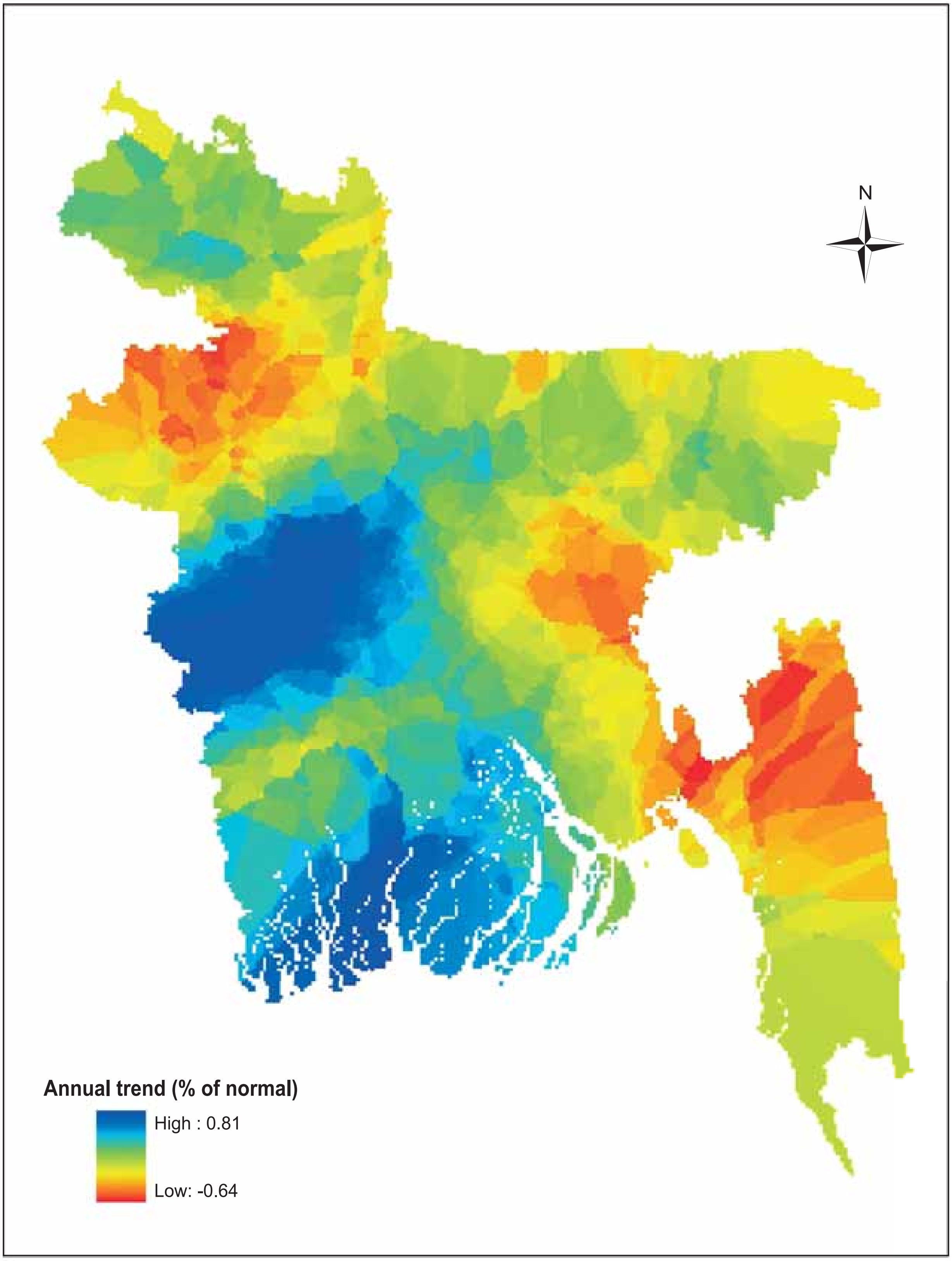


Figure 4.17: Spatial variation of trends in August rainfall (trend per year is expressed as percentage of normal rainfall)

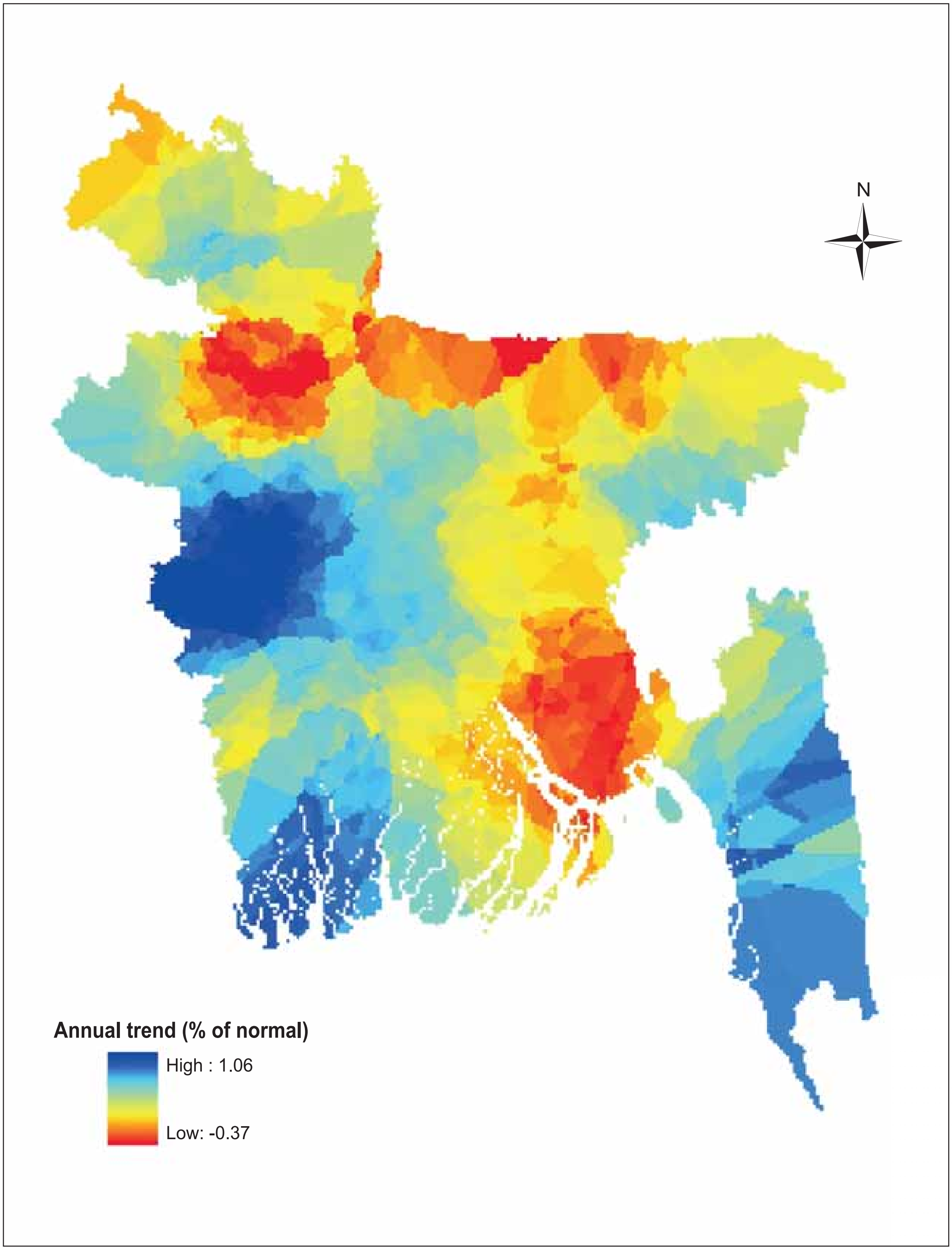


Figure 4.18: Spatial variation of trends in September rainfall (trend per year is expressed as percentage of normal rainfall)

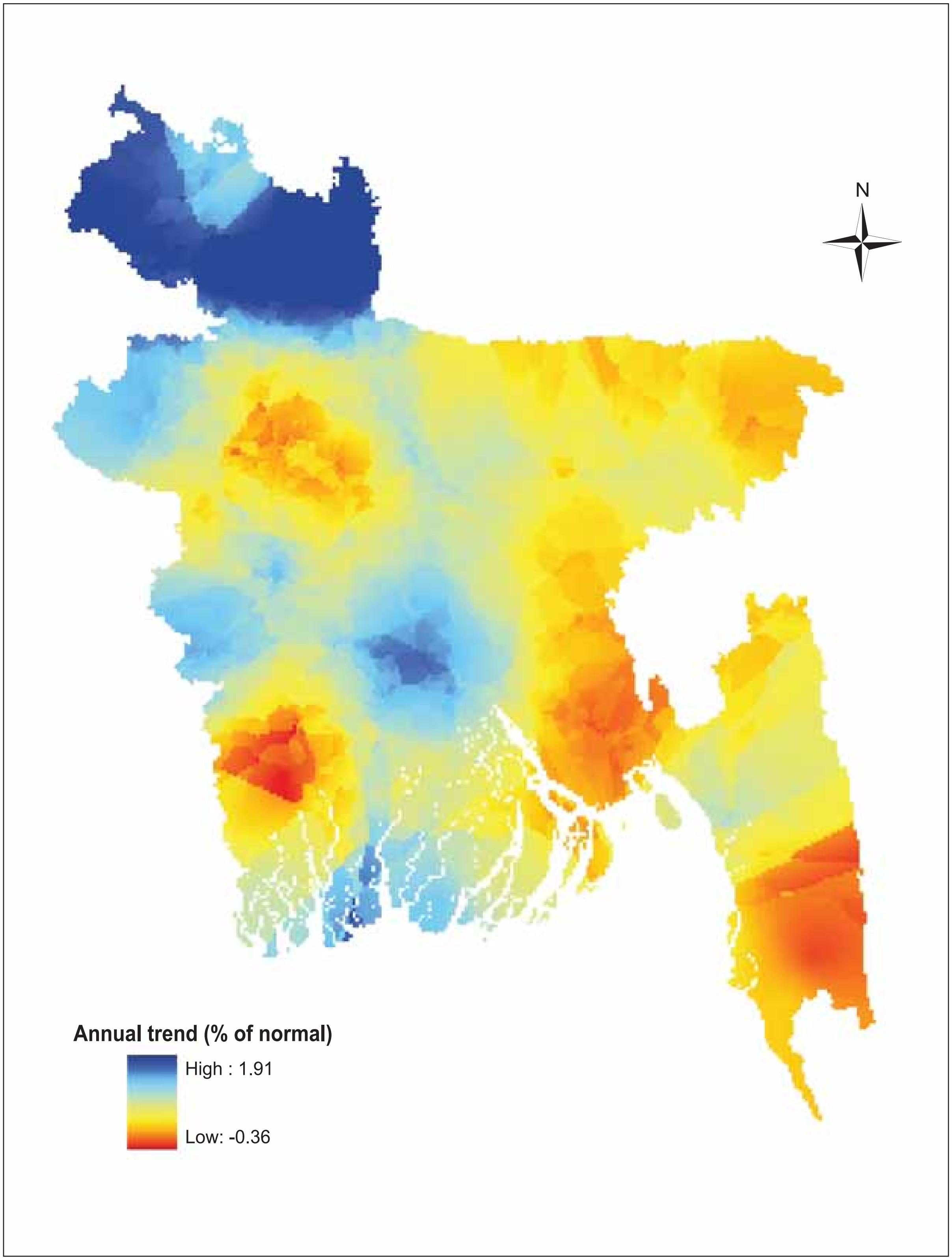


Figure 4.19: Spatial variation of trends in October rainfall (trend per year is expressed as percentage of normal rainfall)

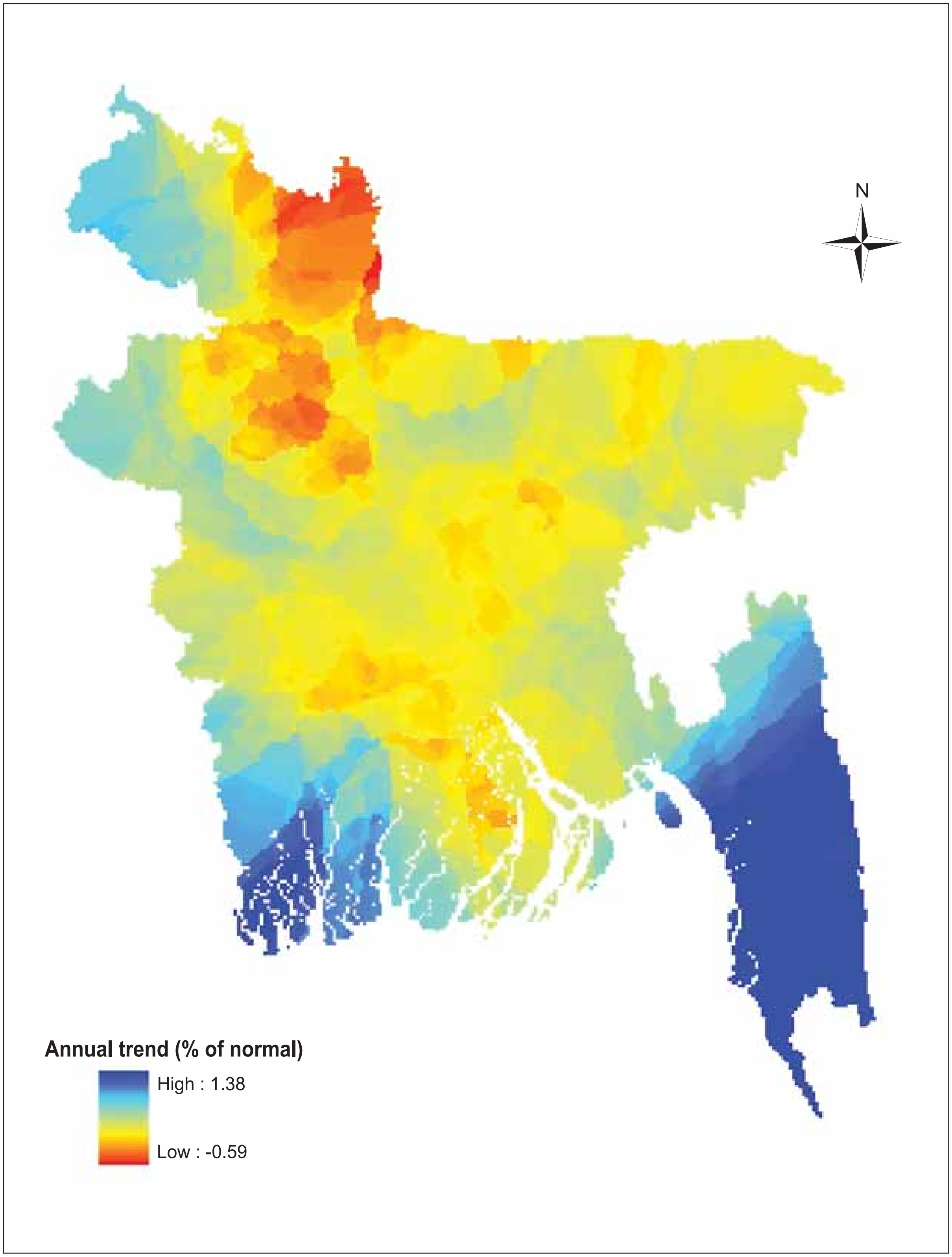


Figure 4.20: Spatial variation of trends in May rainfall (trend per year is expressed as percentage of normal rainfall)

The variability, measured in terms of standard deviation, in all-Bangladesh monthly rainfalls is given in Figure 4.21. It is seen from the figure that the variability in rainfalls in the months of September, March, February, January, October, July and June have increased, while that in the months of August has decreased. It thus appears that the inter-annual variability in rainfalls in most months has increased. This indicates that the rainfall is becoming increasingly more uncertain and unpredictable.

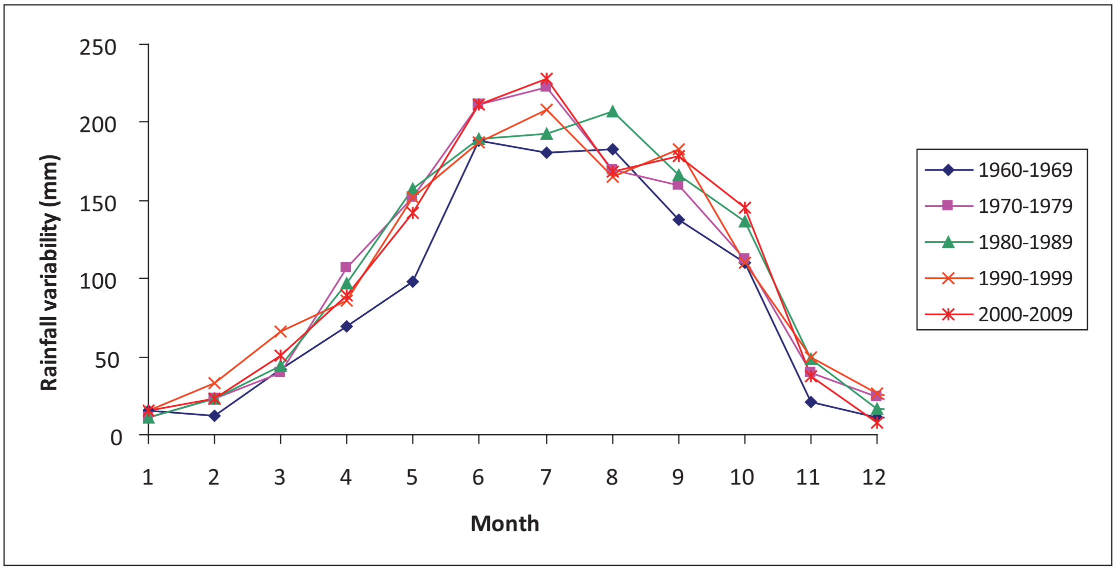


Figure 4.21: All-Bangladesh variability in monthly rainfalls

4.5 Other Rainfall

4.5.1 Annual maximum rainfall

All-Bangladesh normal maximum daily rainfalls were 160, 157 and 152 mm during 1960-1989, 1970-1999 and 1980-2009, respectively. Thus the normal maximum daily rainfalls have remained almost steady.

All-Bangladesh decadal maximum daily rainfalls for different decades are given in Figure 4.22. It is seen from the figure that such rainfalls have also remained almost steady at country level.

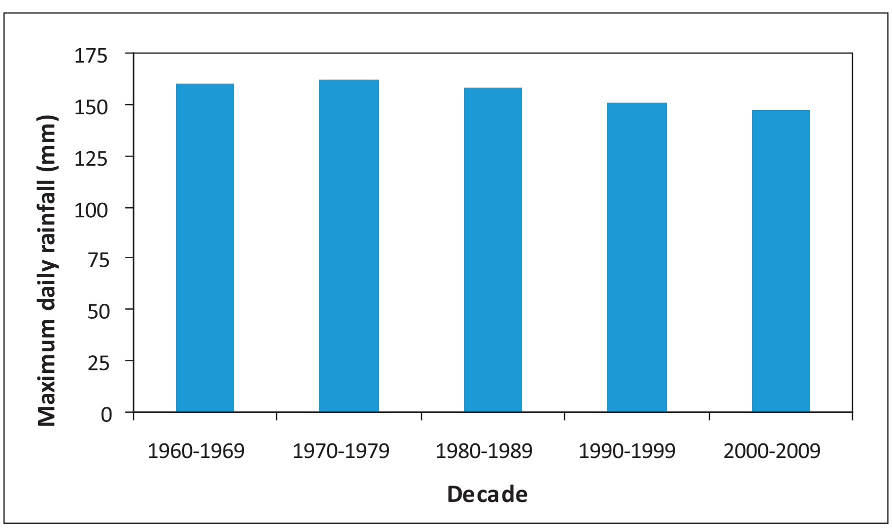


Figure 4.22: All-Bangladesh daily maximum rainfalls in different decades

A time series plot of all-Bangladesh maximum daily rainfalls is given in Figure 4.23. A linear regression line is superimposed on the plot to get a visual impression about the trend in maximum daily rainfalls. It is seen from the figure that the overall rainfall intensity in the country has remained practically trend-free.

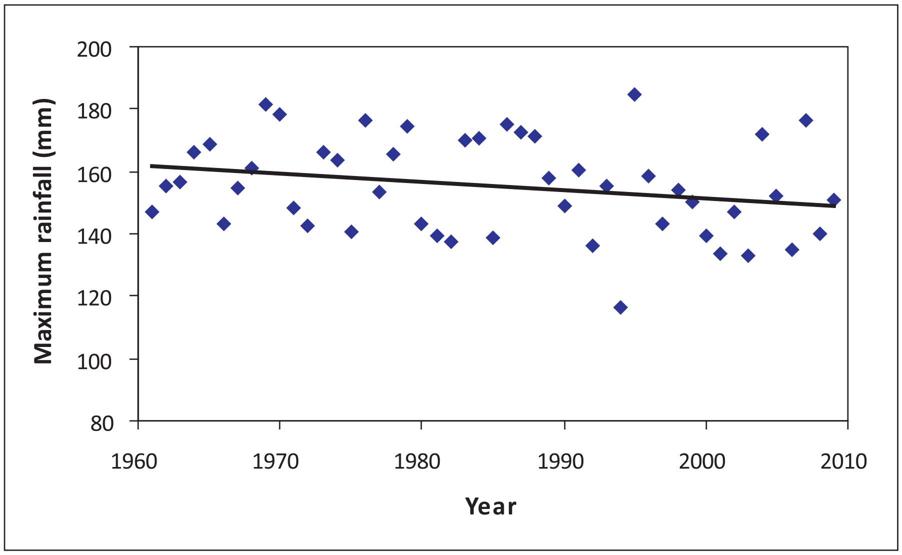


Figure 4.23: Trend in all-Bangladesh maximum daily rainfalls [1961-2009]

The trend in annual maximum rainfalls for each individual station was also estimated. 127 stations were found to have decreasing trends and 114 stations were found to have increasing trends. The spatial variation of trends is shown in Figure 4.25. It is seen from the figure that the north-western part of the country has increasing trends in annual maximum rainfalls. The chance of increase in maximum rainfall is found to be about 47.1%. The median trend, which has an exceedence probability of 50%, was found to be decreasing at a rate of 0.04% per year (Figure 4.24). This means that, over a period of 10 years, the annual maximum rainfall has decreased by 0.4% only. It thus appears that the one-day maximum rainfall at country level has remained almost free of trend, except for some regions.

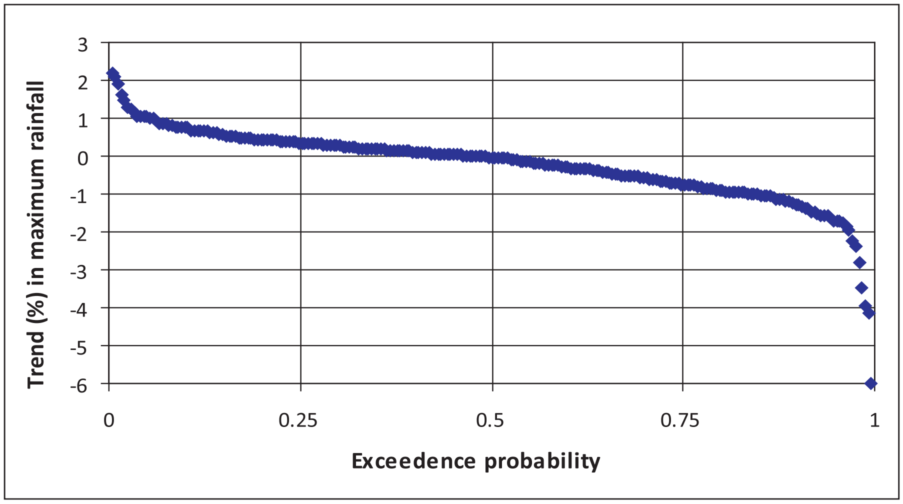


Figure 4.24: Exceedence probability of the trend in annual maximum rainfall

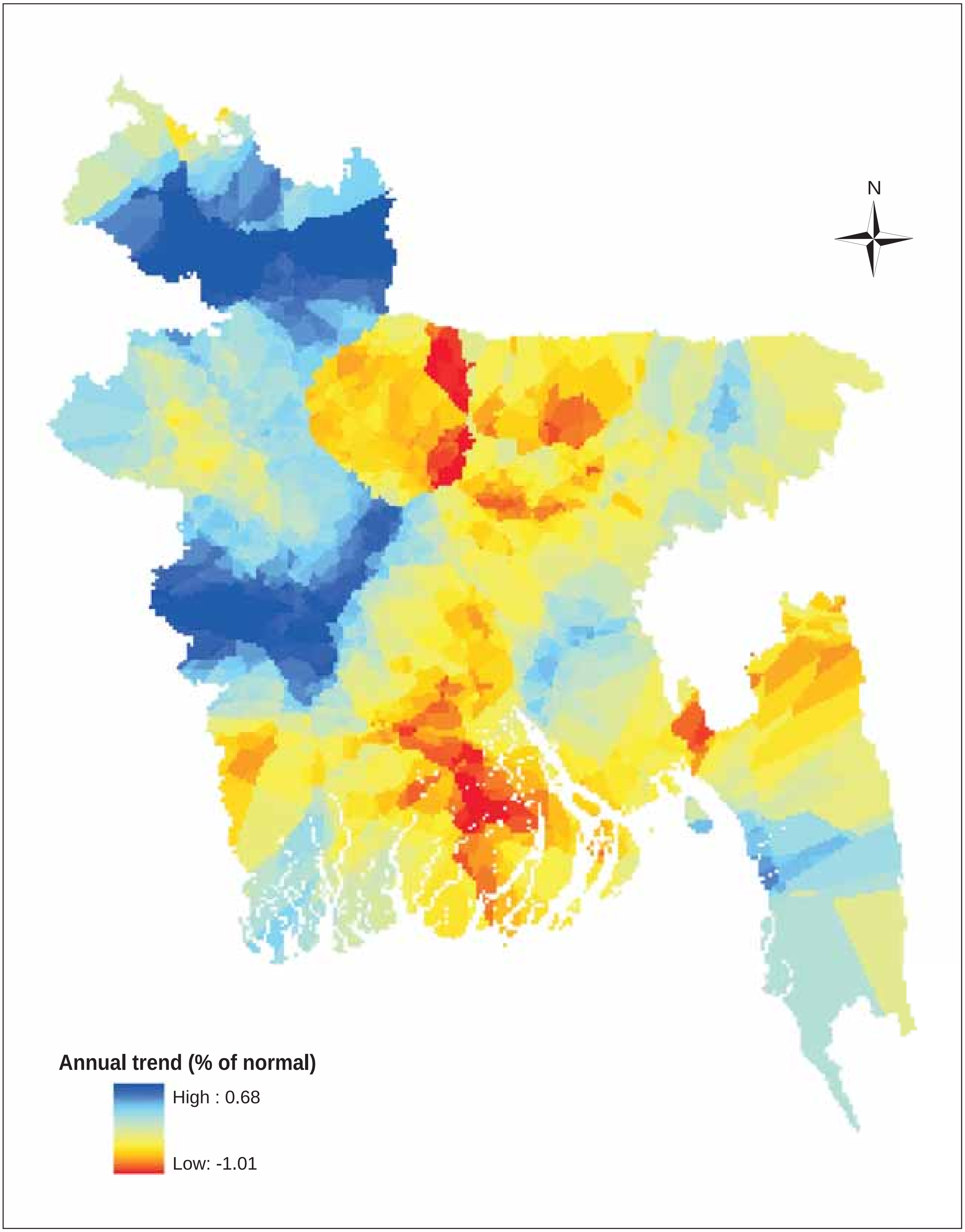


Figure 4.25: Spatial variation of trends in annual maximum rainfall (trend per year is expressed as percentage of normal maximum rainfall)

Trend in variability of all-Bangladesh maximum daily rainfalls is given in Figure 4.26. It is seen from the figure that the variability in extreme rainfall events has either decreased or remained unchanged.

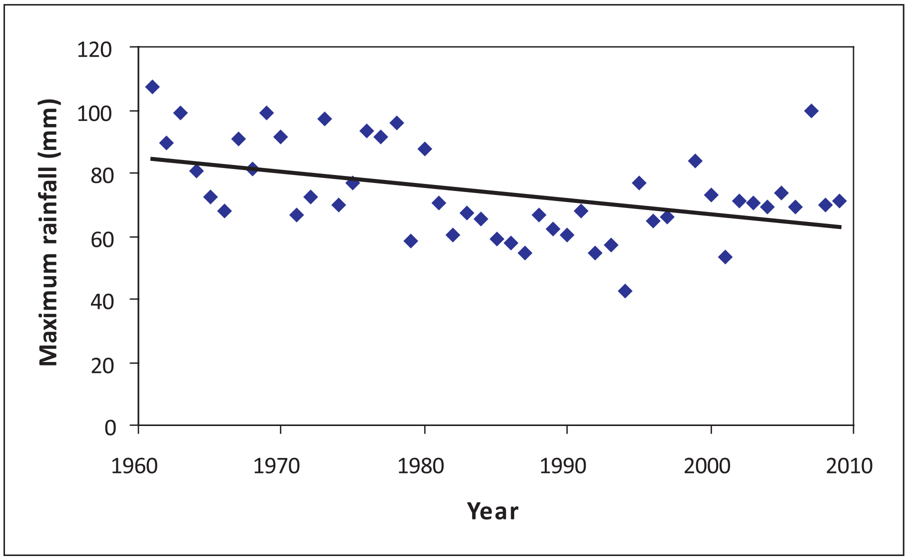


Figure 4.26: Trend in all-Bangladesh maximum daily rainfall variability [1961-2009]

So far reported the results of the analysis of BWDB rainfall data for its better coverage. However, the available period of records of BWDB rainfall data is shorter compared to that of BMD data. Furthermore, the quality of BMD data in our experience of working with both the data sets appeared to be better than the BWDB data. Therefore, some further analyses with the BMD data was carried out. It is to be noted that the results that we have presented so far based on BWDB data are in general comparable to the results to be produced with the BMD data. We have verified this.

Table 4.4 shows the dates of occurrence of historical maximum one-day rainfalls at 17 selected locations in Bangladesh (BMD data). It appears from the table that Cox's Bazar experienced the highest one-day rainfall of 720 mm in Bangladesh on 15 June 2006. The station with the second highest rainfall is Mymensingh with rainfall of 713 mm on 26 September 2004 and the station with the third highest rainfall is Rangpur with rainfall of 710 mm on 18 June 2002. It thus appears that the most extreme one-day rainfall events have occurred in recent years. However, this does not necessarily mean that extreme rainfall events have increasing trends. In fact, our analysis with BMD data suggests that only 3 stations (Rangpur, Dinajpur and Comilla), out of 17 for which long-term data are available, have significant trends (two increasing and one decreasing) and other stations are essentially trend free (Table 4.4).

4.5.2 Rainy days

The number of rainy days for each station and for each year was counted. Then the trend in the number of rainy days for each station was determined. Table 4.5 presents such trends and their statistical significance for some selected stations. BMD data, instead of BWDB data, were used in this analysis for its longer duration of availability and better quality as mentioned earlier. It is seen from the table that the number of rainy days has in general an increasing trend in Bangladesh. Out of the 17 stations listed in the table, Khulna, Rangamati, Satkhira, Dinajpur, Mymensing, Sylhet, Comilla, Maijdi Court and Barisal have increasing trends at a confidence level of 99%. Jessore and Cox's Bazar also have increasing trends, but at a lower level of confidence (80%). The other six stations do not show any trend in the number of rainy days at a confidence level of 80%.

Table 4.4: Dates of occurrences and magnitudes of one-day maximum rainfalls at different locations in Bangladesh

Station	One-day maximum rainfall (mm)	Date of occurrence	Trend in one-day annual maximum rainfaal (mm/decade)	Significance level
Bogra	279	24/06/1988	-0.97	0.772
Comilla	442	03/08/1958	-8.72	0.056
Cox's Bazar	720	15/06/2006	1.78	0.761
Dinajpur	508	29/09/1996	11.35	0.046
Faridpur	370	27/09/1989	-4.01	0.362
Jessore	281	30/06/1965	0.74	0.851
Mymensingh	713	26/09/2004	4.13	0.540
Srimangal	514	07/09/1976	-3.69	0.434
Rangpur	710	18/06/2002	14.43	0.022
Khulna	430	27/08/1986	2.55	0.610
Satkhira	302	27/09/1986	-0.60	0.889
Chittagong	511	04/08/1983	2.31	0.675
Barisal	258	11/10/1967	-1.27	0.731
Maijdi Court	520	18/07/1981	3.28	0.544
Dhaka	341	14/09/2004	-3.37	0.454
Sylhet	508	04/02/1966	-5.17	0.378
Rangamati	352	21/07/1960	6.88	0.293

4.5.3 Consecutive rainy days

The number of consecutive days with rainfalls was also counted for each station and for each year. From this data, the maximum number of consecutive rainy days was sorted out for each station and for each year. Finally, the trend in the maximum number of consecutive rainy days was determined for each station and given in Table 4.6. It is seen from the table that the longest consecutive rainy days in a year show increasing trends at Mymensing, Khulna, Satkhira and Dinajpur. These increasing trends are statistically significant at 95% level of confidence. Srimangal, Rangpur and Rangamati show decreasing, decreasing and increasing trends, respectively, at 90% level of confidence. Faridpur shows a decreasing trend at 80% level of confidence. The other nine stations do not show any trend in the longest consecutive rainy days in a year at a confidence level of 80%.

Table 4.5: Trends in number of rainy days (in a unit of days per decade) at some selected BMD stations

Station	Period of records	Trend	Significance level
Bogra	1948-2010	1.29	0.210
Comilla	1948-2010	2.65	0.010
Cox's Bazar	1948-2010	1.48	0.108
Dinajpur	1948-2010	5.61	0.000
Faridpur	1948-2010	-0.52	0.587
Jessore	1948-2010	1.87	0.104
Mymensingh	1948-2010	4.65	0.000
Srimangal	1948-2010	-1.31	0.257
Rangpur	1948-2010	-0.24	0.803
Khulna	1948-2010	8.05	0.000
Satkhira	1948-2010	5.88	0.000
Chittagong	1949-2010	0.64	0.416
Barisal	1949-2010	1.97	0.029
Maijdi Court	1951-2010	3.64	0.011
Dhaka	1953-2010	0.12	0.901
Sylhet	1956-2010	3.47	0.001
Rangamati	1957-2010	6.23	0.000

Table 4.6: Trends in maximum number of consecutive rainy and non-rainy days (in a unit of days per decade) at some selected BMD stations

Station	Trend in rainy days	Significance level	Trend in non-rainy days	Significance level
Bogra	-0.27	0.400	-0.60	0.739
Comilla	0.35	0.233	-1.99	0.353
Cox's Bazar	-0.42	0.359	-2.77	0.259
Dinajpur	0.80	0.025	-7.08	0.023
Faridpur	-0.41	0.119	-2.49	0.196
Jessore	-0.13	0.656	-2.32	0.213
Mymensingh	1.01	0.003	-0.30	0.886
Srimangal	-0.93	0.081	2.20	0.210
Rangpur	-0.54	0.090	0.17	0.933
Khulna	1.00	0.005	-7.46	0.001
Satkhira	0.61	0.019	-5.01	0.029
Chittagong	-0.23	0.494	-0.23	0.494
Barisal	0.13	0.735	-4.29	0.033
Maijdi Court	0.42	0.435	-2.64	0.234
Dhaka	-0.19	0.523	1.12	0.604
Sylhet	-0.71	0.339	-0.97	0.674
Rangamati	0.94	0.098	-2.01	0.415

4.5.4 Consecutive non-rainy days

The number of consecutive days without rainfalls was counted for each station and for each year. From this data, the maximum number of consecutive non-rainy days was sorted out for each station and for each year. Finally, the trend in the maximum number of consecutive non-rainy days was determined for each station and given in Table 4.6. It is seen from the table that the longest consecutive non-rainy days in a year show in general a decreasing trend across Bangladesh. The decreasing trends at Khulna, Dinajpur, Satkhira and Barisal are statistically significant at 95% level of confidence. The decreasing trend at Faridpur is significant at 80% level of confidence. The other twelve stations do not show any trend in the longest consecutive non-rainy days in a year at a confidence level of 80%. Faridpur shows a decreasing trend in both longest consecutive rainy and non-rainy days.

4.5.5 Consecutive 3-day rainfalls

Trends in 3-day moving average maximum rainfalls are given in Table 4.7. It is seen from the table that the 3-day maximum rainfalls do not show any significant trend except for the stations of Rangpur, Dinajpur and Maijdi Court, where the trends are increasing.

Table 4.7: Trends in consecutive 3-day and 7-day maximum rainfalls (in a unit of mm per day per decade) at some selected BMD stations

Station	Trend in 3-day max rainfalls	Significance level	Trend in 7-day max rainfalls	Significance level
Bogra	-0.28	0.872	-0.48	0.615
Comilla	-2.22	0.260	-1.67	0.117
Cox's Bazar	-1.13	0.655	0.19	0.903
Dinajpur	4.68	0.097	1.59	0.193
Faridpur	-1.21	0.564	-0.74	0.498
Jessore	0.59	0.777	0.95	0.409
Mymensingh	0.78	0.755	-1.24	0.402
Srimangal	-0.26	0.900	0.13	0.908
Rangpur	9.46	0.002	4.22	0.002
Khulna	2.00	0.417	0.98	0.422
Satkhira	0.80	0.756	1.13	0.414
Chittagong	-0.03	0.993	-0.62	0.734
Barisal	-1.62	0.428	-0.60	0.613
Maijdi Court	3.83	0.114	1.56	0.225
Dhaka	1.36	0.533	0.38	0.741
Sylhet	-0.48	0.851	0.19	0.903
Rangamati	4.03	0.301	1.98	0.353

4.5.6 Consecutive 7-day rainfalls

Trends in 7-day moving average maximum rainfalls are given in Table 4.7. It is seen from the table that the 7-day maximum rainfalls do not show any significant trend except for the stations of Rangpur, Comilla and Dinajpur. Rangpur and Dinajpur show an increasing trend and Comilla shows a decreasing trend. It thus appears that only two stations - Rangpur and

Dinajpur - located in the far north-western part of Bangladesh show a consistent increasing trend in consecutive 3-day and 7-day rainfalls.

4.5.7 Days with 50 mm or more rainfalls

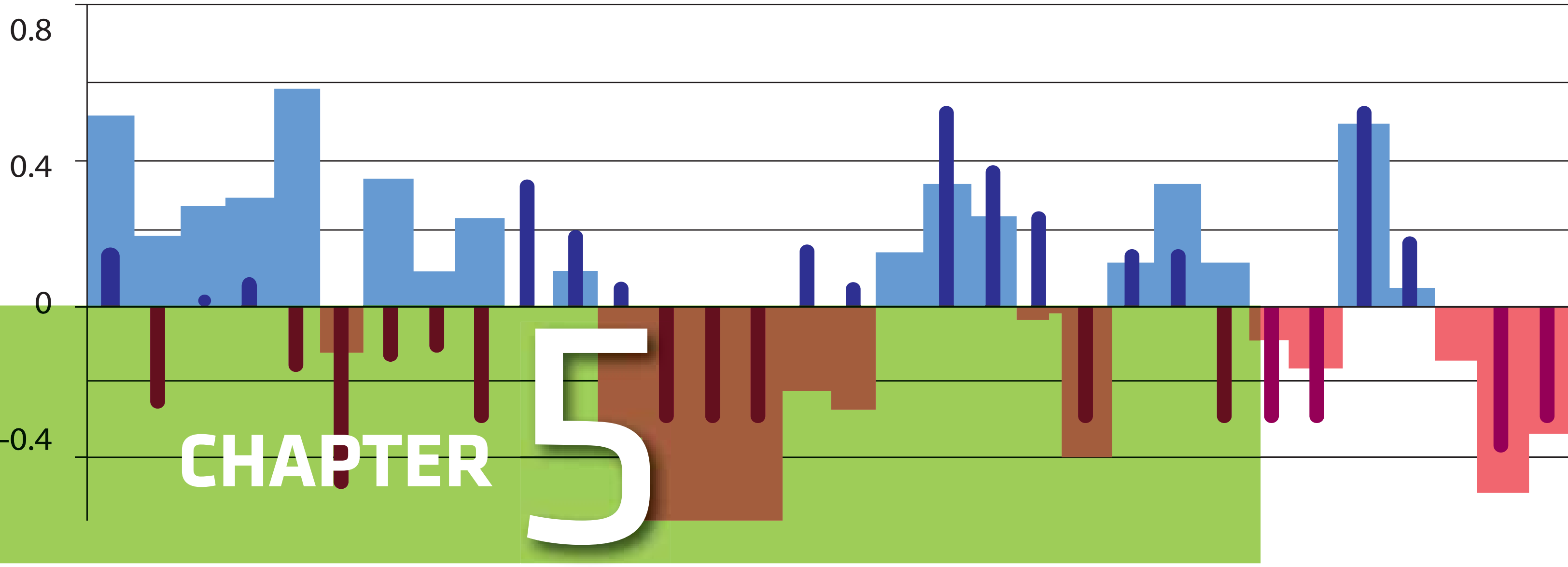
Trends in number of days with rainfalls equal to or greater than 50 mm are given in Table 4.8. It is seen from the table that Comilla, Rangpur, Faridpur, Dinajpur, Barisal and Rangamati show some trends in the number of days with 50 mm or more rainfalls in a year. Rangpur, Dinajpur and Rangamati show an increasing trend and Comilla, Faridpur and Barisal show a decreasing trend. The other 11 stations do not reveal any trend at a confidence level of 80%.

Table 4.8: Trends in number of days with rainfalls equal to or exceeding 50 mm and 100 mm (in a unit of days per decade) at some selected BMD stations

Station	Trend in no. of days with 50 mm or more rainfalls	Significance level	Trend in no. of days with 100 mm or more rainfalls	Significance level
Bogra	0.05	0.852	-0.02	0.839
Comilla	-1.50	0.000	-0.31	0.040
Cox's Bazar	0.27	0.513	-0.10	0.676
Dinajpur	0.41	0.114	0.25	0.029
Faridpur	-0.42	0.099	-0.17	0.155
Jessore	0.25	0.254	0.11	0.144
Mymensingh	-0.03	0.917	-0.04	0.716
Srimangal	-0.08	0.802	-0.03	0.833
Rangpur	0.79	0.006	0.22	0.135
Khulna	0.13	0.574	0.04	0.623
Satkhira	0.17	0.475	0.00	0.974
Chittagong	-0.19	0.579	-0.18	0.654
Barisal	-0.43	0.140	-0.11	0.394
Maijdi Court	-0.19	0.645	0.04	0.840
Dhaka	0.29	0.334	-0.08	0.529
Sylhet	0.16	0.761	0.08	0.742
Rangamati	0.54	0.188	0.21	0.292

4.5.8 Days with 100 mm or more rainfalls

Trends in number of days with rainfalls equal to or greater than 100 mm are given in Table 4.8. It is seen from the table that Dinajpur, Comilla, Rangpur, Jessore and Faridpur have some trends in the number of days with 100 mm or more rainfalls in a year. Dinajpur, Rangpur and Jessore have an increasing trend and Comilla and Faridpur have a decreasing trend. The other 12 stations do not reveal any trend at a confidence level of 80%. It thus appears that only two stations - Rangpur and Dinajpur - located in the far north-western part of Bangladesh show a consistent increasing trend in the number of days with rainfalls 50 mm or more as well as with rainfalls 100 mm or more. Another two stations - Comilla and Faridpur - show a consistent decreasing trend in the above aspects. It is to be noted here that we have also used the non-parametric techniques of testing the significance of trend in the above rainy days. There was no noticeable difference in the results between the two methods.



CHAPTER 5

Analysis of Observed Sunshine Duration

5.1 Introduction

Daily data on bright sunshine duration available at different stations of BMD were collected. The data were available for 34 stations. Initial scrutiny suggested that the length of available records for Mongla station was not adequate to carry out any analysis and hence it was dropped. A list of the stations along with the length of available records is given in Annexure B. The data were available for a period of 50 years (1961-2010). A map showing the locations of the stations is given in Figure 5.2.

5.2 Annual Sunshine Duration

As a whole Bangladesh annual normal sunshine duration for a period of 30 years (1980-2009) is found to be 6.38 hours. Such durations were 7.17 and 6.77 hours during 1960-1989 and 1970-1999, respectively. It thus appears that the annual normal sunshine durations have decreased gradually in Bangladesh.

All-Bangladesh decadal (10 years) sunshine durations are shown in Figure 5.1. It is seen from the figure that the sunshine durations started falling since 1970s. The highest sunshine duration was observed during the 1970s and the lowest during the 1990s. There is an overall decreasing trend in decadal sunshine durations.

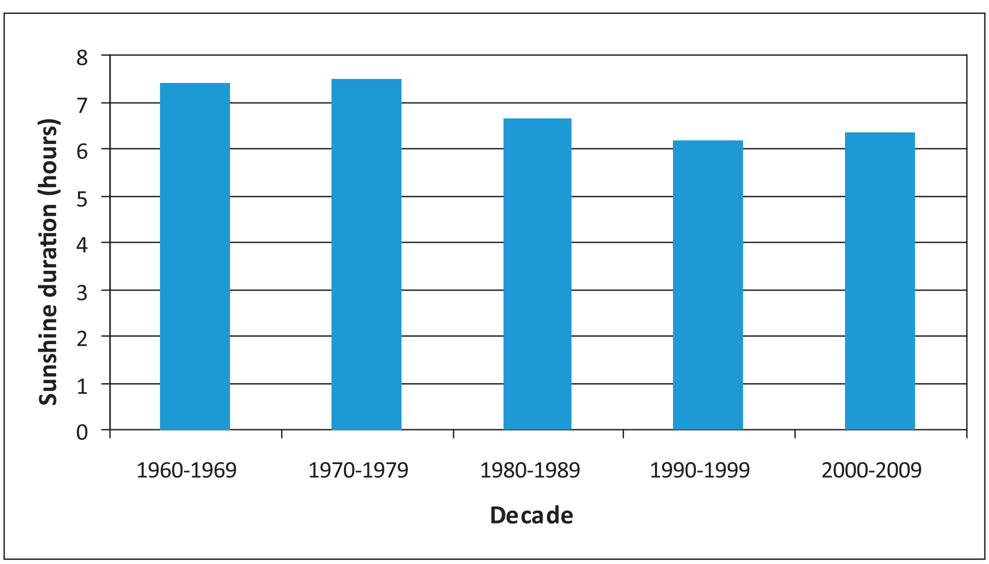


Figure 5.1: All-Bangladesh sunshine during different decades

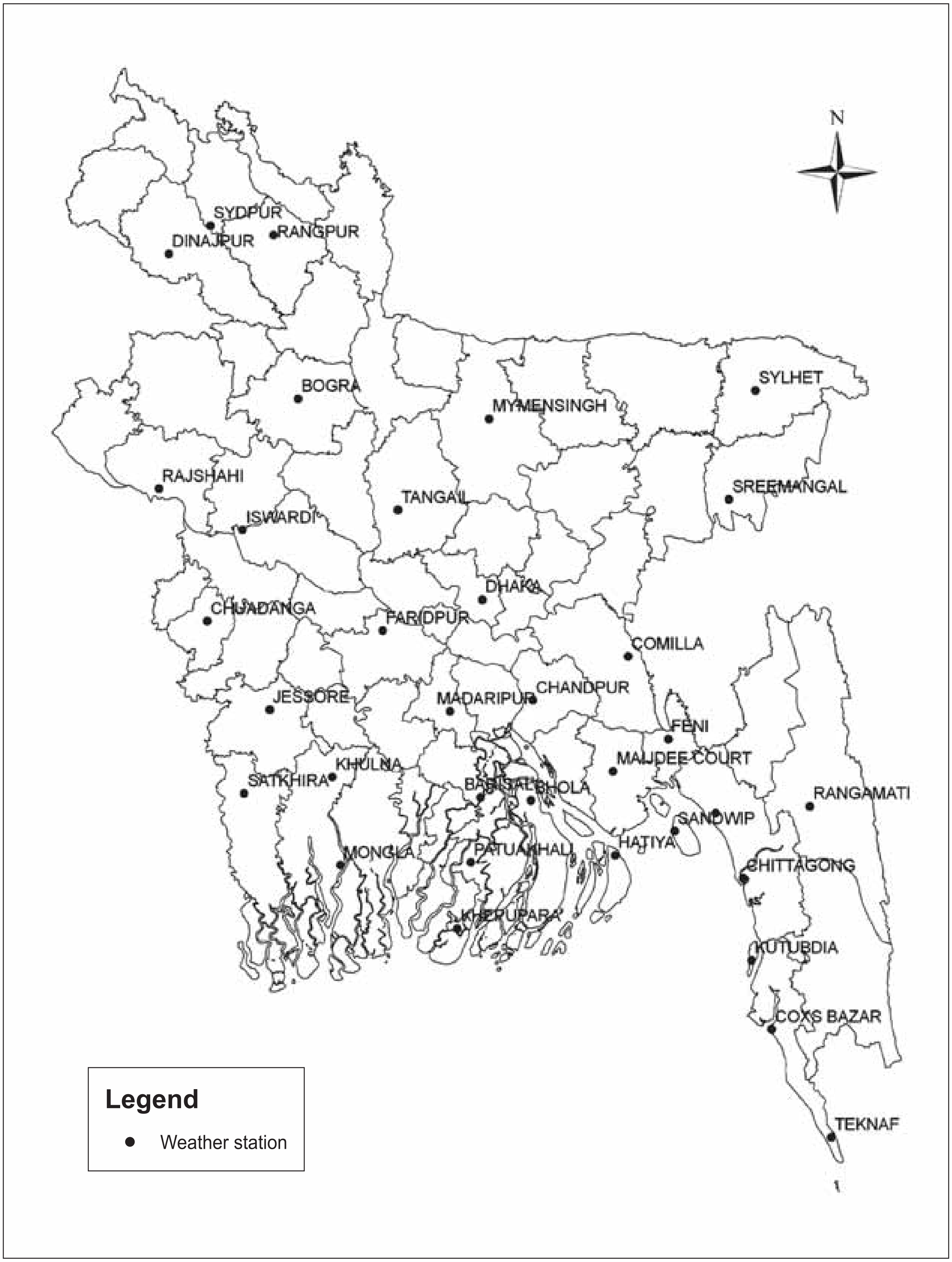


Figure 5.2: Locations of the BMD Weather stations

A time series plot of all-Bangladesh annual sunshine duration is given in Figure 5.3. It is seen from the figure that there is a decreasing trend in annual sunshine duration. The trend was found to be about 5.3% per decade. The trend is also found to be statistically significant at a confidence level of 99%.

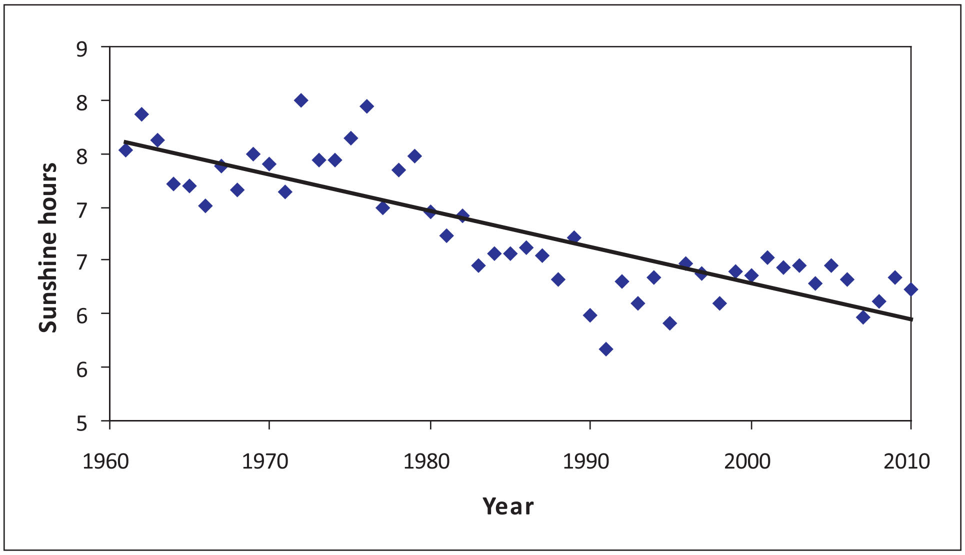


Figure 5.3: All-Bangladesh annual sunshine duration time series [1961-2010]

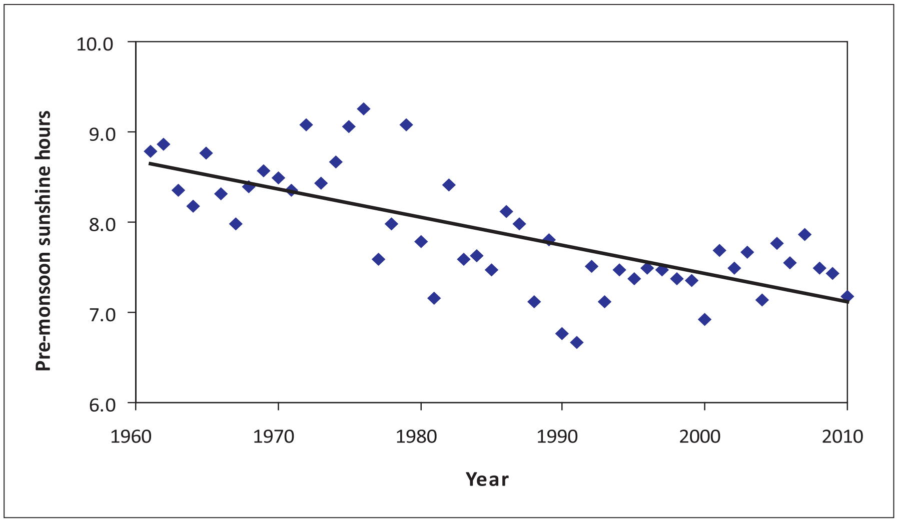
5.3 Seasonal Sunshine Duration

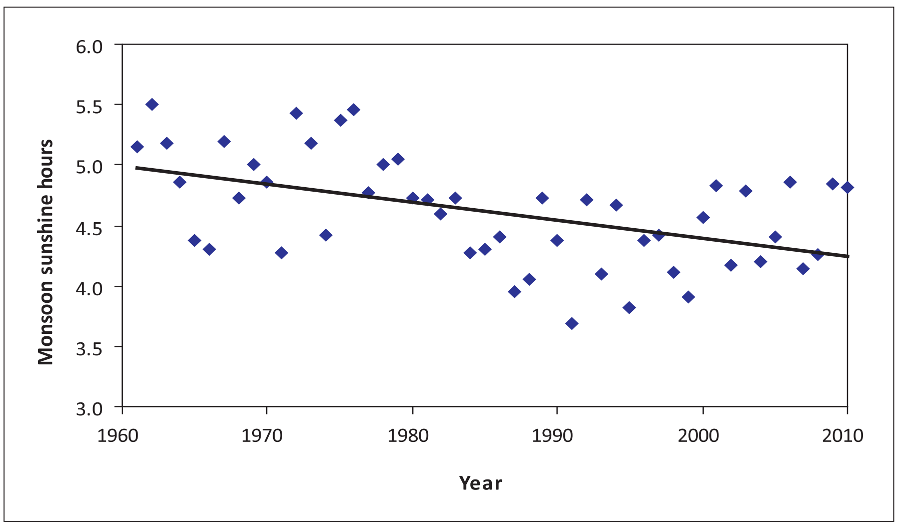
Time series plots of all-Bangladesh sunshine durations for different seasons are shown in Figure 5.4. It is seen from the figure that the sunshine durations in all the seasons have decreasing trends. The trends are found to be 4.1%, 3.4%, 5.3% and 8.1% per decade during the pre-monsoon, monsoon, post-monsoon and winter seasons, respectively (Table 5.1). The winter sunshine duration is decreasing at a staggering rate of 8.1% per decade. Moreover, the trends in the four seasons were found to be statistically significant at a confidence level of 99%.

Table 5.1: Trends in sunshine durations in different seasons

Season	Normal sunshine hours (1980-2009)	Trend [1] (% per decade)	Significance [2]
Pre-monsoon (Mar-May)	7.49	4.1	***
Monsoon (Jun-Sep)	4.39	3.4	***
Post-monsoon (Oct-Nov)	7.18	5.3	***
Winter (Dec-Feb)	7.40	8.1	***

*Note: [1]based on data of all 34 stations from 1961-2010; [2]***indicates that the trend is significant at a confidence level of 99%.*





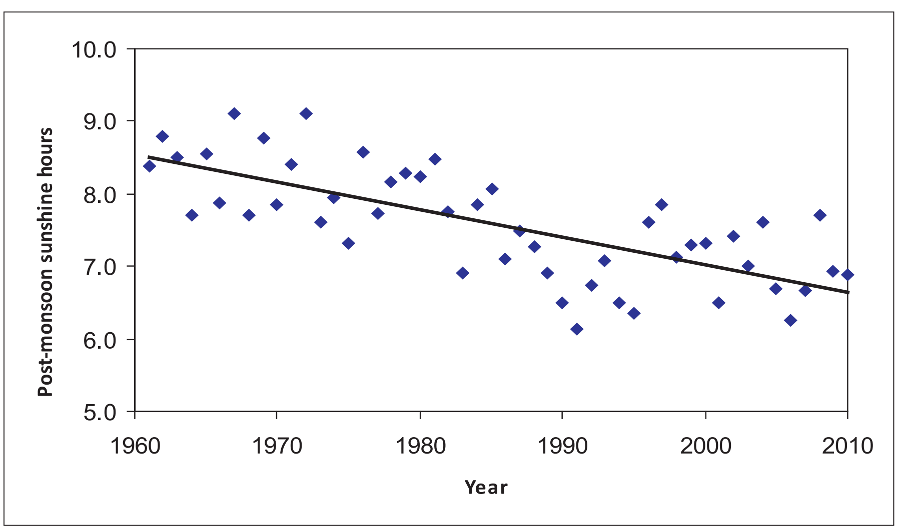


Figure 5.4: Trends in all-Bangladesh seasonal sunshine duration time series

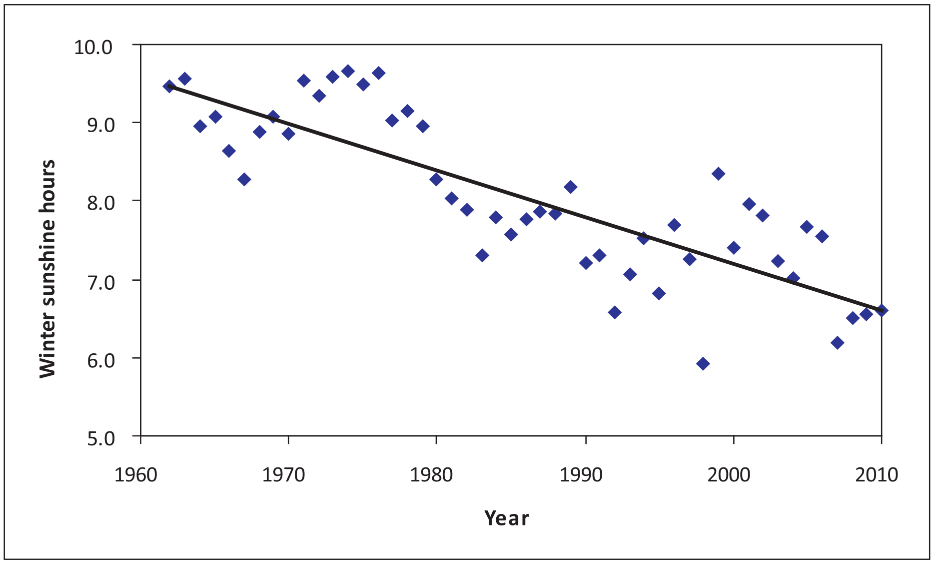


Figure 5.4: (continued)

5.4 Monthly Sunshine Duration

All-Bangladesh monthly normal sunshine duration variations are given in Figure 5.5. It is seen from the figure that the normal sunshine durations in all the months have decreased. The decrease is higher during November-February and lower during June-August.

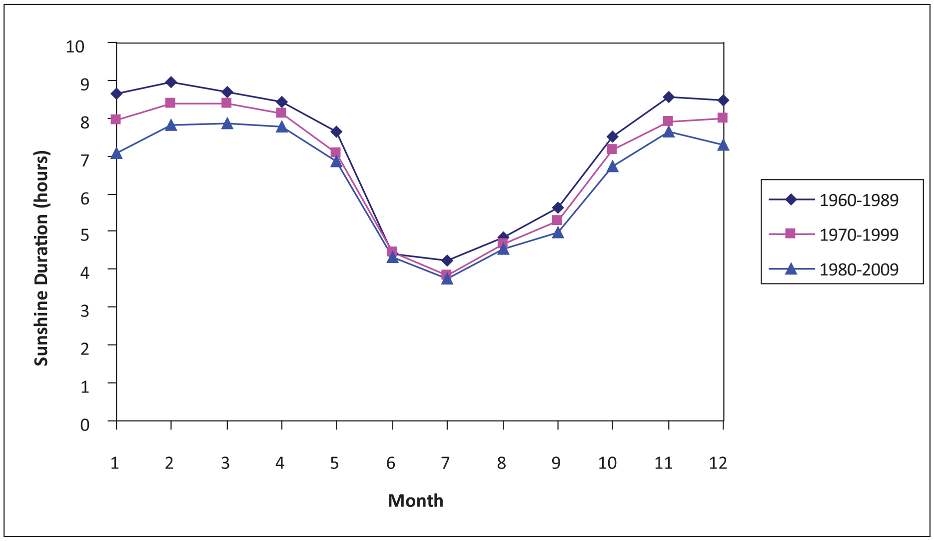


Figure 5.5: All-Bangladesh normal sunshine duration in different months

The trends in all-Bangladesh monthly sunshine durations are given in Table 5.2. It is seen from the table that the sunshine in all the months has decreasing trends. The trend is the highest during the month of January which is the peak period of winter. The trends are lower during June and August of the monsoon season and they are not significant at a level of confidence of 90%. For July, the trend is significant at 90% level of confidence. For the remaining months of September-May, the trends are significant even at 99% level of confidence.

Table 5.2: Trends in sunshine durations in different month

Month	Normal sunshine hours (1980-2009)	Trend[1] (% per decade)	Significance
Jan	7.0	-9.8	***
Feb	7.8	-6.0	***
Mar	7.9	-4.2	***
Apr	7.8	-3.6	***
May	6.8	-4.8	***
Jun	4.3	-0.5	NS
Jul	3.8	-5.0	**
Aug	4.6	-2.2	NS
Sep	5.0	-5.8	***
Oct	6.7	-4.8	***
Nov	7.6	-5.6	***
Dec	7.2	-8.0	***

Note: *1based on data of all 34 stations from 1961-2010; *** and ** indicate that the trends are significant at a confidence level of 99% and 95%, respectively, and NS indicates that the trend is not significant at a confidence level of 90%.*

The spatial distribution of trends in monthly sunshine duration was also investigated and is shown in Figures 5.6 and 5.7 for the months of January and June, respectively. The presence of some spatial patterns in the declining rates is evident from the figures. There is a declining trend in sunshine duration all over Bangladesh during January. The rates of decline increase from the south to the north (Figure 5.6). Though there are some increasing trends in the sunshine duration of June in the south, the overall pattern of trends is the same - the declining rate increases from the south to the north (Figure 5.7).

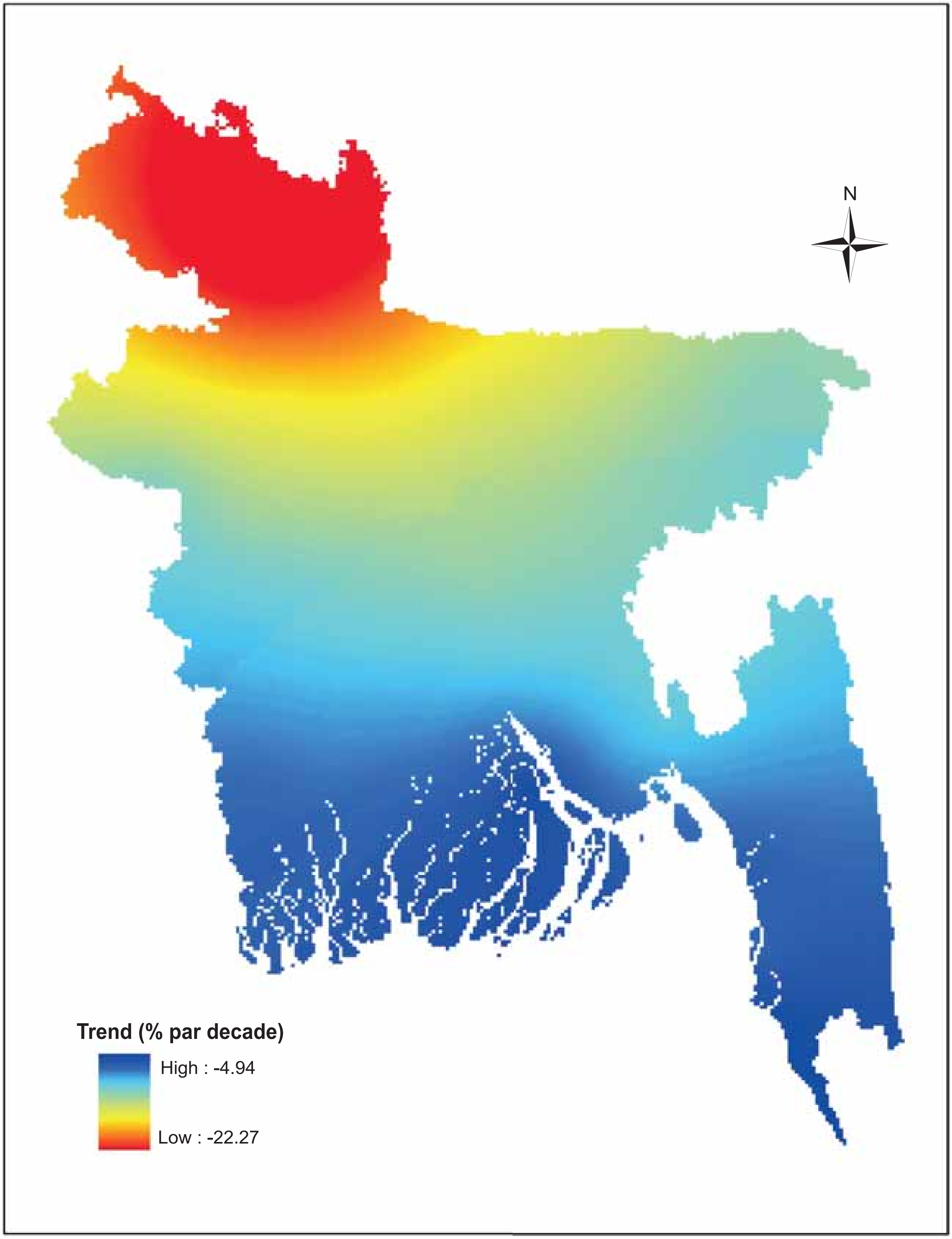


Figure 5.6: Spatial distribution of the trends in sunshine duration (% per decade) during the month of January

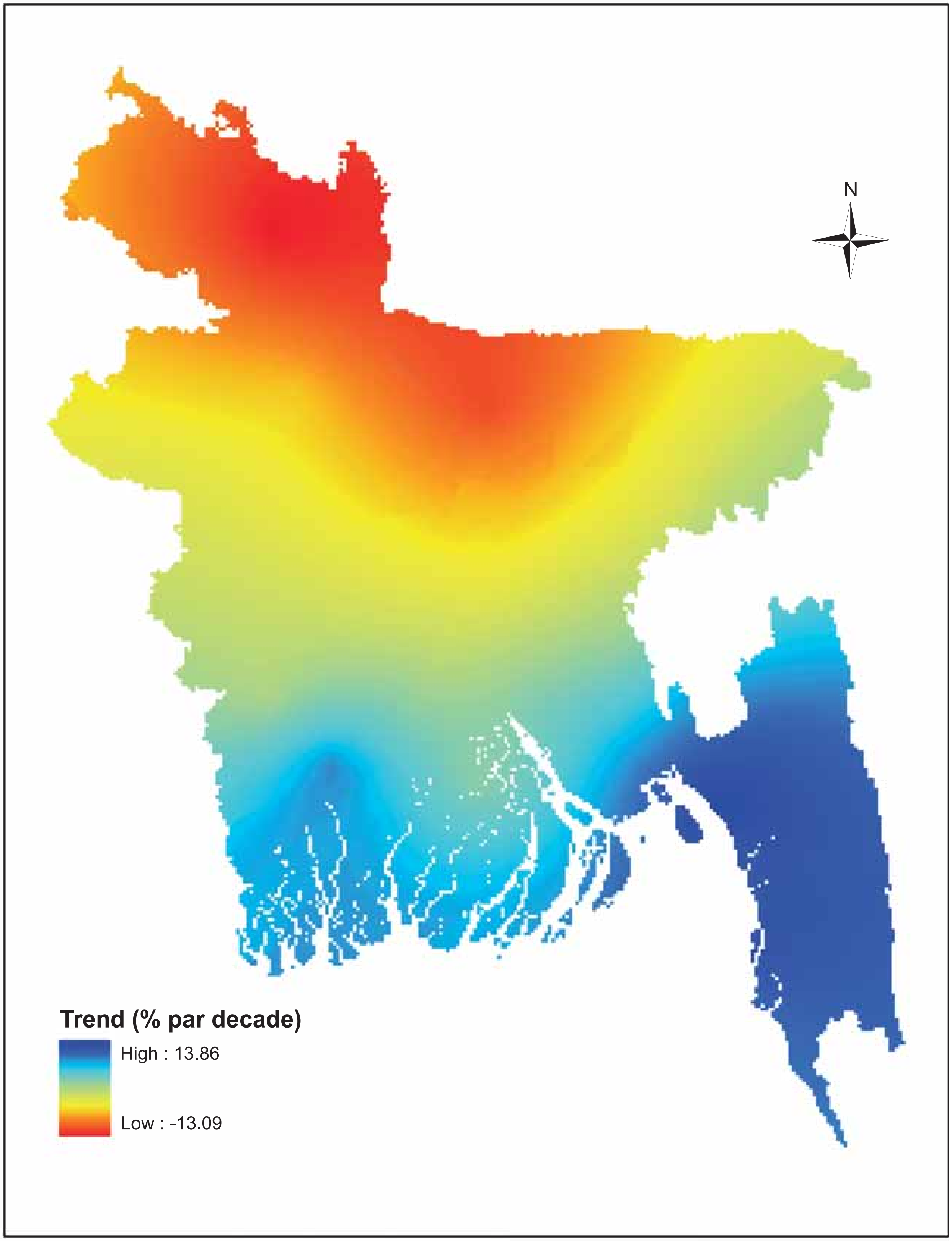


Figure 5.7: Spatial distribution of the trends in sunshine duration (% per decade) during the month of June

CHAPTER 6

Analysis of Observed Humidity

6.1 Introduction

Daily data on relative humidity available for different stations of BMD were collected. The data were available for 34 stations. Initial scrutiny suggested that the length of available records for Mongla station was not adequate to carry out any analysis and it was dropped. A list of the stations along with the length of available records is given in Annexure C. The data were available for a period of 63 years (1948-2010). A map showing the locations of the stations was given earlier in Figure 5.2 of Chapter Five.

6.2 Annual Humidity

All-Bangladesh annual normal relative humidity for a period of 30 years (1980-2009) is found to be 78.4%. Such humidity was 77.1%, 75.9% and 76.9% during 1970-1999, 1960-1989 and 1950-1979, respectively. It thus appears that the annual normal humidity has increased gradually in Bangladesh since 1960s.

6.3 Seasonal Humidity

The normal relative humidity for different seasons is given in Figure 6.1. It is seen from the figure that the humidity has changed more in recent years compared to the distant past during the winter and post-monsoon seasons. The humidity has increased by about 3.2% and 3.0% during the winter and post-monsoon seasons, respectively, during 1980-2009 compared to 1950-1979. In contrast, the humidity has decreased by about 0.5% during the monsoon season. The pre-monsoon humidity has increased by only about 0.7% during 1980-2009 compared to 1950-1979.

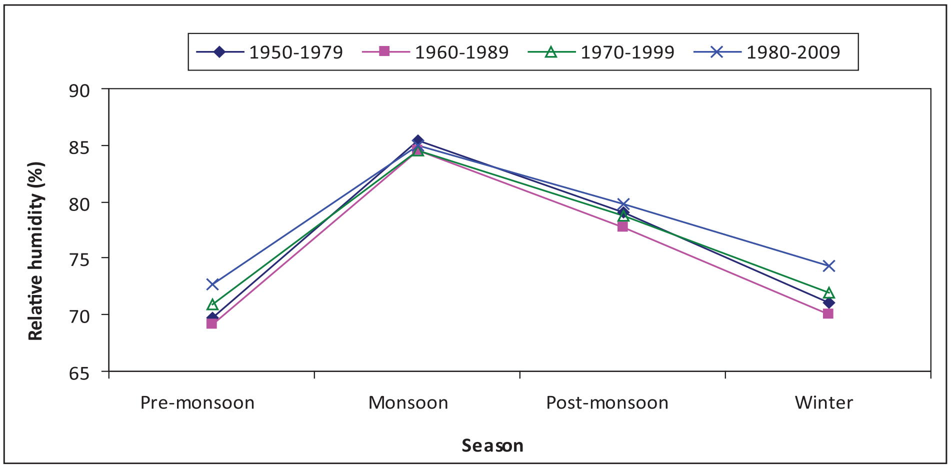


Figure 6.1: All-Bangladesh normal humidity during different seasons

Time series plots of all-Bangladesh humidity for different seasons are shown in Figure 6.2. It is seen from the figure that the humidity has an increasing trend in the pre-monsoon, post-monsoon and winter seasons and a decreasing trend in the monsoon season. The increasing trend in the winter and pre-monsoon seasons actually started during the 1960s which incidentally coincides with the beginning of the green revolution. The irrigated area during the dry season has gradually increased since 1960s. This could lead to an increase in relative humidity during the winter and pre-monsoon seasons. The relative humidity during the post-monsoon season also started rising since the 1960s. The overall trends in humidity over a period of 63 years (1948-2010) are found to be 1.0%, -0.2%, 0.3% and 1.1% during the pre-monsoon, monsoon, post-monsoon and winter seasons, respectively (Table 6.1). The winter and pre-monsoon trends are found to be statistically significant at a confidence level of 99% and the monsoon trend is found to be statistically significant at a confidence level of 95%. The post-monsoon trend is significant only at a confidence level of 80%.

Table 6.1: Trends in all-Bangladesh relative humidity in different seasons

Season	Normal (1980-2009) humidity (%)	Trend [1] (% per decade)	Significance [2]
Pre-monsoon (Mar-May)	72.7	1.0	***
Monsoon (Jun-Sep)	84.9	-0.2	**
Post-monsoon (Oct-Nov)	79.8	0.4	*
Winter (Dec-Feb)	74.3	1.1	***

*Note: [1]based on data of all 34 stations from 1948-2010; [2]***indicates that the trend is significant at a confidence level of 99%; **indicates that the trend is significant at a confidence level of 95%; * indicates that the trend is significant at a confidence level of 80%.*

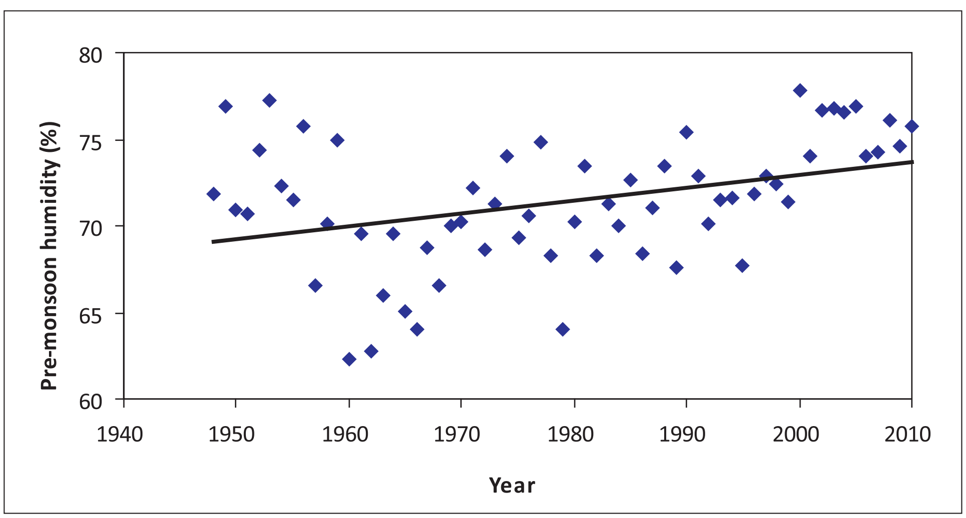


Figure 6.2: Trends in all-Bangladesh seasonal humidity time series

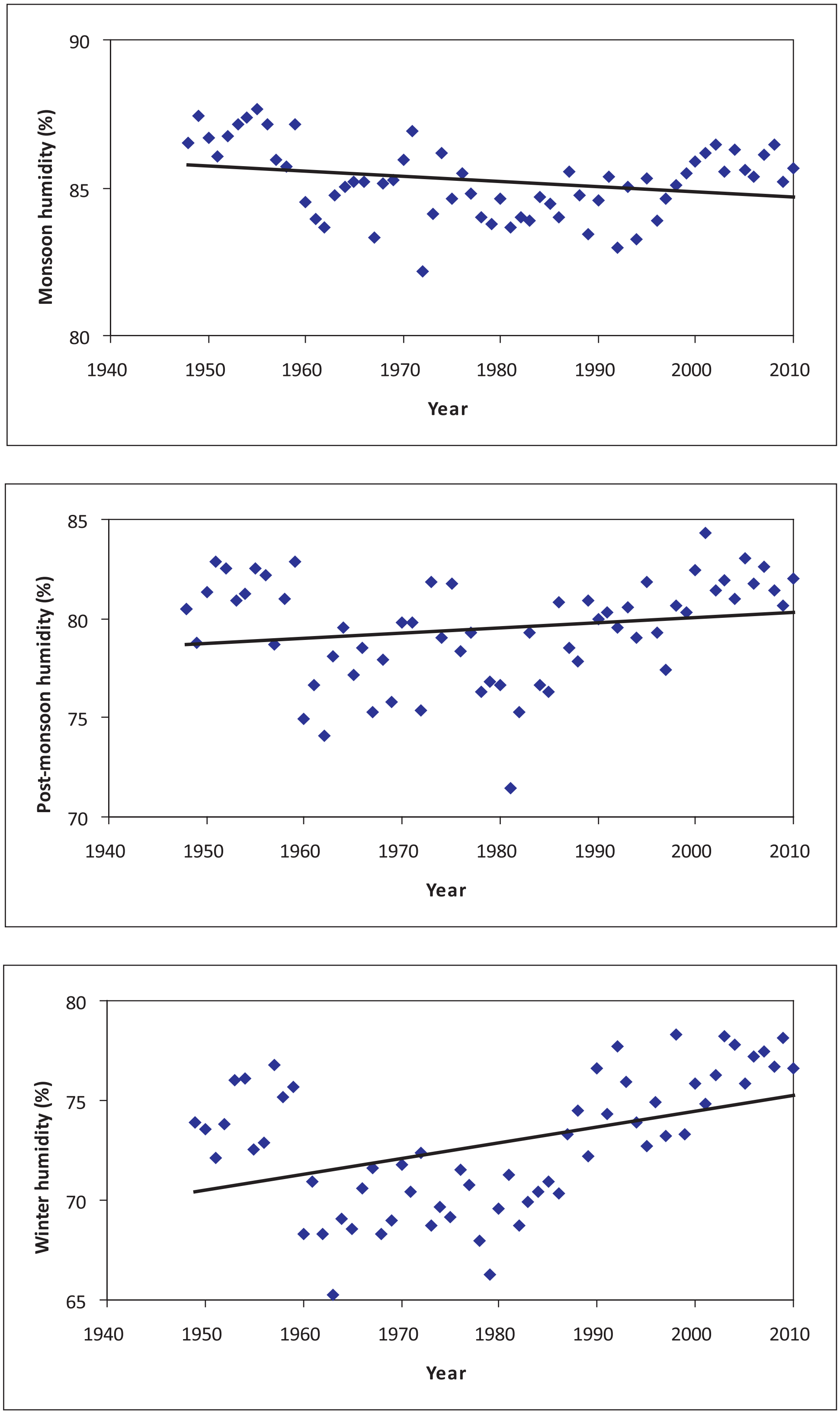


Figure 6.2: (continued)

The spatial distribution of trends in seasonal humidity was also investigated and is shown in Figures 6.3-6.6 for the seasons of winter, pre-monsoon, monsoon and post-monsoon seasons, respectively. It is seen from the Figure 6.3 that the winter season has an increasing trend in humidity all over Bangladesh. The median trend was found to be 1.9% per decade. The mid-western part and the coastal region have higher trends in winter humidity compared to the rest of the country.

The pre-monsoon season (Figure 6.4) also has increasing trend in humidity except at Dhaka, Chittagong, Cox's Bazar and Sandwip. The median trend was found to be 1.4% per decade. The central-west part has a higher trend in humidity compared to the rest of the country. This could be due to the extensive irrigation development in the region.

The monsoon season (Figure 6.5) has a mixed trend in humidity. About 20 stations have increasing trends and 13 stations have decreasing trends. The median trend was found to be only 0.1% per decade. The north-eastern part (Sylhet.-Srimangal-Mymensing-Dhaka-Comilla), Faridpur-Jessore-Khulna-Satkhira region, and south-eastern part (Chittagong-Cox's Bazar-Kutubdia) have decreasing trends in monsoonal humidity. Bogra has also a decreasing trend in humidity.

The post-monsoon season (Figure 6.6) has an increasing trend in humidity except at Dhaka, Chittagong, Sylhet. and Srimangal. The coastal region and the central-west part have higher trends in humidity compared to the rest of the country. The median trend was found to be 1.1% per decade.

It thus appears that the country has in general increasing trend in humidity except at Chittagong for all seasons, at Dhaka for pre-monsoon, monsoon and post-monsoon seasons, at Srimangal for monsoon, post-monsoon and winter seasons, at Sylhet. for monsoon and post-monsoon seasons, and at Cox's Bazar for pre-monsoon and monsoon seasons. The monsoon season has mixed trends in humidity.

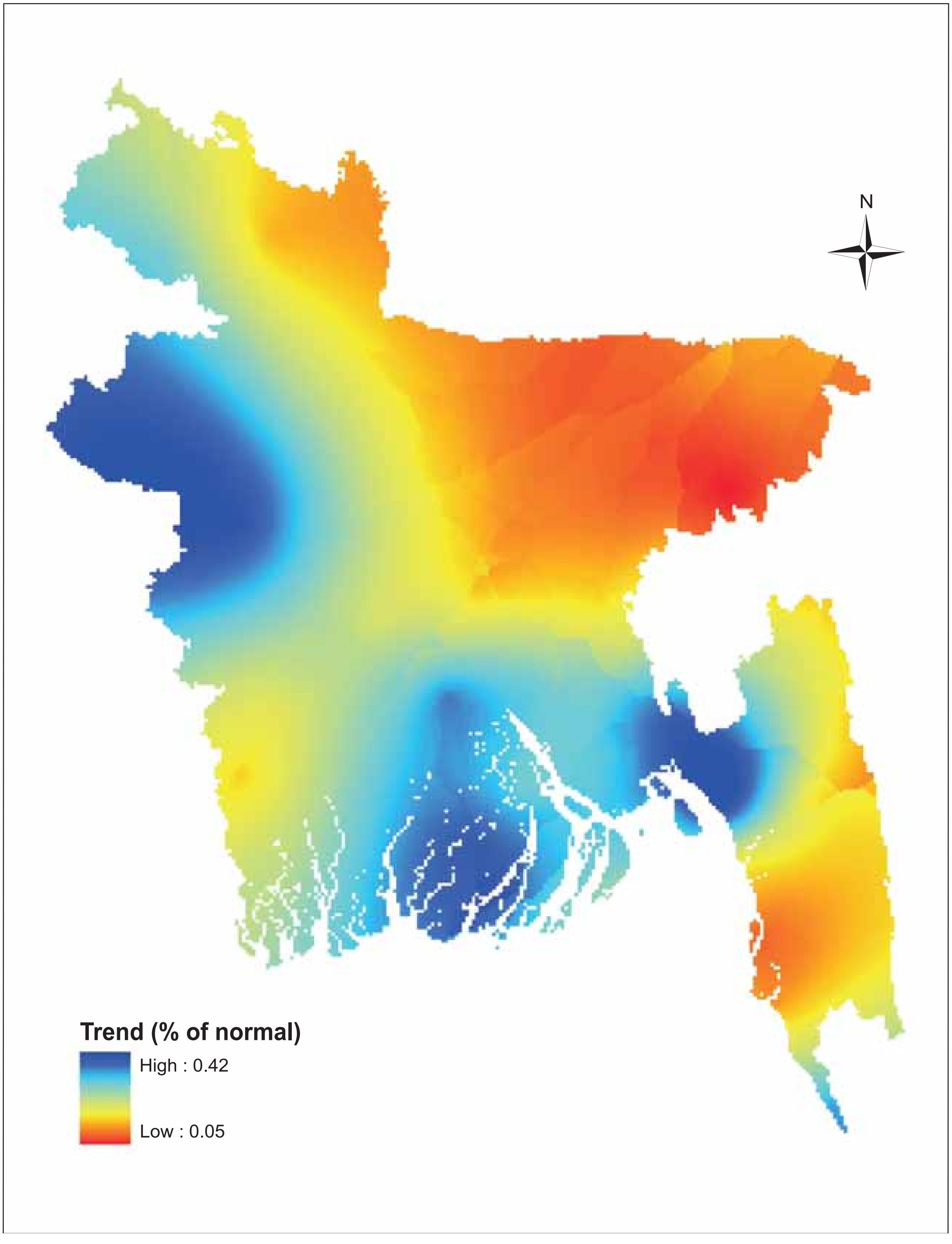


Figure 6.3: Spatial distribution of the trends in relative humidity (% per year) during the winter season (December-February)

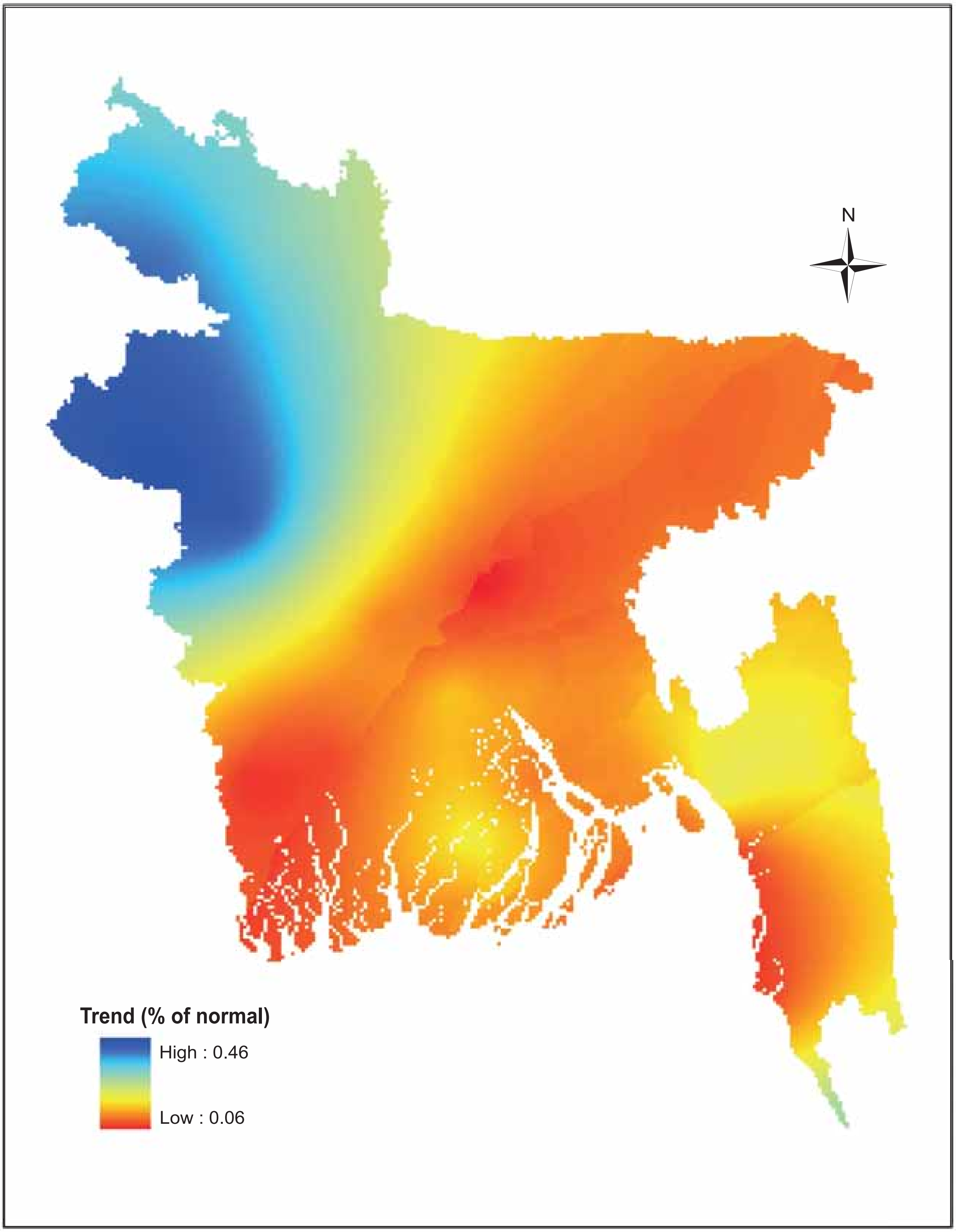


Figure 6.4: Spatial distribution of the trends in relative humidity (% per year) during the pre-monsoon season (March-May)

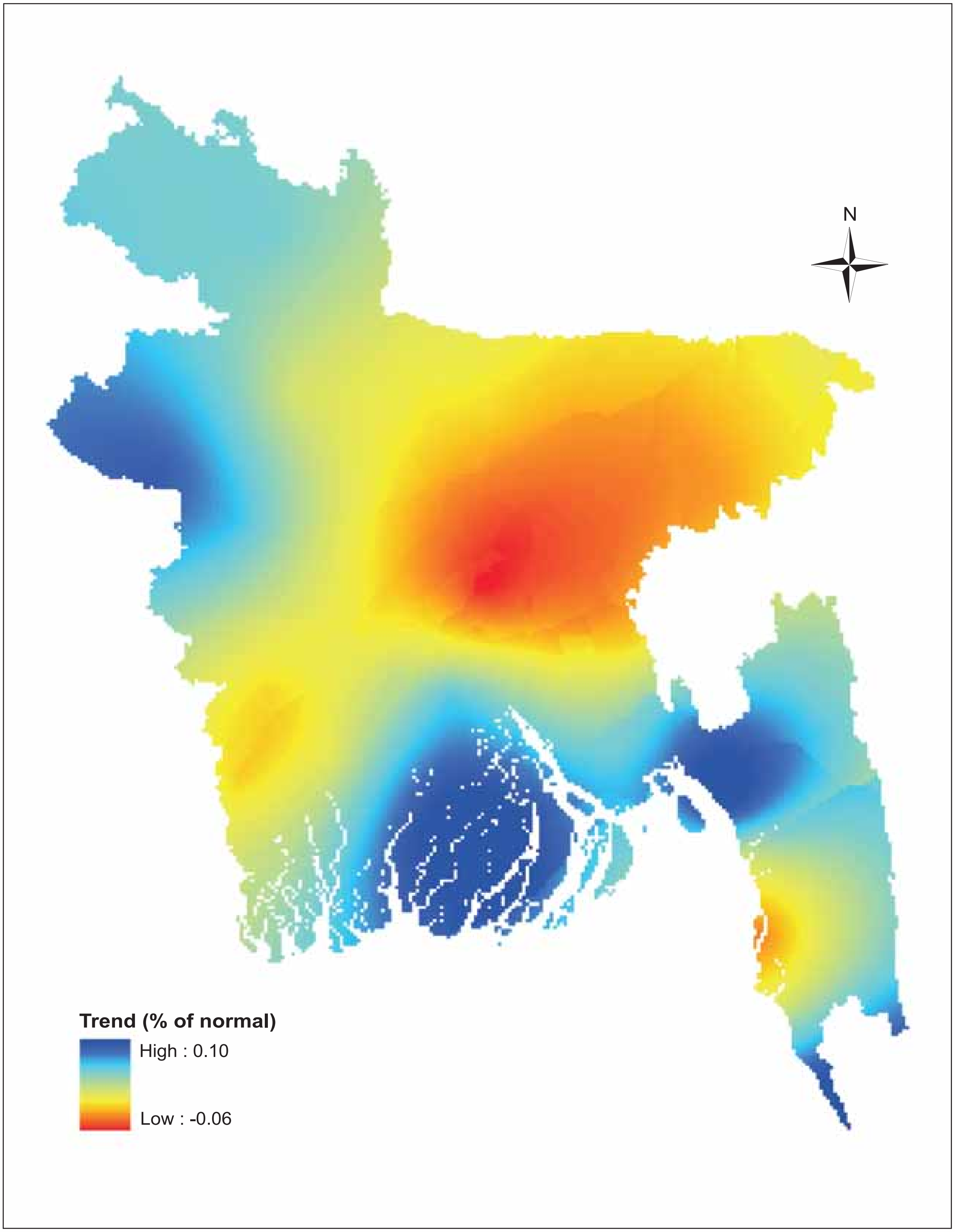


Figure 6.5: Spatial distribution of trends in relative humidity (% per year) during the monsoon season (June-September)

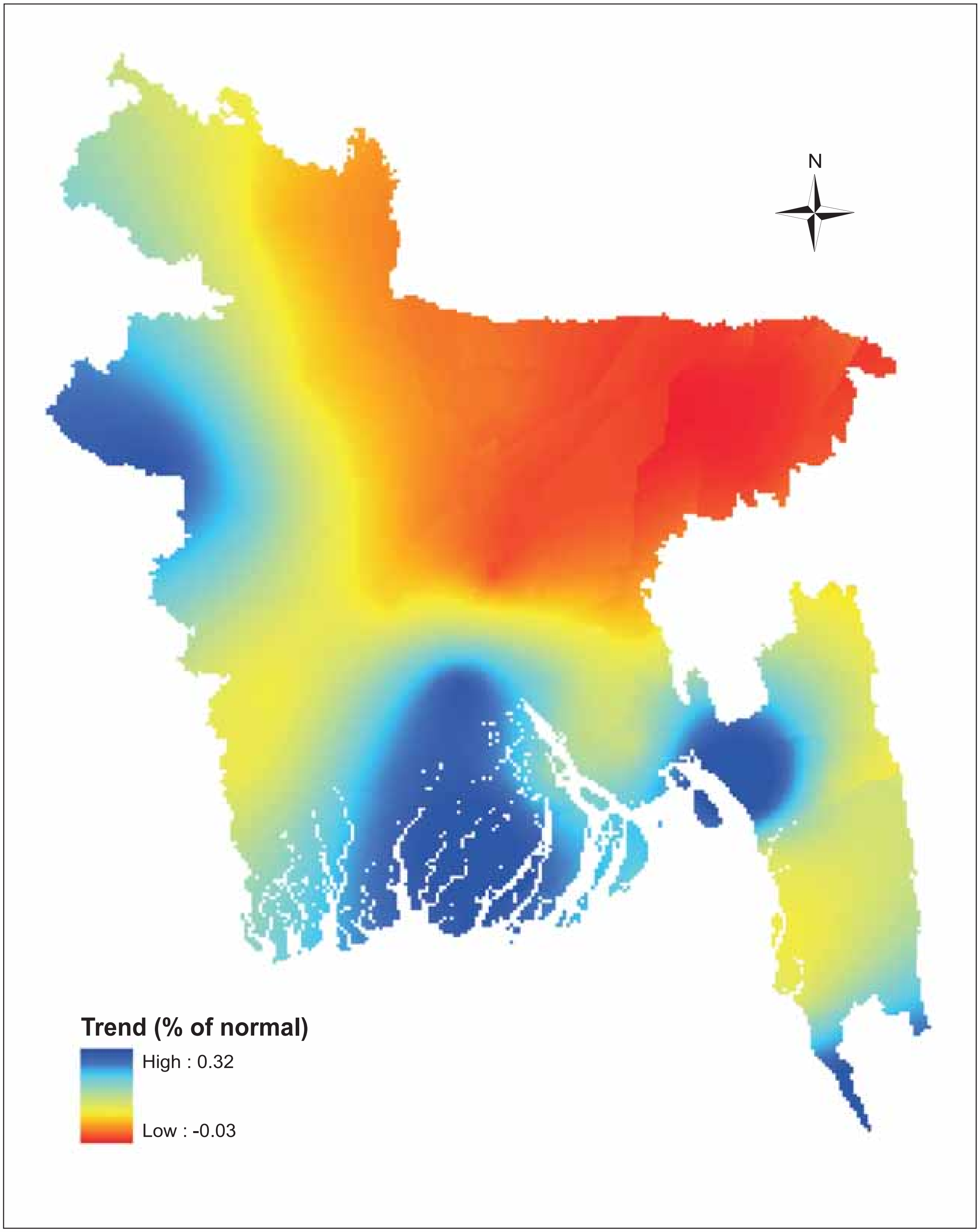


Figure 6.6: Spatial distribution of the trends in relative humidity (% per year) during the post-monsoon season (October-November)

6.4 Monthly Humidity

All-Bangladesh monthly normal relative humidity variations are given in Figure 6.7. It is seen from the figure that the normal relative humidity has increased in all months except for June and August. The increase in humidity is higher during the months of November-April. The changes in humidity during the months of June-September are not much.

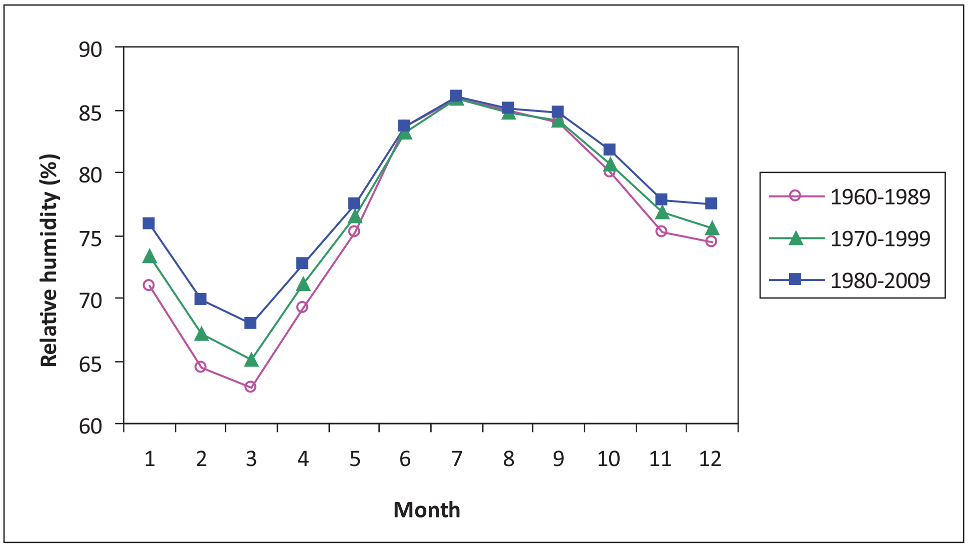


Figure 6.7: All-Bangladesh normal humidity variation in different months

Table 6.2: Trends in all-Bangladesh relative humidity for different months

Month	Normal humidity (%) (1980-2009)	Trend[1] (% of normal)	Significance
Jan	75.8	0.13	***
Feb	69.9	0.13	***
Mar	68..0	0.15	**
Apr	72.7	0.15	***
May	77.5	0.03	NS
Jun	83.7	-0.03	*
Jul	86.1	-0.01	NS
Aug	85.1	-0.04	***
Sep	84.8	0.01	NS
Oct	81.7	0.01	NS
Nov	77.8	0.06	**
Dec	77.4	0.09	***

*Note: [1]based on data of all 34 stations from 1948-2010; ***, ** and * indicate that the trends are significant at a confidence level of 99%, 95% and 90%, respectively, and NS indicates that the trend is not significant at a confidence level of 90%.*

The monthly trends in all-Bangladesh humidity are given in Table 6.2. It is seen from the table that the humidity in all the months have increasing trends except for June, July and August. The long-term trends in the months of June, July and August of the monsoon season are decreasing. The trend is the highest during the month of April which is the warmest month of the year. For December, January, February, April and August, the long-term trends are significant at 99% level of confidence. For March and November, the trends are significant at 95% level of confidence, and for June, the trend is significant at 90% level of confidence. For the remaining months, the long-term trends are not statistically significant at 90% level of confidence.

A comparison of trends in recent humidity with the trends in long-term humidity is made in Figure 6.8. It is seen from the figure that the recent trend (1980-2010) is much higher than the long-term trend (1948-2010). The trends for the months of October-April have increased a lot in recent years. Furthermore, the negative trends in the months of June-August have become positive in recent times. The statistical significance of the monthly trends has either decreased or remained static indicating that the confidence level of recent trends are higher than or similar to the long-term trends.

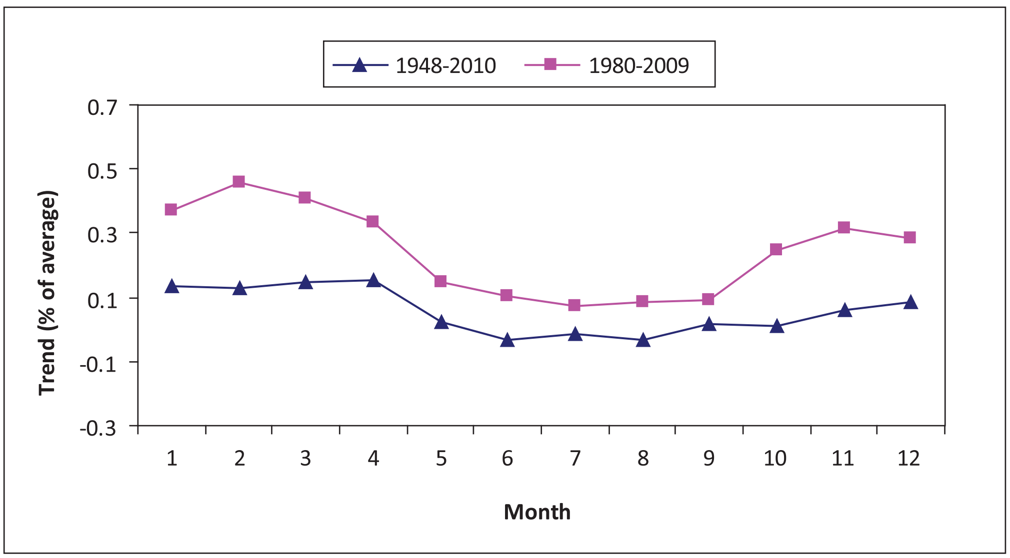


Figure 6.8: Comparison of recent (1980-2010) trend with long-term (1948-2010) trend of all-Bangladesh monthly relative humidity

CHAPTER 7

Spatial Pattern of Changes in Future Climate

7.1 Simulation of Baseline (1961-1990) Climate

The regional climate has been simulated over the Bangladesh domain using SRES balanced scenario A1B. Simulation was conducted from 1961 to 2100 using lateral boundary condition data. However, the period from 1961 to 1990 has been taken as baseline period as suggested by the fourth assessment report of IPCC. Using the daily maximum, minimum and mean temperatures, and precipitation, spatial distribution maps of baseline climate condition are developed over Bangladesh using surface interpolation. To create smooth surface, thin plate spline spatial interpolation technique has been used. Figure 7.1 shows the average spatial distribution maps of the mean, maximum and minimum temperatures, and precipitation based on the model data during 1961-1990. It is seen from the figure that the northern and north-eastern parts of Bangladesh are cooler than the southern and south-western parts. The main reason for this temperature variation is the circulation of the wind. Maximum precipitation is observed in Srimongal, which is located in the north-eastern part of the country. Spatial distribution map of the mean precipitation follows the monsoonal wind circulation pattern blowing from the south-west to the north-east direction. The highest precipitation is found in the north-eastern part of the country. A summary of mean values of baseline climate during 1961-1990 obtained from the high resolution regional climate model (PRECIS) is presented in Table 7.1. No attempt was made to compare the PRECIS results with the GCM results presented in IPCC fourth assessment reports because there is a huge difference in spatial resolution between the two modeling systems. The PRECIS output is at a finer resolution for Bangladesh and the GCM outputs are at coarser resolution for the South Asia.

Table 7.1: Baseline climate of Bangladesh obtained from the PRECIS model during 1961-1990

Variable	Annual	Monsoon (Jun-Sep)	Winter (Dec-Feb)
Mean temperature (^{0}C)	24.6	31.83	16.2
Precipitation (mm/day)	3.5	7. 24	0.59

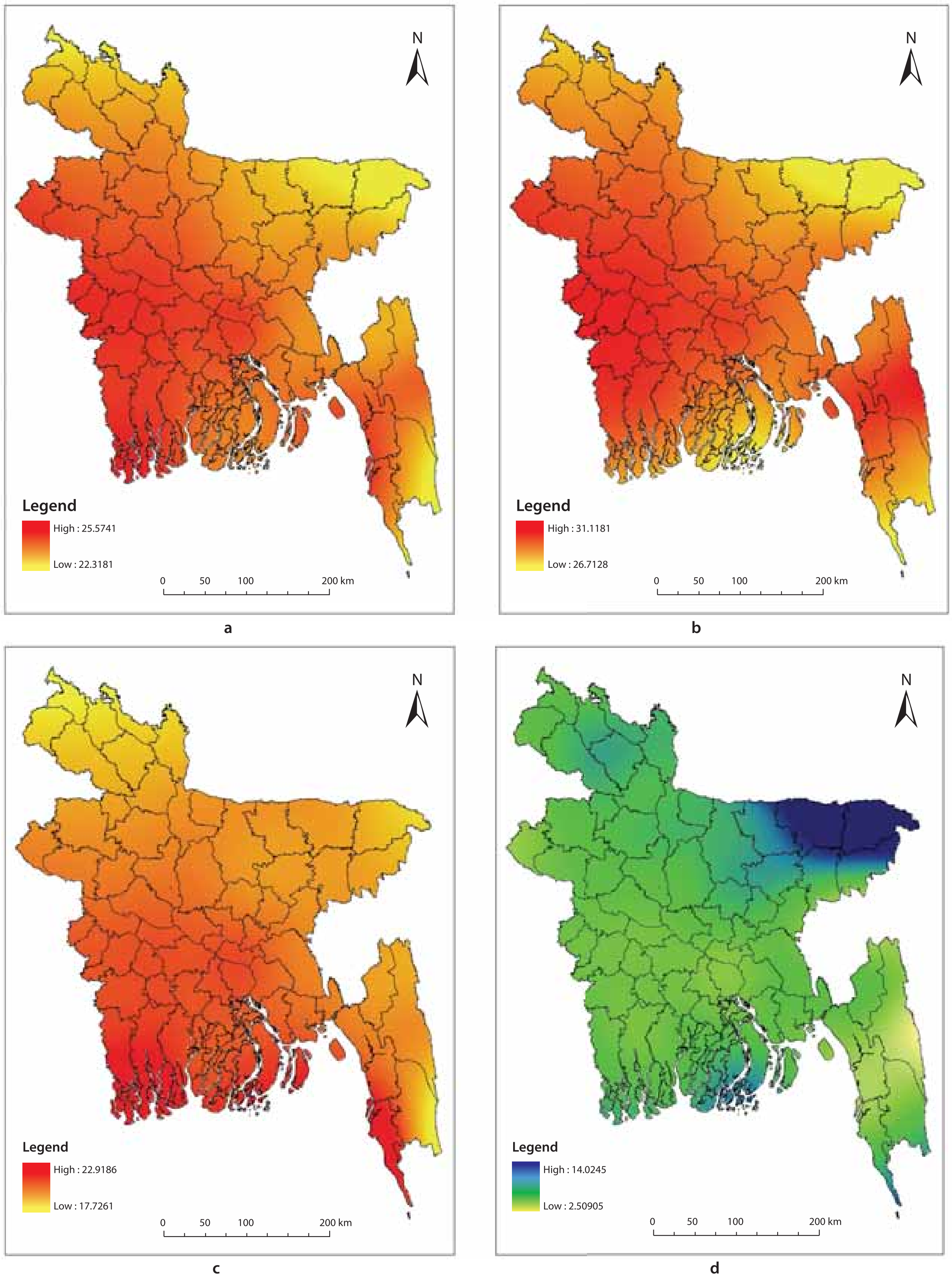


Figure 7.1: Simulated average annual (a) mean, (b) maximum, (c) minimum temperature in ^{0}C and (d) precipitation in mm per day during 1961-1990

7.2 Trends in Future Climate

Trends in future temperatures and precipitation are studied for A1B scenario. Figure 7.2 shows the trends in mean, maximum and minimum temperatures, and precipitation over Bangladesh using time series data from 1961 to 2100. It is found from the figure that the annual mean, maximum and minimum temperatures exhibit trends of about 4.6^{0}C per century. The trend in annual mean precipitation is about 180 mm per century (0.5 mm/day per century).

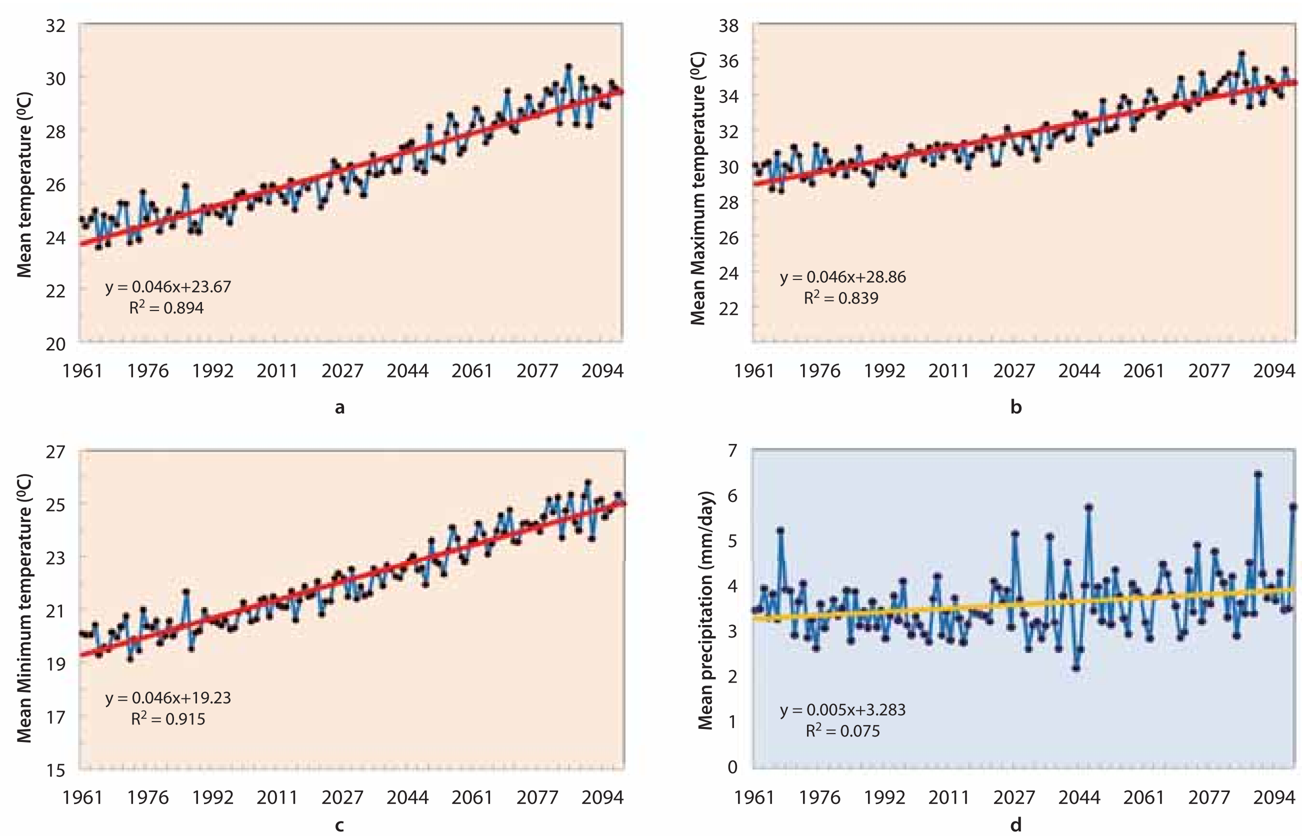


Figure 7.2: Trends in annual (a) mean, (b) maximum, (c) minimum temperatures in ^{0}C and (d) precipitationin mm per day

Anomalies from the baseline period 1961-1990 were studied to reveal the pattern of changes that may occur in future. Figure 7.3 shows the anomalies of mean, maximum and minimum temperatures and precipitation. It is clearly evident from the figure that the temperature would constantly increase over this century. However, the precipitation anomaly shows no significant increasing trend like the temperature in this century.

7.3 Spatial Patterns of Future Climate

Future climate change has been projected as a difference from the baseline period. The differences of mean annual temperature and precipitation during 1911-1941 and 1971-2100 from the baseline period of 1961-1990 have been calculated and are shown as spatial distributed map in Figure 7.4. It is found from the difference map of mean temperature that the north-west and south-west part of the country will be much warmer in future than the north-east and south-east part of the country. On the other hand, precipitation could occur more in the north-east part of the country than any other parts. Figure 7.5 shows the spatial distribution map of the difference of mean temperature and precipitation for the monsoon (June-September) season from baseline to the two future periods as mentioned earlier. During the monsoon season, the pattern of spatial distribution has been found to be similar to the annual distribution. Figure 7.6 shows the spatial distribution map of the difference of mean temperature and precipitation for the winter (December-February)

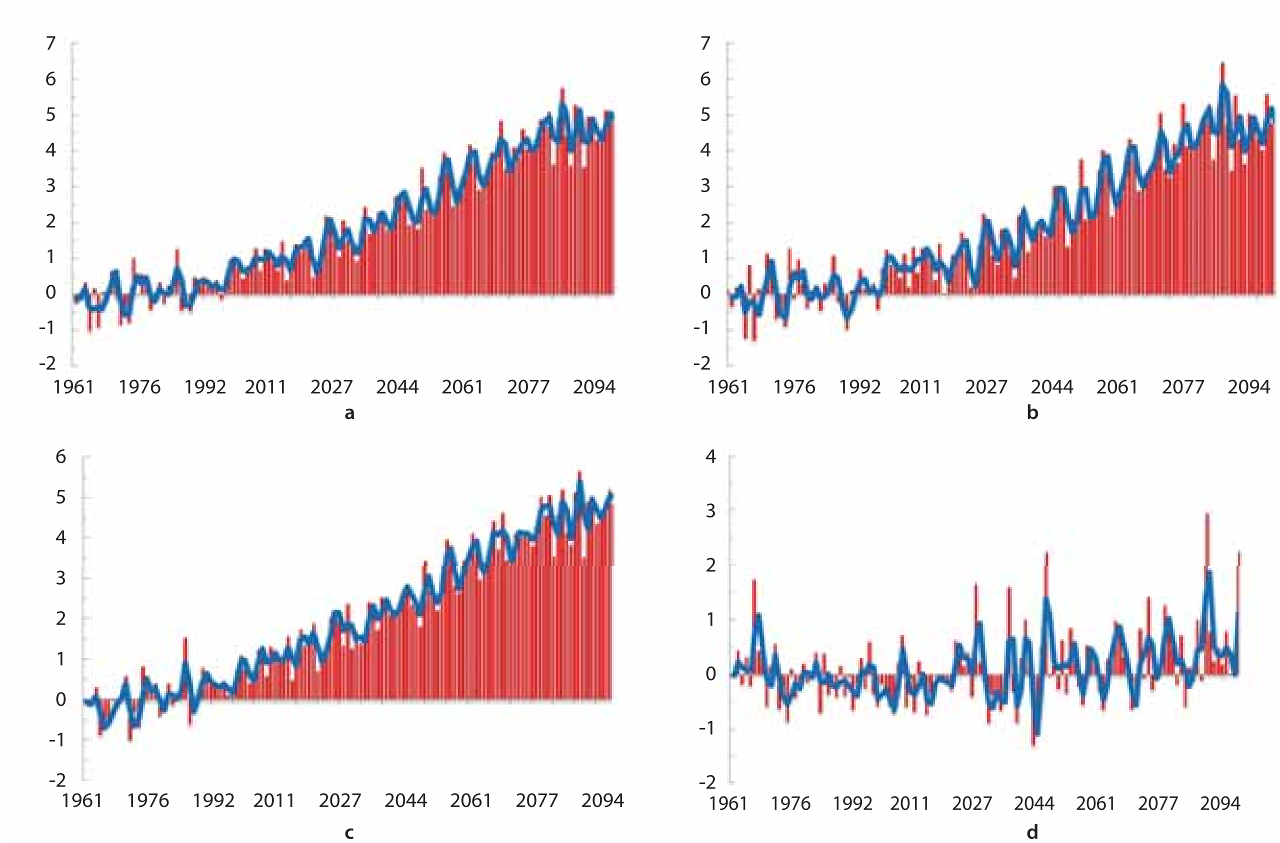


Figure 7.3: Anomalies of annual (a) mean, (b) maximum, (c) minimum temperatures in ^{0}C and (d) precipitation in mm per day from the baseline period 1961-1990

season for the same two future periods. Mean temperature during the winter will be much higher in the western and central parts of the country in these two future periods. However, winter precipitation may not change significantly in these two future periods.

A summary of the average difference of mean annual, monsoon and winter temperatures from the baseline period of 1961-1990 to the two future periods (as mentioned above) are provided in Table 7.2. It is found from the table that the winter temperature would rise much higher in future than the temperatures of annual and monsoon periods. During 2011-2041, mean annual, monsoon and winter temperatures would increase by about 1.49, 1.50 and 1.80 ^{0}C, respectively, from the baseline period of 1961-1990. However, mean annual, monsoon and winter temperatures will further increase during 2071-2100 from the baseline period by about 4.34^{0}, 3.43^{0} and 5.37 ^{0}C, respectively.

The mean annual and monsoon precipitation would increase by 0.64 and 1.40 mm per day, respectively, during 2011-2041 from the baseline period. However, mean winter precipitation would decrease by 0.05 mm per day during 2011-2041 from the baseline period. The mean annual, monsoon and winter precipitation would increase by about 0.90, 1.43 and 0.03 mm per day, respectively, during 2071-2100 from baseline period. It is noted that the changes in precipitation towards the end of this century might be the same as the middle of the century. However, the mean temperature would increase consistently throughout the century.

Table 7.2: Difference of mean annual, monsoon and winter temperature and precipitation from baseline period 1961-1990 to 2011-2040 and 2071-2100

Variable	From 1961-1990 to	Annual	Monsoon (Jun-Sep)	Winter (Dec-Feb)
Temperature (^{0}C)	2071-2100	4.34	3.43	5.37
	2011-2041	1.49	1.50	1.80
Precipitation (mm/day)	2071-2100	0.90	1.43	0.03
	2011-2041	0.64	1.40	-0.05

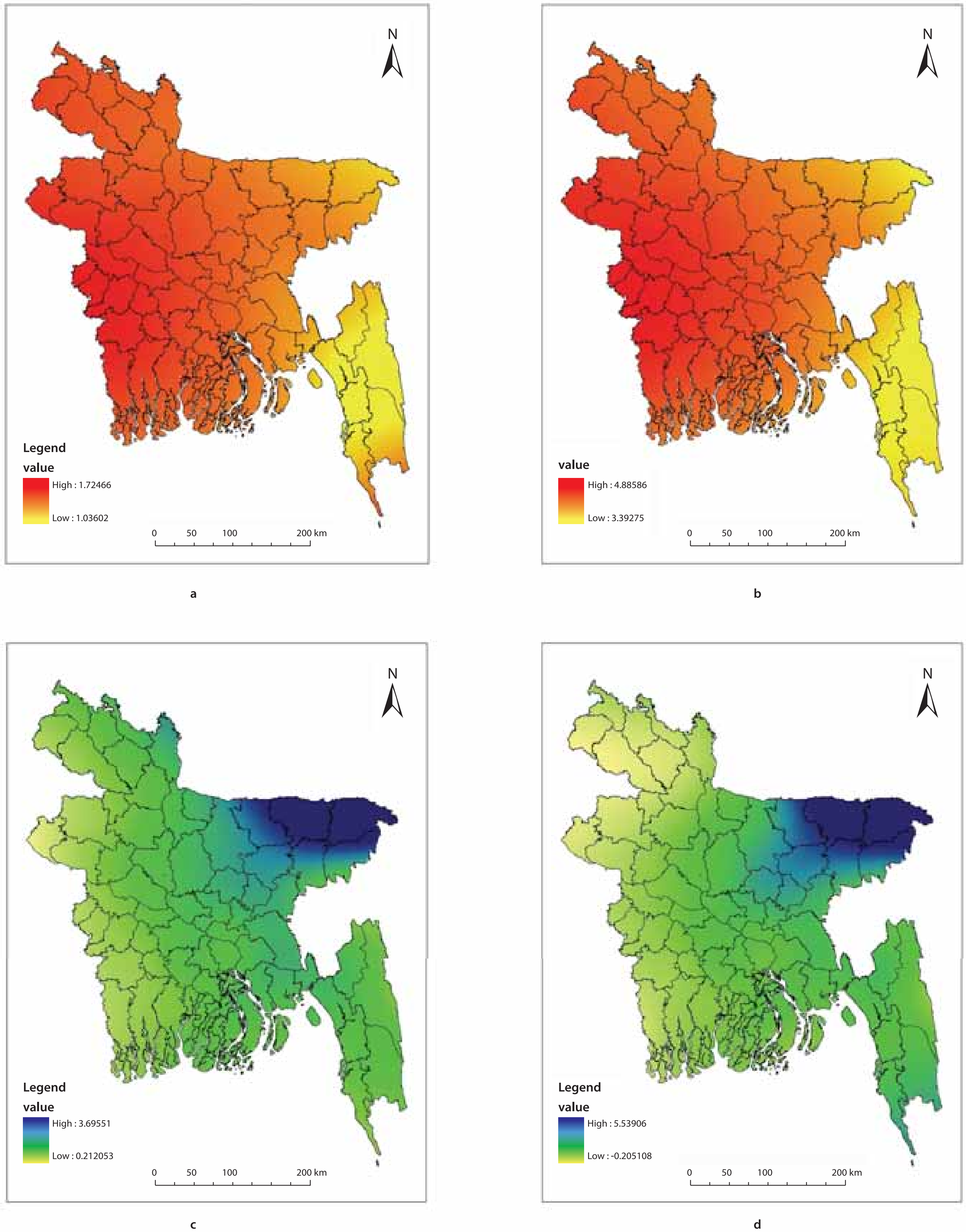


Figure 7.4: Difference of annual mean temperature (^{0}C) from 1961-1990 to (a) 2011-2040, (b) 2071-2100 and precipitation (mm/day) to (c) 2011-2040 and (d) 2071-2100.

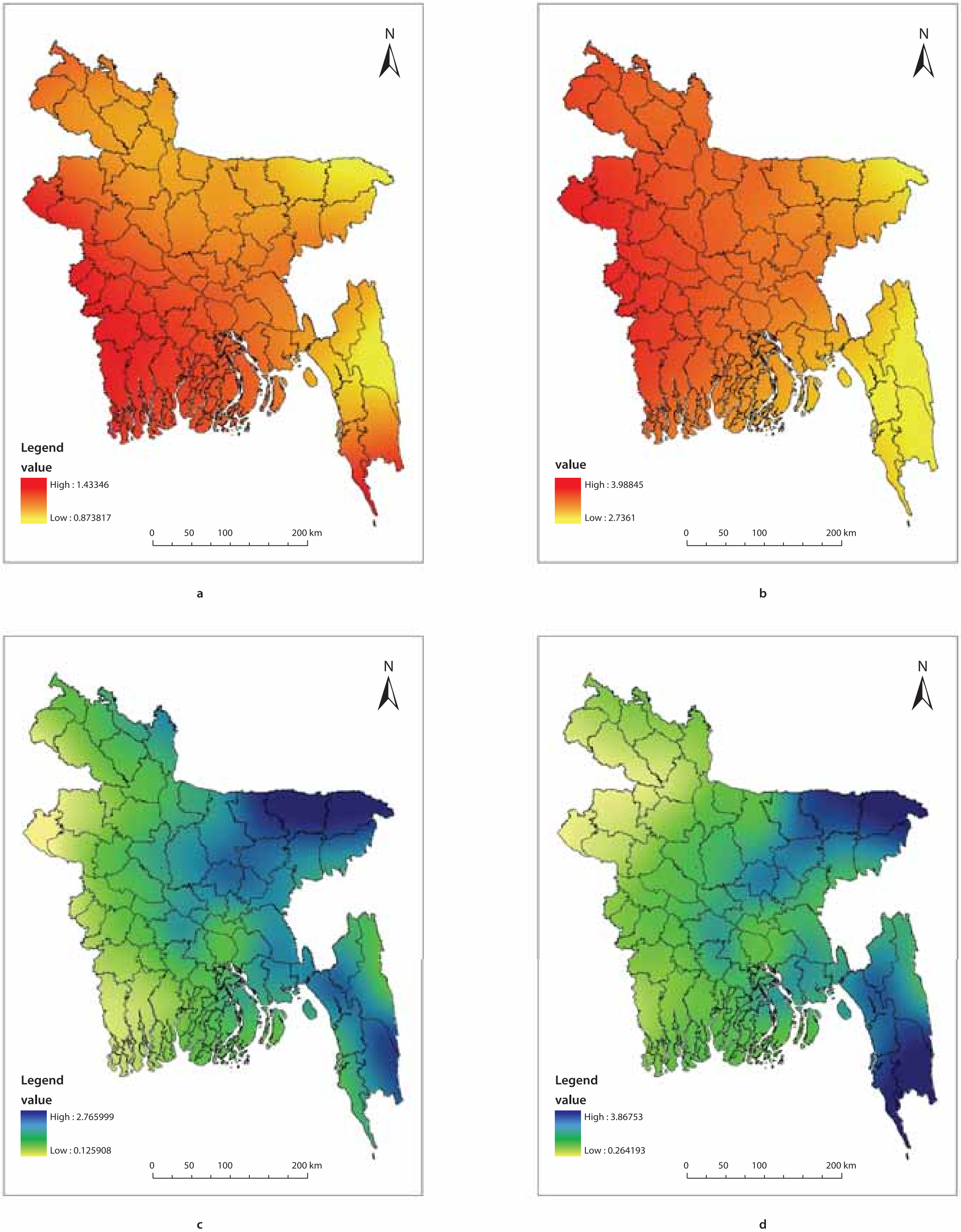


Figure 7.5: Difference of monsoon mean temperature (^{0}C) from 1961-1990 to (a) 2011-2040, (b) 2071-2100 and precipitation (mm/day) to (c) 2011-2040 and (d) 2071-2100

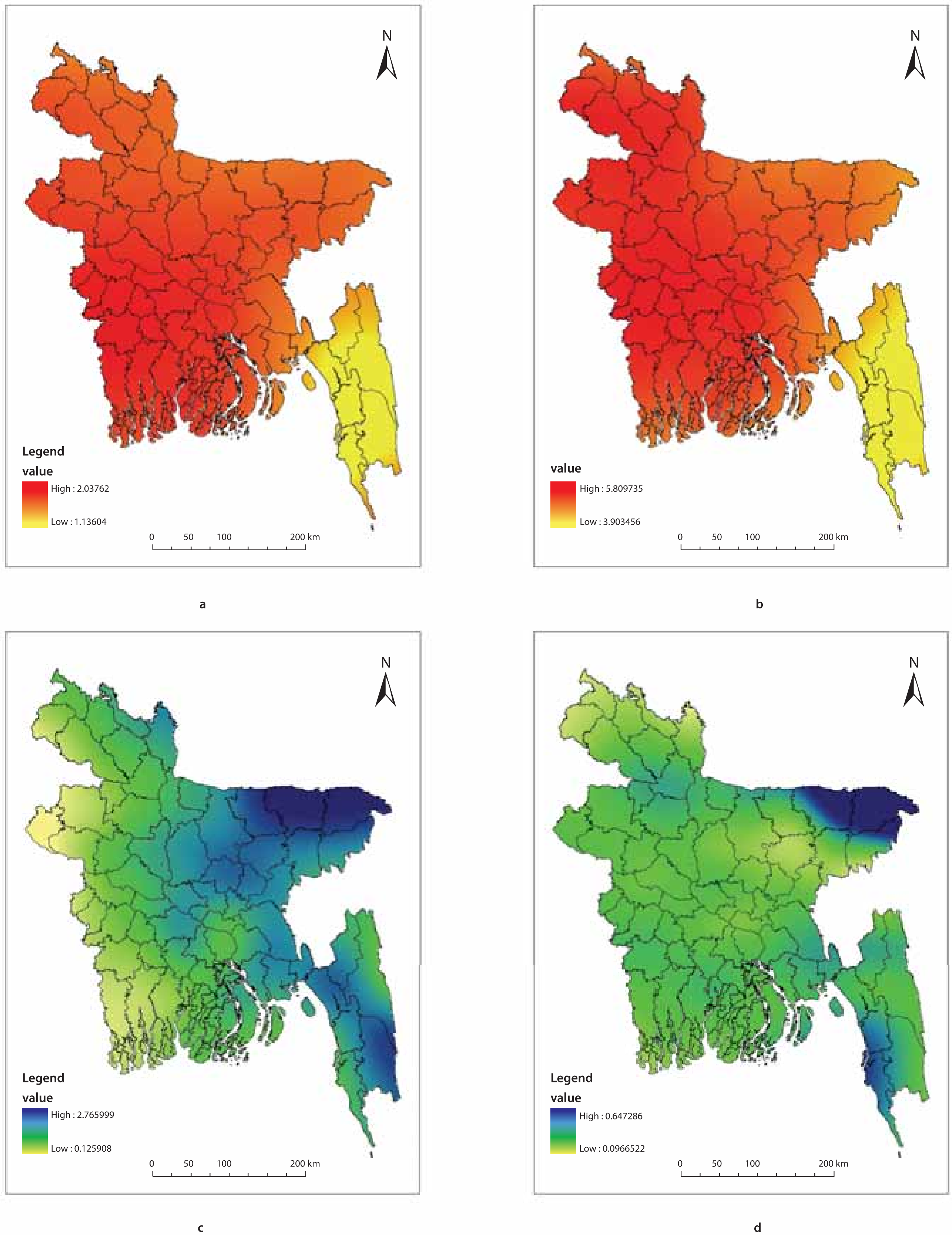


Figure 7.6: Difference of winter mean temperature (^{0}C) from 1961-1990 to (a) 2011-2040, (b) 2071-2100 and precipitation (mm/day) to (c) 2011-2040 and (d) 2071-2100.

CHAPTER 8

Crop Vulnerability

8.1 Introduction

Agricultural crops are always vulnerable to unfavorable weather events and climatic conditions. Climatic factors, such as temperature, rainfall, solar radiation, atmospheric carbon dioxide, etc., are closely linked with crop production. Despite technological advances, such as improved crop varieties and irrigation systems, weather and climate play significant roles to crop productivity. Climatologically, Bangladesh often experiences little rainfall (drought condition) during the dry season (November-May) and heavy downpours and floods during the monsoon season (June-September), with significant crop losses during both these extreme conditions. Both rice and wheat are severely affected by the changing weather and climatic condition. As mentioned in Chapter Two, the effect of climate change on agriculture has been assessed in this study through a model simulation. The simulations were made for assessing the potential impacts of climate change on *boro* rice, T. *aman* and wheat using the crop growth model named Decision Support System for Agrotechnology Transfer (DSSAT). The simulation study was conducted for the years of 1975, 2025, 2055 and 2085. In this study, *boro* rice variety of BR 14, *aman* rice variety of BR 22 and wheat variety of Kanchan were selected to assess the potential impacts of climate change on crop yield. In addition, the perceptions of the local people regarding climate change and crop vulnerability at the four selected sites (Rajbari, Sunamganj, Chapai Nawabganj and Satkhira) were gathered.

Table 8.1: Typical crop management data of wheat used in the model simulation

Parameter	Input data
Planting method	Dry seeding
Seeding date	15 November
Planting distribution	Broadcasting
Plant population at seedlings (per m^2)	220
Plant population at emergence (per m^2)	220
Planting depth (cm)	3
Fertilizer (N) application:	
1st application (during seeding)	70 kg/ha
2nd application (40 days after seeding)	50 kg/ha
Application of irrigation	150 mm in 3 applications

8.2 Data Used in the DSSAT Model

The crop management data required in the model was collected directly from the fields and the typical values of different parameters are reported in Tables 8.1 and 8.2 for wheat and rice, respectively.

Table 8.2: Typical crop management data of rice used in the model simulation

Parameter	Boro	T. aman
Planting method	Transplant	Transplant
Transplanting date	15 Jan	15 July
Planting distribution	Hill	Hill
Plant population at seedlings (per m^2)	35	35
Plant population at emergence (per m^2)	40	40
Row spacing (cm)	18	16
Transplanting age (days)	40	30
Plant per hill	3	3
Fertilizer (N) application:		
1st application	70 kg/ha at tillage	70 kg/ha at tillage
2nd application	70 kg/ha at 40 DAP	50kg/ha at 30 DAP
3rd application	70 kg/ha at 70 DAP	-
Application of irrigation	800 mm from 12 irrigations	350 mm from 7/8 irrigations

*Note: *DAP is the days after planting.*

The genetic coefficients for the BR 3 and BR 14 cultivars of *boro* rice and for the BR 11 and BR 22 cultivars of T. *aman* rice are available in the DSSAT model. In this study, BR 14 for *boro* and BR 22 for T. *aman* rice were used in model simulations. The genetic coefficients for other cultivars, which are cultivated in our country, are not available in the model as well as in literature and hence could not be used. The genetic coefficients for the Kanchan variety of wheat were developed by Hussain (2008) and were used in this study. Tables 8.3 and 8.4 show the values of different genetic coefficients used in this study.

Table 8.3: Genetic coefficients for the Kanchan variety of wheat (source: Hussain, 2008)

Crop	Variety	Coefficient						
		P1V	P1D	P5	G1	G2	G3	PHINT
Wheat	Kanchan	0.4	100	370	12	35	1.7	120

Table 8.4: Genetic coefficients for *boro* and *T. aman* rice

Crop	Cultivar	Genetic coefficient							
		P1	P2R	P5	P20	G1	G2	G3	G4
Boro	BR 14	560	200	500	11.5	45	0.026	1	1
Aman	BR 22	650	110	400	12	60	0.025	1	1

Table 8.5: Values of different soil parameters obtained at Nachole upazila of Chapai Nawabganj district

Sample no.	Depth	pH	^{O}C (%)	Total N (%)	CEC (meq/100gm)
CN - 1	0	6.6	0.50	0.054	18.61
CN - 2	15	6.9	0.58	0.044	10.70
CN - 3	30	6.9	0.39	0.036	13.19
CN - 4	45	7.0	0.27	0.033	15.85

Table 8.6: Values of different soil parameters obtained at Jamalganj upazila of Sunamganj district

Sample no.	Depth	pH	^{O}C (%)	Total N (%)	CEC (meq/100gm)
JR-1	0	5.0	1.56	0.135	24.00
JR-2	15	5.1	1.21	0.104	19.33
JR-3	30	5.2	1.25	0.108	28.43
JR-4	45	5.6	0.86	0.074	24.74

Table 8.7: Values of different soil parameters obtained at Pangsha upazila of Rajbari district

Sample no.	Depth	pH	^{O}C (%)	Total N (%)	CEC (meq/100gm)
PR-1	0	7.2	1.87	0.161	21.28
PR-2	15	7.1	1.21	0.104	24.61
PR-3	30	7.6	1.09	0.094	18.00
PR-4	45	7.7	0.78	0.067	15.64

Table 8.8: Values of different soil parameters obtained at Shyamnagar upazila of Satkhira district

Sample no.	Depth	pH	OC (%)	Total N (%)	CEC (meq/100gm)
SS-1	0	6.0	1.17	0.103	28.10
SS-2	15	6.0	0.35	0.090	31.73
SS-3	30	6.8	0.76	0.066	31.73
SS-4	45	6.8	0.35	0.065	26.64

8.3 Potential Impact of Climate Change on Crop Yield

The yields of wheat, *boro* and *aman* rice were simulated with the DSSAT model for base and future climatic conditions. Soil parameters used in the model were from laboratory analyses, and the crop, input and management data from either field measurements or discussion with / interview of local people. The yields obtained in the base condition for different crops at different locations from model matched reasonably well with the field information, except for *boro* and wheat at Satkhira. The model over estimated the yield at this location for the two crops because it could not incorporate the effect of salinity. The detailed results of simulations for the three crops are discussed below.

8.3.1 Impact on Wheat

Predicted yield of wheat for different locations in Bangladesh is shown in Table 8.9. Simulated yield of wheat ranges from 2063 kg/ha at Chapai Nawabganj to 2866 kg/ha at Sunamganj in 1975, from 1862 kg/ha at Chapai Nawabganj to 2718kg/ha at Sunamganj in 2025, from 1790 kg/ha at Satkhira to 2226 kg/ha at Rajbari in 2055, and from 1286 kg/ha at Chapai Nawabganj to 2144 kg/ha at Sunamganj in 2085. It is seen from the table that wheat yield would reduce in future at all the locations. The maximum reduction, which is about 49.69%, could occur in Satkhira in 2085. The minimum reduction, which is about 0.85%, could happen in Rajbari in 2055. It is noted that the highest reduction could take place during the year of 2085. Among the four selected locations, Sunamganj and Satkhira could experience a high reduction in wheat yield, followed by Chapai Nawabganj, and Rajbari could experience the least reduction.

Table 8.9: Predicted yield (kg/ha) of wheat (Kanchan) at some selected locations of Bangladesh for some selected years

Location	Simulated yield (kg/ha) in the years of				Change in yield (%) in the years of		
	1975	2025	2055	2085	2025	2055	2085
Rajbari	2245	2207	2226	1936	- 1.69	- 0.85	- 13.76
Nawabganj	2063	1862	1802	1734	- 9.74	- 12.65	- 15.95
Satkhira	2556	2374	1790	1286	- 7.12	- 29.97	- 49.69
Sunamganj	2866	2718	1827	2144	- 17.17	- 36.25	- 25.19

Wheat is very sensitive to temperature. The optimum temperature for wheat in vegetative, reproductive and ripening stages are 20-25, 25-28 and 28-32^{0}C, respectively. A high temperature during the reproductive and grain filling stages is one of the main causes of yield loss of wheat in Bangladesh (Rahman *et. al.*, 2009). High temperature enhances leaf senescence causing reduction in green leaf area during the reproductive stage. The rapid leaf senescence ultimately results in less reproductive tillers per plant, which is a major cause of yield loss of wheat. All the selected locations show significant increases in both maximum and minimum temperatures (see, for example, Figure 8.1). Predicted maximum temperature would exceed the optimum temperature limit for wheat cultivation. As a result, wheat production could fall drastically in the predicted years.

Solar radiation is another important factor that limits the wheat production. Although solar radiation might increase in vegetative stage (November-December), a decreasing tendency is found for the years of 2025, 2055 and 2085 (see, for example, Figure 8.2) in the reproductive stage, particularly in grain filling and ripening stages (January-March). During the grain filling stage, solar radiation is essential for photosynthesis. Any shortage of solar radiation in this period decreases the grain filling rate, which results in wheat yield reduction. It has been reported that a decrease in solar radiation by 1.7 $MJm^{-2}day^{-1}$ could reduce wheat yield by 800 kg/ha in the Indo-Gangetic Plains (Pathak *et. al.*, 2003). So both temperature and solar radiation could have affected the predicted yield of wheat in the years of 2025, 2055 and 2085.

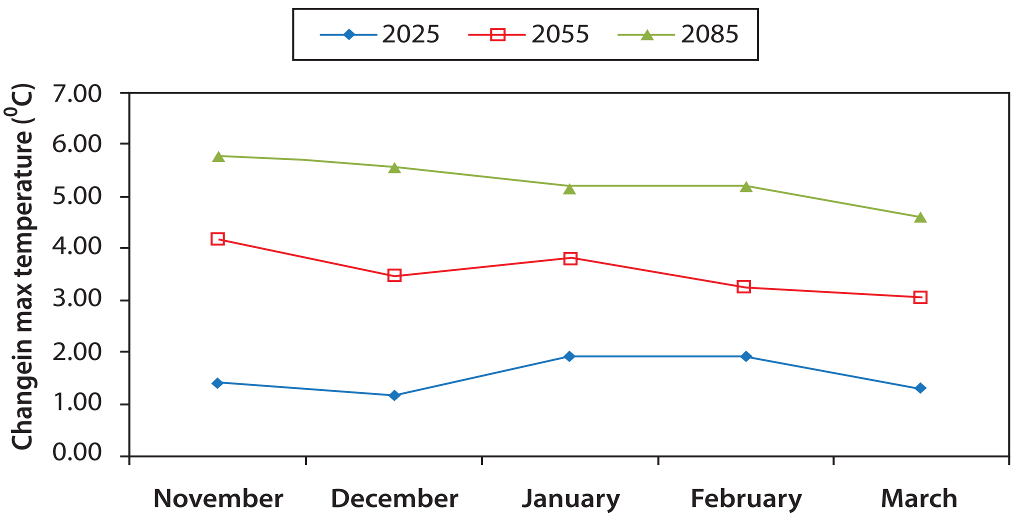


Figure 8.1: Climate model predicted change in monthly average maximum temperature at Chapai Nawabganj during the wheat growing period

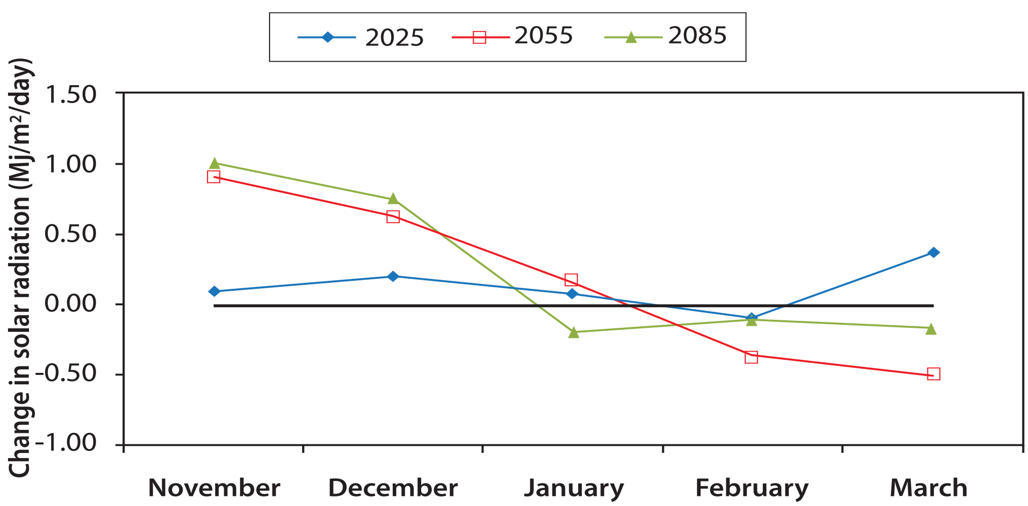


Figure 8.2: Climate model predicted change in monthly average solar radiation at Chapai Nawabganj during the wheat growing period

8.3.2 Impact on *boro* rice

Table 8.10 shows the predicted *boro* rice yield for the four locations. It shows a reduction in yield of *boro* rice in future years compared to the base year of 1975 across all the locations except at Chapai Nawabganj for the year of 2025. Simulated yield of *boro* rice ranges from 5123 kg/ha at Chapai Nawabganj to 5612 kg/ha at Rajbari in 1975, from 5186 kg/ha at Chapai Nawabganj to 5462 kg/ha at Rajbari in 2025, from 5025 kg/ha at Chapai Nawabganj to 5322 kg/ha at Rajbari in 2055 and from 4054 kg/ha at Satkhira to 5049 kg/ha at Sunamganj in 2085. Compared to the yield of 1975, the higher reduction which is about 26.08% could occur in Satkhira for the year 2085 and minimum reduction (1.30%) in Sunamganj for the year of 2025. The table also reveals that the reduction in *boro* yield could be more in the coastal part followed by the central, haor and upland areas.

Table 8.10: Predicted yield (kg/ha) of BR 14 variety of boro rice at some selected locations of Bangladesh for some selected years

Location	Simulated yield (kg/ha) in the years of				Change in yield (%) in the years of		
	1975	2025	2055	2085	2025	2055	2085
Rajbari	5612	5462	5322	4990	- 2.67	- 5.17	- 11.08
Chapai Nawabganj	5123	5186	5025	4966	1.23	- 1.91	- 3.06
Satkhira	5484	5307	5043	4054	- 3.23	- 8.04	- 26.08
Sunamganj	5524	5452	5211	5049	- 1.30	- 5.67	- 8.60

Both the maximum and minimum temperatures at these locations are predicted to be increased in the years of 2025, 2055 and 2085 compared to the base year of 1975 (see, for example, Figure 8.3). Higher temperature accelerates the physiological development, resulting in hastened maturation and reduced yield. Predicted temperatures for the above years exceed the optimum temperature for ripening stage, which is about 21-22 ^{0}C (Amin *et. al.*, 2004). Thus, the increasing temperature can be attributed to be a reason for the reduction of yield of *boro* rice in future years (see also the sensitivity analysis presented later in this chapter). This is in conformity to the findings by Karim *et. al.* (1996) who reported that a higher future temperature could reduce the yields of *boro* rice all over Bangladesh. Peng *et. al.* (2004) also found from field experiments in Philippines that the grain yield of dry season rice was negatively related, at a confidence level of 99%, to minimum temperature.

Solar radiation is another important parameter which affects many physiological processes, particularly photosynthesis of rice plants. The grain yield of rice becomes comparatively low at inadequate light intensity at later stage of crop growth (Yoshida, 1981). Shading during the reproductive and ripening phases cause significant reduction in yield by reducing panicle number, final spikelet. number and grain weight (Islam and Morison, 1992). Predicted solar radiation in the *boro* rice growing period, particularly in reproductive and ripening stages (March-May), shows a decreasing trend (see, for example, Figure 8.4) which could have affected the yield of *boro* rice. Zaman and Mondal (2011) found from a rice growth simulation modeling using ORYZA 2000 that a 20% decrease in solar radiation could reduce *boro* rice yield in Bangladesh by about 4.3%. Their findings were consistent with Stanhill and Cohen (2001), who in a review paper indicate that a 10-20% decrease in solar radiation reaching the surface of the earth, if unaccompanied by the other climatic changes, would probably have a minor effect on crop yields and plant productivity. However, referring to other studies (Ahmad *et. al.*, 2008; Horie, 1987; Islam and Morison, 1982; Islam *et. al.*, 1995; Ramanathan and Crutzen, 2001) they mentioned that their model might have underestimated the true effect of solar dimming on rice yield.

Rainfall may also affect the yield of *boro* rice, particularly in water-stressed areas. However, in model simulation in all cases, an irrigation of about 800 mm was applied and thus the rainfall had no major effect on *boro* rice production.

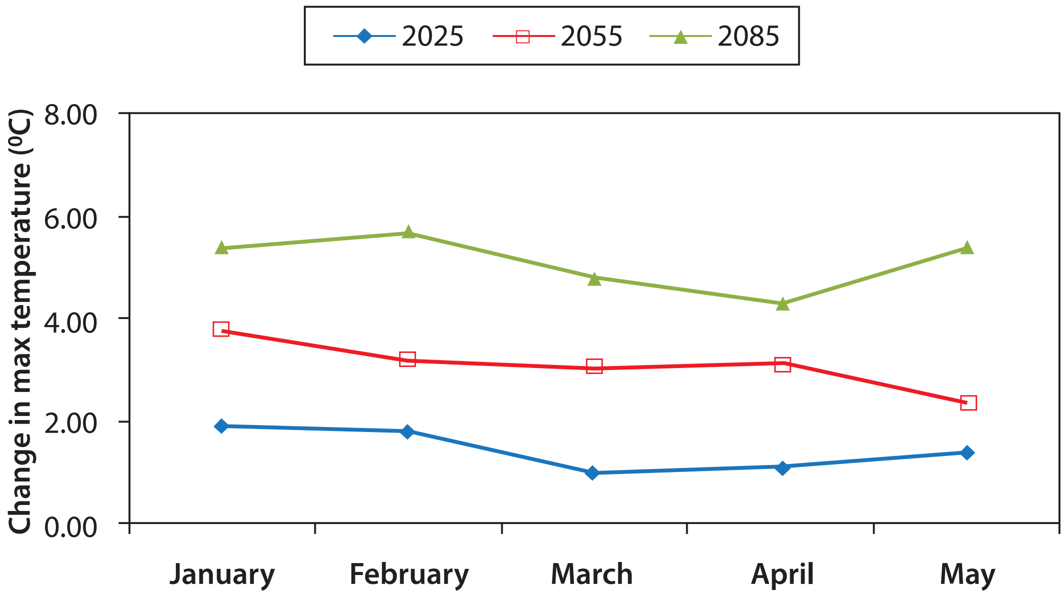


Figure 8.3: Climate model predicted change in monthly average maximum temperature at Rajbari during the *boro* season

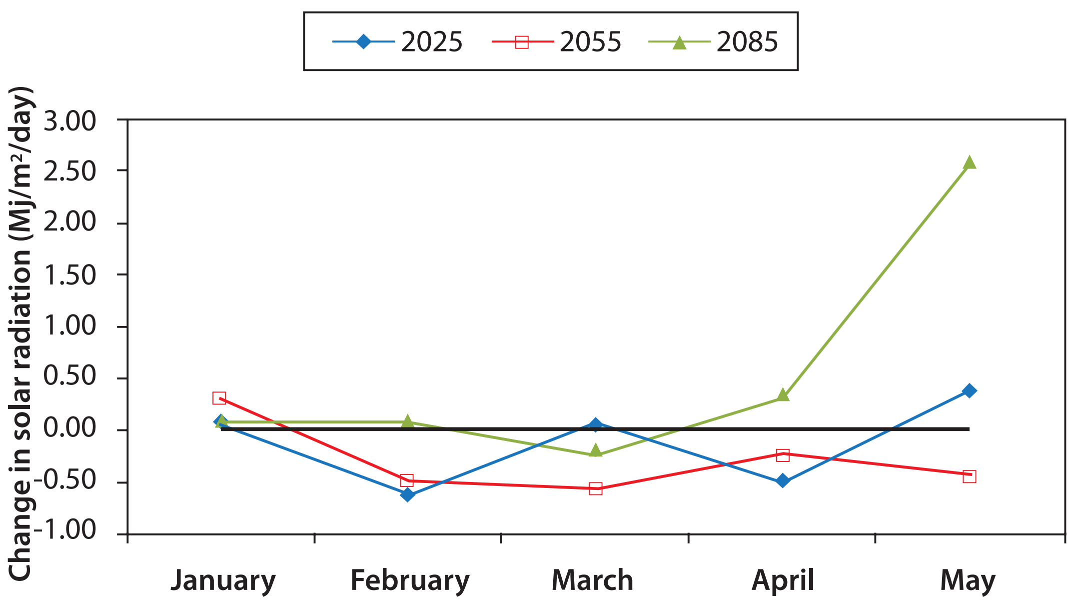


Figure 8.4: Climate model predicted change in monthly average solar radiation at Rajbari during the *boro* season

8.3.3 Impact on aman rice

The model simulated yield of BR 22 variety of T. *aman* at the four selected locations of Bangladesh for some selected years is given in Table 8.11. It is seen from the table that the simulated yield of *aman* rice ranges from 4343 kg/ha at Chapai Nawabganj to 4941 kg/ha at Rajbari in 1975; from 4417 kg/ha at Chapai Nawabganj to 4840 kg/ha at Satkhira in 2025; from 4329 kg/ha at Chapai Nawabganj to 4883 kg/ha at Satkhira in 2055; and from 4382 kg/ha at Chapai Nawabganj to 5022 kg/ha at Satkhira in 2085. Compared to the base condition yield of 1975 (average of 1960-1990), the predicted yield of *aman* rice shows different degrees of change. In some cases, the predicted yield is found to be decreased, whereas in other cases the predicted yield is found to be increased. The maximum yield reduction (2.04%) compared to 1975 could occur at Rajbari in 2025 because of the low solar radiation throughout the season, particularly in September (Figure 8.5). The yield could also reduce by 1.17% in 2055 in the Rajbari region. In Sunamganj, the *aman* rice yield could decrease by about 0.22% and 0.17% in the years of 2025 and 2055, respectively. Compared to Rajbari and Sunamganj, the impact of climatic parameters on *aman* rice yield would be less at Chapai Nawabganj and Satkhira. In Chapai Nawabganj, T. *aman* rice yield might decrease only in the year of 2055 by about 0.32%. In Satkhira, the decrease could only be in the year of 2025 by about 0.07%. It is to be noted that there is a yield gap between the *boro* and *aman* rice in Bangladesh. The lower level of sunshine is the principal cause of lower yield of the *aman* rice.

The second reason of the decrease in T. *aman* rice yield is the exceedence of the optimum temperature in both vegetative and reproductive stages (Figures 8.6 and 8.7). Optimum temperatures for T. *aman* rice during the vegetative and reproductive stages are 20-30 ^{0}C and 30-33 ^{0}C, respectively (BRRI, 2006). A high temperature in the reproductive phase of rice plant induces spikelet sterility (Haque *et. al.*, 1983). Furthermore, a higher minimum temperature during the ripening stage also affects the grain yield significantly (Amin *et. al.*, 2004). An increased temperature leads to forced maturity and poor harvest index. Mathauda *et. al.* (2000) conducted a study using CERES-rice model to simulate the yield of *aman* rice in Punjab area of India. The authors found that the *aman* rice yield decreases with the increase in mean temperature above the normal temperature. A temperature increase of 1 ^{0}C resulted in a decrease of 4.9% in *aman* rice yield and an increase of 2 ^{0}C resulted in a decrease of 8.4%.

Table 8.11: Predicted yield (kg/ha) of BR 22 variety of aman rice at some selected locations of Bangladesh for some selected years

Location	Simulated yield (kg/ha) in the years of				Change in yield (%) in the years of		
	1975	2025	2055	2085	2025	2055	2085
Rajbari	4941	4840	4883	5022	-2.04	-1.17	1.64
Nawabganj	4343	4417	4329	4382	1.70	-0.32	0.90
Satkhira	4432	4429	4525	4580	-0.07	2.10	3.34
Sunamganj	4586	4576	4578	4683	-0.22	-0 .17	2.12

In contrast to the above decreases, the yield of T. *aman* rice was found to be increased in some other cases. The maximum increase, which could be about 3.34%, might occur in Satkhira in the year of 2055. The increases could be 1.70% in 2025 and 0.90% in 2085 at Chapai Nawabganj; 2.12% at Sunamganj in 2085; and 1.64% at Rajbari in 2085. T. *aman* is one of the important rainfed crops in Bangladesh. Rainfall plays a significant role in T. *aman* production. In the years of increased yield, predicted precipitation (Figure 8.8) in T. *aman* season was found to have exceeded the water requirement for T. *aman* rice (1000-1100 mm). More importantly, solar radiation was predicted to be increased in those years. These in combined could be the reasons for the T. *aman* rice yield increases for those cases.

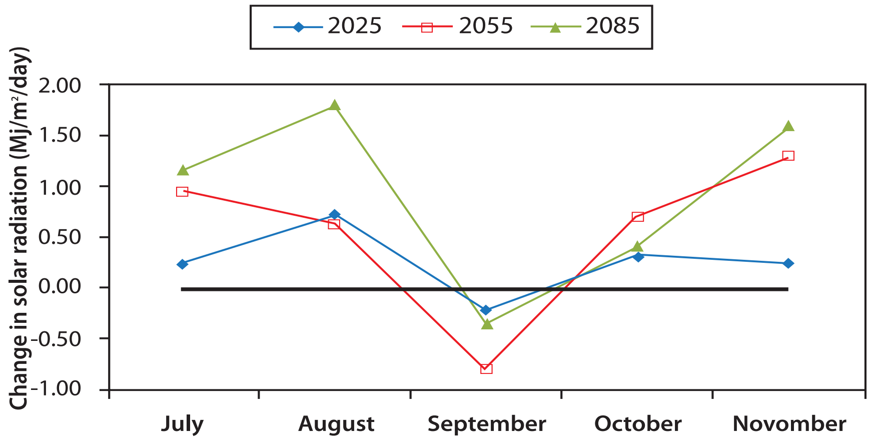


Figure 8.5: Climate model predicted change in monthly average solar radiation at Rajbari during the *aman* season

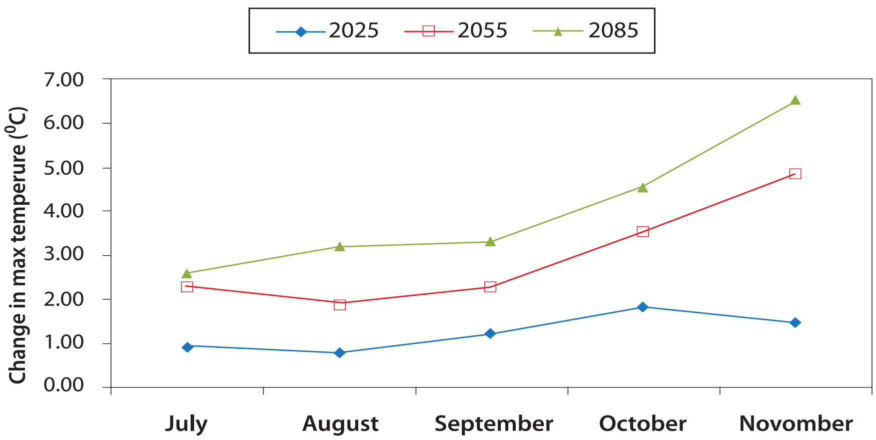


Figure 8.6: Climate model predicted change in monthly average maximum temperature at Rajbari duringthe *aman* season

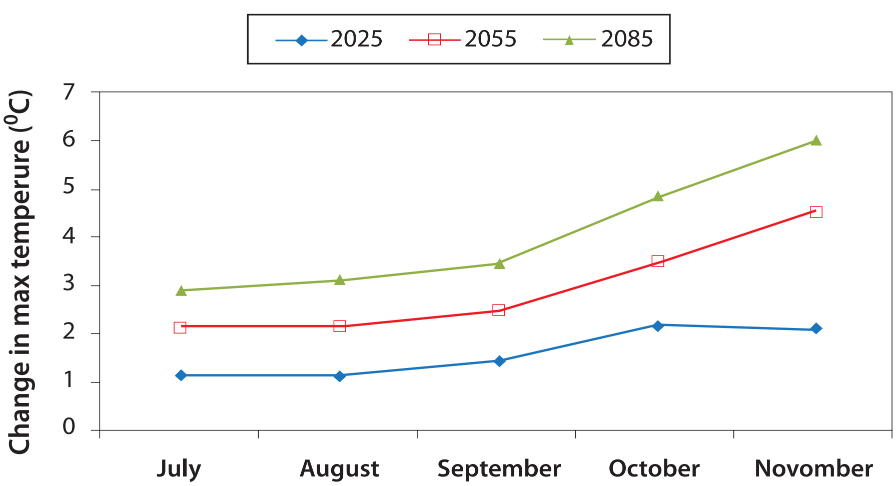


Figure 8.7: Climate model predicted change in monthly average minimum temperature at Rajbari during the *aman* season

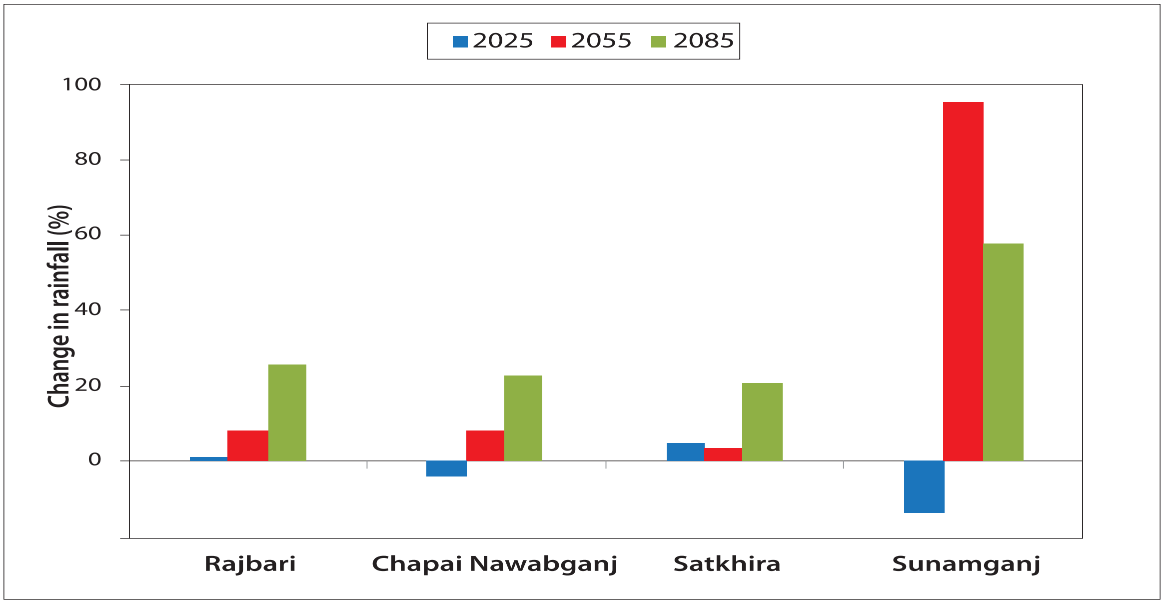


Figure 8.8: Climate model predicted change in total precipitation during the T. *aman* rice growing period at some selected locations for some selected years

8.4 Sensitivity Analysis and Further Discussion

In the preceding section, potential effects of future climates on three crops - wheat, *boro* rice and *aman* rice - were assessed using a crop growth model called DSSAT. The direction and the degree of such effects depend on a number of factors including the crop physiological and phonological responses to the projected climatic changes. Such responses also depend on the complex interaction among the different controlling factors and are usually difficult to understand and explain for non-agriculturists. Sensitivity analysis, as an alternative, was carried out to provide possible explanation of the effects of climatic changes on the three crops.

8.4.1 Sensitivity of wheat to different parameters

8.4.1.1 Sensitivity to temperature

Temperature affects most plants and crop-level processes underlying yield determination and hence the complexity of the final yield response. High temperatures severely limit wheat yield. They accelerate plant development and specifically affect the floral organs, fruit formation and the functioning of the photosynthetic apparatus. Heat stress during the reproductive stage of wheat affects the assimilate availability, translocation of photo-synthates to the grain, starch synthesis and deposition in the developing grain. The net result is a lower weight of grain (FAO, 2002). Over the range of 12-26 ^{0}C, any increase in mean temperature during grain filling reduces grain weight at a rate of 4-8% per ^{0}C (Wiegand and Cuellar, 1981). Acevedo *et. al.* (1991) reported a mean reduction of 4% in grain weight per ^{0}C increase in mean temperature during grain filling.

The effects of temperature on simulated grain yield of wheat at Chapai Nawabganj are presented in Table 8.12. The table shows a gradual decrease in wheat yield with the increase in maximum temperature, minimum temperature, or both these temperatures. The yield of wheat is reduced by 1.59%, 2.58% and 5.07% with the increase of maximum temperature alone by 1^{0}C, 2^{0}C and 3^{0}C, respectively. With the increase in minimum temperature alone by 1^{0}C, 2^{0}C and 3^{0}C, the wheat yield is reduced by 1.50%, 2.41% and 3.62%, respectively. Thus, the increase in the maximum temperature is found to be more sensitive than the similar increase in the minimum temperature. The maximum reduction in yield occurs when both the maximum and minimum temperatures are increased beyond 1^{0}C. With the increase of both the maximum and minimum temperatures by 3^0C, wheat yield is found to be reduced by about 14.5%. Such sensitivity of wheat yield to temperature provides a clear explanation of the projected decreases in wheat yield at different locations of Bangladesh.

Table 8.12: Sensitivity of wheat yield (kg/ha) to maximum and minimum temperatures at Chapai Nawabganj

Temperature	Without change	+ 1^0C	+ 2^0C	+ 3^0C	Change in yield (%) for +1^0C	Change in yield (%) for +2^0C	Change in yield (%) for +3^0C
Maximum temperature	2073	2040	2014	1968	-1.59	-2.85	-5.07
Minimum temperature	2073	2042	2023	1998	-1.50	-2.41	-3.62
Both maximum and minimum temperatures	2073	2069	1937	1773	-0.19	-6.56	-14.47

8.4.1.2 Sensitivity to solar radiation

The growth and yield of wheat are derived from photosynthesis, dependent on the receipt and capture of solar radiation. Solar radiation activates the photo-system by which light reaction of photosynthesis is started and electrons generated by photolysis of water moves to produce energy carriers. A recent study (Ahmad and Hassan, 2011) revealed a positive correlation between wheat yield and total solar radiation at anthesis and maturity in Pakistan. The sensitivity of simulated yield of wheat to solar radiation for Chapai Nawabganj is presented in Table 8.13. It is seen from the table that a slight increase in solar radiation from the base condition results in the highest yield of wheat. With an increase of solar radiation by 0.25 $MJ/m^2/day$ from the base condition, the wheat yield increases by 1.4%. Any increase in solar radiation beyond 0.5 $MJ/m^2/day$ brings in a reduced yield compared to the base condition. In case of gradual reduction in solar radiation from 0.25 to 2.0 $MJ/m^2/day$, wheat yield decreases gradually from about 0.8% to 13%. Thus, any reduction in solar energy from its present level due to global dimming can be more harmful for wheat production than a similar increase.

Table 8.13: Sensitivity of wheat yield to solar radiation at Chapai Nawabganj

Change in solar radiation ($MJ/m^2/day$)	Predicted yield (kg/ha)	Change in yield (%)
Without change	**2073**	**-**
+0.25	**2102**	**+1.40**
+0.5	**2093**	**+0.96**
+1.0	**2072**	**-0.05**
+2.0	**2014**	**-2.85**
-0.25	**2057**	**-0.77**
-0.5	**2025**	**-2.32**
-1.0	**1959**	**-5.50**
-2.0	**1804**	**-12.98**

8.4.1.3 Sensitivity to CO2

Wheat yield is sensitive to atmospheric carbon dioxide (CO_2) concentration. An elevated CO_2 level increases the net. photosynthesis rates and reduces the stomatal conductance, resulting in reduced transpiration. Moreover, higher CO_2 concentration increases leaf and plant water use efficiency (Wu *et. al.*, 2004). It also has indirect effects on growing season duration and water availability. The effect of elevated CO_2 on grain yield of wheat in relation to the base yield for Chapai Nawabganj is given in Table 8.14. CO_2 concentrations of 460, 535 and 626 ppm for the years of 2025, 2055 and 2085, respectively, based on the IPCC projection in the fourth assessment report of 2007, were taken to simulate the future yields (IPCC, 2007). With the increase of the CO_2 concentration by 126 ppm, 201 ppm and 292 ppm, the wheat yield at Chapai Nawabganj increases by 3.57%, 5.89% and 8.35%, respectively. Patel and Shekh (2005) predicted that when CO_2 concentration was doubled, the grain yield increased up to 43%. It thus appears that the negative effect of increased temperature on wheat yield in future would be offset. to some extent by the positive effect of increased CO_2. The details can be found in Madhu (2011).

Table 8.14: Sensitivity of wheat yield at Chapai Nawabganj to atmospheric CO_2 concentration

CO_2 concentration (ppm)	Predicted yield (kg/ha)	Change in yield (%)
334	2073	-
460	2147	3.57
535	2195	5.89
626	2246	8.35

8.4.1.4 Sensitivity to sowing date

The time of sowing seeds is very important for wheat cultivation as the yield depends on the selection of suitable time of sowing. One of the most important reasons for reduction in wheat yield is delayed sowing. In Bangladesh, the optimum time for sowing wheat cultivars ranges from the second week to the last week of November. Since the growth of wheat plant is very susceptible to temperature, a delayed sowing after the optimum planting time can result in reduction in yield of around 44 kg/ha (BARI, 2010). In this study, the effect of sowing date on the yield of wheat was assessed by set.ting the planting date on 5 November, 15 November, 25 November, 5 December and 15 December. Table 8.15 shows the predicted yield of wheat for different dates of sowing. It is seen from the table that the 15 November is the optimum time for sowing wheat seeds

Table 8.15: Sensitivity of wheat yield at Chapai Nawabganj to sowing dates

Sowing date	Predicted yield (kg/ha)	Change in yield (%)
5 Nov	2057	-0.77
15 Nov	2073	-
25 Nov	1375	-33.67
5 Dec	1022	-50.70
15 Dec	794	-61.70

because the yield of wheat reduces drastically if sown after this date. If the wheat is sown on 25 November, 5 December and 15 December, the yield may fall by 33.67%, 50.70% and 61.70%, respectively. The yield may fall by more than 50% if wheat seeds are sown after 5 December. However, if the seeds are sown little earlier, the effect may not be significant.

8.4.1.5 Sensitivity to irrigation

Generally 2-3 irrigations are required for wheat cultivation in Bangladesh. The requirement varies from place to place depending on the variation of climatic conditions and soil types. In Rajshahi region, the first irrigation is applied at 17-21 days after sowing (crown root initiation stage). The second irrigation is applied at 50-55 days after sowing (heading stage) and the third irrigation at 65-75 days after sowing (primary grain filling stage). The effect of the number of irrigations applied on the yield of wheat is given in the Table 8.16. It is seen from the table that the highest yield (2073 kg/ha) may occur with three irrigations. The yield may reduce with the decrease of the number of irrigations. Without the first irrigation (i.e., with two irrigations), wheat yield may reduce by 33%. The first irrigation is usually applied during the tillering stage. Peterson *et. al.* (1984) stated that the stage of tillering is very sensitive to water stress, the yield being almost halved if conditions are dry enough. The most affected physiological process during this stage is the leaf area index development, which finally affects the yield. Without the first and second irrigations (i.e., with only one irrigation), yield may reduce by 56%. A drastic decrease in yield (about 63%) may occur at without irrigation condition because water deficit at different stages have multiplicative effect on the final yield of wheat. Irrigation is vital for both the tillering and flower initiation stages. Water deficit just before flower initiation may decrease the number of spikelets (Oosterhuis and Cartwright, 1983). Mild to moderate water deficits during the vegetative stage decrease cell growth and leaf area with a consequent decrease of photosynthesis per unit area (Acevedo, 1991). Grain number decreases sharply when water stress occur during the spike growth period (Hochman, 1982). Yield reduction is at a maximum when water stress develops from ten days before spike emergence (Moustafa *et. al.*, 1996). It thus appears that the yield of wheat is very sensitive to the quantity of irrigation applied.

Table 8.16: Sensitivity of wheat yield at Chapai Nawabganj to the number of irrigations applied

No. of irrigations	Predicted yield (kg/ha)	Change in yield (%)
3 irrigations	2073	-
2 irrigations (without 1st)	1395	-32.70
1 irrigation (without 1st & 2nd)	905	-56.34
No irrigation	776	-62.57

8.4.1.6 Sensitivity to soil pH

Soil pH is important in det.ermining the availability of nutrients to the plant. Changes in soil pH may affect the yield of wheat. The initial soil pH of Nachole upazila in 2010 ranged from 6.6-7.0 at different layers of soils. Table 8.17 shows the sensitivity of simulated yield of wheat to initial soil pH. With a gradual increase of soil pH in each of the four layers by 0.25-1.0., simulated yield is found to decrease by 9.5-25%. With the decrease of soil pH by 0.25, 0.5 and 1.0 in each layer, the yield reduces by 3.42%, 1.93% and 0.24%, respectively. Thus, it appears that the wheat yield is very sensitive to soil pH. It can also be said that the soil pH at present is around the optimum level and any change in pH unaccompanied by changes in other soil and climatic parameters would be detrimental to wheat yield.

Table 8.17: Sensitivity of wheat yield at Chapai Nawabganj to soil pH

Change in soil pH	Predicted yield (kg/ha)	Change in yield (%)
Without change	2073	-
+0.25	1876	-9.50
+0.5	1684	-18.77
+1.0	1539	-25.76
-0.25	2002	-3.42
-0.5	2033	-1.93
-1.0	2068	-0.24

8.4.1.7 Sensitivity to organic carbon

The initial contents of organic carbon (OC) in different soil layers ranged between 0.27% and 0.58% at Nachole upazila in the year of 2010. The sensitivity of simulated wheat yield to soil OC is shown in Table 8.18. It is seen from the table that with the addition of soil OC by 0.25%, the wheat yield may increase by 1.88% compared to the base condition. However, any further increase in OC beyond 1% would be detrimental to wheat yield if other soil and climatic parameters remain unchanged. With the decrease of soil OC, wheat yield is reduced significantly. At zero level of initial soil OC, wheat yield may reduce by 11.82%. Thus, the wheat yield is found to be sensitive to the decrease in soil OC than its increase.

Table 8.18: Sensitivity of wheat yield at Chapai Nawabganj to soil organic carbon

Change in OC (%)	Predicted yield (kg/ha)	Change in yield (%)
Without change	2073	-
+0.25	2112	+1.88
+0.5	2075	+0.10
+1.0	1969	-5.02
+2.0	1701	-17.95
-0.25	1885	-9.07
At 0 level	1828	-11.82

8.4.1.8 Sensitivity to cation exchange capacity and total nitrogen

The initial soil cation exchange capacity (CEC) in 2010 ranged from 10.7 to 18.61 meq/100gm and total nitrogen (TN) from 0.033% to 0.54% in different layers. From the sensitivity analysis, it was found that there are no major effects of initial soil CEC and TN on wheat yield. The effect of initial soil nitrogen contents becomes unimportant due to the application of N fertilizer.

8.4.2 Sensitivity of rice to different parameters

8.4.2.1 Sensitivity to temperature

The growth and yield of rice plant are sensitive to temperature change. The mean, sum, range, distributional pattern and diurnal variation of temperature influence both growth duration and growth pattern of a rice plant and are correlated with rice yield. However, the responses to temperature vary depending on the development stage of a rice plant. Optimum temperature in vegetative stage ranges normally from 20-30^{O}C and the low and high temperatures are 10-12^{O}C and 40^{O}C, respectively. During the first week after germination, which is the early part of the vegetative stage, the rate of growth is proportional to temperature when temperature ranges from 22-31^{O}C. Seedlings grow best at temperatures of 25-30^{O}C and reasonably well at temperature up to 35^{O}C. Above a temperature of 35^{O}C, the growth declines sharply and the seedlings may die at a temperature beyond 40^{O}C. The critical minimum temperatures for shoot and root elongations are 7-16 OC and 12-16^{O}C, respectively. Optimum temperature for tillering is between 25^{O}C and 31^{O}C. A higher temperature, accompanied by an adequate sunlight, increases the rate of leaf emergence and provides more tiller buds. From the above data and information, it appears that, even within the vegetative stage, rice plant responses differently to temperature at different sub-stages and it would not be easy to depict the relationship between temperature and yield of rice.

In the reproductive stage of a rice plant, optimum temperature varies between 30^{0}C and 35^{0}C and the low and high temperatures are 20^{0}C and 35^{0}C, respectively. However, for the panicle initiation stage within the reproductive stage, the minimum critical temperature is about 15-18^{0}C. The rice is most sensitive to high temperatures at heading and flowering stages. A high temperature during anthesis induces a high percentage of spikelet sterility resulting from disturbed pollen shedding and impaired pollen germination (Satake and Yoshida, 1978; Yoshida, 1981). A higher temperature on the day of flowering of a rice plant causes sterility in most spikelet.s. A higher temperature just before the anthesis has the second most detrimental effect on spikelet sterility, but a higher temperature after the anthesis has little effect. The optimum temperature for the anthesis stage is 30-33^{0}C and the critical low and high temperatures are 22^{0}C and 35^{0}C, respectively. A field study in 1990 (Haque et. al., 1992) revealed a high level of grain sterility (40-90%) in *boro* rice in several regions of Bangladesh due to the unusual fall of temperature in the month of March.

In the final growth stage of a rice plant, which is the ripening stage, the optimum, low and high temperatures are 30-35^{0}C, 12^{0}C and 35^{0}C, respectively. The optimum temperature for the ripening of rice is 21-22^{0}C (Amin *et. al.*, 2004). At a temperature below 35^{0}C, translocation is usually decelerated, while at a temperature above 22^{0}C, respiration rate is usually accelerated and the grain-filling period is shortened. Islam *et. al.,* (1995) found a significant effect of a higher minimum temperature during the ripening phase on grain yield of rice.

Sensitivity of *boro* rice yield to joint increases in maximum and minimum temperatures at Satkhira is given in Table 8.19. It is seen from the table that an increase in temperature has in general an adverse effect on rice yield. The effect is colossal at increases in mean temperature of 4^{0}C and above. However, the effect is less severe in case of increases in minimum temperature alone (Table 8.20) compared to the increases in both maximum and minimum temperatures. This was observed across all the four sites. The effect of increases in maximum temperature was found to be slightly less than or similar to that of minimum temperature. For increases in maximum temperature of 1, 2 and 4^{0}C, the *boro* rice yield at Satkhira was found to be decreased by 1.8, 3.0 and 3.6%, respectively. It is to be noted that Basak (2009) also studied the sensitivity of *boro* rice yield in Bangladesh to climatic parameters. However, the methodology followed in the study for sensitivity analysis using climatic scenario of 2070 was flawed. Moreover, the author reported a very large variation in yield (a drop of up to 67%) across locations and time, which cannot be explained conceptually and practically. The possible reasons could be that he did not use any measured field data in his modeling exercise and the model setup was flawed. The latter observation appeared from the fact that the duration of *boro* rice from his model output was found to be about 80 days, whereas this was about 160 days in our model study. Field data and literature (BRRI, 2004) suggest a duration of about 160 days for BR 14 variety of rice. The sensitivity of *aman* rice to different climatic parameters was not investigated as the predicted impact of climate change on irrigated *aman* rice did not appear to be very significant.

Table 8.19: Sensitivity of *boro* rice yield at Satkhira to increases in both maximum and minimum temperatures

Temperature	Base condition	+1 ^{0}C	+2 ^{0}C	+3 ^{0}C	+4 ^{0}C	+6 ^{0}C
Yield (kg/ha)	5484	5484	5365	5219	5113	3478
Change in yield (%)	-	-2.2	-3.5	-6.8	-10.4	-36.6

8.4.2.2 Sensitivity to solar radiation

The rate of photosynthesis and hence the growth and development of a rice plant depend on the quantity of solar radiation absorbed by its canopy. For a rice plant, the most critical period in term of solar energy requirement is from the panicle initiation to 10 days before maturity (Stansel, 1975). The accumulation of dry matter depends on the solar energy received during this period. Accumulation of starch in leaves and culms starts at about 10 days before heading and in grains occurs markedly during the 30-day period following heading (Murata, 1966; Yoshida and Ahn, 1968). Thus, a period of about 40-45 days before harvest is critical for grain production in term of solar radiation. Furthermore, the solar radiation available during a 25-day period before flowering is important as it det.ermines the number of spikelet.s (Yoshida, 1977). A highly significant correlation was found between solar radiation and rice yield in the tropics by Datta and Zarate (1970). For the same quantity of daily solar radiation, photosynthesis rate also increases with day length.

Table 8.20: Sensitivity of *boro* rice yield at Satkhira increase in minimum temperature

Temperature	Base condition	+1 ^{0}C	+2 ^{0}C	+3 ^{0}C	+4 ^{0}C	+6 ^{0}C
Yield (kg/ha)	5484	5460	5270	5225	5208	5013
Change in yield (%)	-	-0.4	-3.9	-4.7	-5.0	-8.6

The sensitivity of *boro* rice yield to solar radiation is given in Table 8.21. It is seen from the table that the yield is sensitive to change in solar radiation. The yield generally increases with the increase in radiation and vice versa. However, the reduction in radiation is found to be slightly more sensitive than the similar increase in radiation. Moreover, the effect is not very dramatic. Our simulation results show somewhat lower sensitivity of *boro* rice yield in Bangladesh to solar radiation than that reported by Bashak (2009). The limitations of the latter study were mentioned in an earlier section. Zaman and Mondal (2011) also found a lower sensitivity of *boro* rice in Bangladesh to solar radiation using a different crop growth simulation model (ORYZA 2000).

Table 8.21: Sensitivity of *boro* rice yield at Rajbari and Satkhira to solar radiation

Solar radiation condition (MJ/m^2)	Rajbari		Satkhira	
	Yield (kg/ha)	Change in yield (%)	Yield (kg/ha)	Change in yield (%)
Base condition	5612	-	5484	-
+0.25	5628	0.3	5512	0.5
+0.50	5667	0.9	5525	0.7
+1	5711	1.8	5553	1.3
+2	5805	3.4	5625	2.6
+3	5928	5.6		
-0.25	5593	-0.3	5431	-1.0
-0.50	5592	-0.4	5423	-1.1
-1	5520	-1.6	5401	-1.5
-2	5417	-3.5	5306	-3.2
-3	5277	-6.0		

8.4.2.3 Sensitivity to CO_2

The rice being a C3 plant responds readily to increased CO_2 concentration. A higher concentration of CO_2 in the atmosphere results in a higher difference in partial pressure between the air outside and inside the plant leaves. This difference leads to the absorption of more CO_2 by a rice plant and the production of more carbohydrates (Rosenzweig and Hillel, 1995). A study in Philippines (Singh and Padilla, 1995) found that CO_2 would bring beneficial effects for rice in terms of grain yield, reduced transpiration, increased efficiency in the use of water, radiation and nitrogen, and reduced nitrogen losses. The benefits would be more in high input irrigated rice. A doubling of CO_2 could raise productivity by about 30% for most field crops (Reilly *et. al.*, 1996).

The sensitivity of *boro* rice yield to CO_2 concentration in the atmosphere is given in Table 8.22. It is seen from the table that any increase in the CO_2 concentration in the atmosphere has a positive effect on rice yield. Thus the negative effect of increasing temperature may be compensated to some extent by an increasing level of CO_2 in the atmosphere. This finding is consistent with that of Karim *et. al.* (1994) who reported that the negative effect of temperature rise on rice yield at two locations in Bangladesh (Barisal and Mymensigh) could be offset by the positive physiological effect of CO_2 hike.

Table 8.22: Sensitivity of *boro* rice yield at Rajbari and Satkhira to CO_2 concentration

CO_2 concentration (ppm)	Rajbari		Satkhira	
	Yield (kg/ha)	Change in yield (%)	Yield (kg/ha)	Change in yield (%)
330	5612	-	5484	-
460	6084	8.4	5667	3.3
535	6098	8.7	5755	4.9
620	6129	9.2	5829	6.3

8.5 Local Perception on Crop Vulnerability

8.5.1 Central area

From the central part of the country, Modapur union of Pangsha upazila in Rajbari district was selected. The area is flood free due to the presence of the Ganges right embankment, is moderately to well drained, and has soils of silty loam and silty clay loam textures. The general soil type of the area is predominantly calcareous dark grey. The organic matter content of the soils in ridges is low and that in the basins is moderate. The general fertility level of the soils is medium to high.

During the field visits, two FGDs with the local farmers, five KIIs - one with a block supervisor, one with the upazila agriculture officer of Pangsha upazila, one with a local farmer-cum-businessman and two with highly educated local farmers - and some informal interviews were conducted to gather the local perception on crop vulnerability due to climate change.

This area is well known for high agricultural production. Rice, jute, wheat, sugarcane, oil seeds, pulses, onions, etc., are the major agricultural crops in the area. The dominant cropping patterns in the higher lands are rabi crops followed by jute and in the lower lands are *boro* rice followed by *aman* rice. In the visited area, BRRI Dhan 28 and BRRI Dhan 29 varieties of *boro* rice are usually cultivated with seed-to-seed durations of 145 and 165 days, respectively. Recently, however, BRRI Dhan 33, BRRI Dhan 41 and BRRI Dhan 39 are being cultivated with durations of 120-125 days. Due to a shorter duration of the latter varieties, they can be cultivated avoiding the peak irrigation requirement period of late April and early May. During the field visits, the upazila agriculture officer informed that they were emphasizing wheat cultivation because of lower irrigation water requirement of wheat compared to rice and due to water scarcity during the critical period of the dry season. The main varieties of wheat cultivated are Sonalika and Kanchan, which can be seeded up to the first week of December. Recently, a new variety, named Prodip, has evolved. This variety can be seeded up to 25 December without affecting much the yield.

Erratic rainfall, foggy weather, shortening of the winter season and increased temperature were identified to be the main climatic hazards to agricultural crops in the area. The local people said that the timing of rainfall in the area has changed - the months of Ashar and Srabon used to be the peak rainy months and there used to be less rains towards the end of Bhadro; this pattern of rainfall has changed and rainfall has also decreased. These experiences of the local people are consistent with the findings of observed rainfall analysis. In some years, the cultivation of T. *aus* rice, jute and T. *aman* rice was delayed due to the delay in occurrence of rainfall. If these crops had experienced a lower temperature towards the end of the growing period, their flowering got affected and yield reduced. Irrigation is required these days for crop production due to irregular pattern of rainfall. They informed that, earlier they could cultivate the rabi crops with the residual soil moisture. But now such moisture level has gone down due to lower rainfall, among other factors, and as such, all crops require irrigation. After the germination, irrigation is provided to all the rabi crops including lentil, pea, chick pea, garlic, onion and black cumin. The farmers were also facing the problem of jute rotting in recent years because of less rainfall during the monsoon.

The local people informed that the prevalence of foggy environment, which damaged the crops of the visited area, has increased. This is again consistent with the finding of the sunshine duration analysis. A continuous highly foggy weather caused the incidence of aphid, locally called jab, and the root rotting disease in rabi crops. Such damped weather affected the yields of mango, oil-seed and onion seed in particular.

The summer in the area has become warmer and the peak winter cooler. The duration of the winter season has decreased. The winter season has also been shifted. These experiences of the local people are more or less consistent with the results of the analysis of the observed temperature data. Some locals have linked these climatic shifts and extremes to erratic pattern of rainfall and lower rainfall. These changes, according to the farmers, have affected the growths and yields of wheat, lentil, mustard, grass pea, pea and chick pea. Grain sterility has increased and grain weight has decreased for wheat with the increase in temperature during the time of flowering. The quality of some crops, such as cauliflower, may also have decreased due to a rise in temperature towards the end of the growing period. The early blight and late blight diseases have appeared in potato due to the shortening of winter season affecting the production drastically. The seedbed of *boro* rice and the young seedlings in the field became susceptible to cold injury and foggy weather during the period from 22 December to 15 February as there is an indication that the peak winter is becoming cooler day by day. Because of severe cold, the bee's population, which helps in pollination of flowers of many crops, has decreased, affecting the production of those crops including onions and mustards.

Regarding the positive changes in climate, the occurrence of thunder storms in the area has decreased which was beneficial for *boro* rice and rabi crops. The production of sugarcane has also increased due to the increase in temperature.

8.5.2 Haor area

From the haor basin, the Pagner haor in Jamalganj upazila under Sunamganj district was visited. Soils of the area are grey silty clay loams and clay loams on the higher parts which dry out seasonally and grey clays in the wet. basins. The soils have a low to moderate content of organic matter due to the submergence for a period of 6-7 months and soil reaction is mainly acidic. Fertility level is medium to high. Groundwater table is far below the land surface. In this area rainfall is high. Average humidity is high in this region. Fog is very common in winter. This area is the cloudiest part of Bangladesh.

During the field visits, three FGDs with the local farmers, five KIIs - one each with a farmer, an agriculturist, two CNRS officials and a sub-assistant agriculture officer who was also in charge of Jamalganj agriculture office - and some informal interviews with the local people were held to gather data and information.

About 70-75% of the area is low lying and the remaining 25-30% is high land locally *known* as *kanda. Kandas* are mostly khas lands. About 25% of the people of the visited area are landless. In the past, their livelihoods were mostly dependent on fishing. But at present, due to a system of leasing out of the haors, they are not allowed to fish by the lease holders and they become jobless after the harvesting of *boro* rice. For this reason, they seasonally migrate to other places for works.

The main crop of the area is *boro* rice which is cultivated during December-May. About 75% of the net. cropped area is under *boro* cultivation. BRRI Dhan 28, BRRI Dhan 29, BRRI Dhan 36 and BRRI Dhan 45 are the main varieties of *boro* rice cultivated. About 15-20% of the area is under other crops. *Aman* is cultivated on high lands near the roads. But its coverage is low compared to the total haor area. Besides these, small amount of winter crops are cultivated. Potato, wheat, chili, egg plant, mustard, ladies finger, etc., are also cultivated on the *kandas*.

This area is highly vulnerable to flash flood which occurs during April-May. The period coincides with the ripening and harvesting periods of *boro* rice. Besides this, an irregular pattern in rainfall is being noticed by the local people and was mentioned during the field visits. During the field visits, the farmers informed that low rainfall occurred during the rabi season of the year 2009-10. Moreover, towards the end of the season, an unexpected flash flood damaged the standing *boro* rice in the year of 2009-10. The farmers also informed that no flash flood occurred during the harvesting period of *boro* rice in the year of 2010-11 and they had harvested the rice safely. Moreover, the *aman* rice yield in the year of 2010 was good due to the well distributed rainfalls throughout the season. This is consistent with the findings of rainfall analysis (number of rainy days). Delayed drainage is another main problem for this area. The farmers said that the drainage is delayed until December. The increase in rainfall in September and October can partly be the reason. One of the CNRS officials added that the rivers of the area have been silted up which is further aggravating the drainage problem and increasing the flash flood. Storage capacity of the rivers has decreased. Before it took about 10 days to fill in the surrounding rivers; now it takes only about 3 days. The water-logged area in the Pagner haor has increased. At present, the incoming water from the hills contains more sediment compared to the past. Other hazards of the area are hail storm, haze, cold injury, and irrigation water scarcity. The temperature of the area has increased and is also behaving erratically - it was too cool and foggy in the last year (2010). The temperature rising is affecting the cultivation of winter vegetables. Hail-storm occurring around mid-April damages the *boro* rice. The occurrence of fogs results in twisting of chili leaves. Incidence of fungi attacks becomes frequent in the event of fogs.

8.5.3 Upland area

From the upland area, Hajidanga and Nejampur villages of Nachole upazila in Chapai Nawabganj district were visited. The visited area located in the north-west region of Bangladesh near the boarder with India. The climate of the area is generally warm and humid. Rainfall is comparatively little in this region. It mainly occurs during the monsoon. During the pre-monsoon, this area experiences extreme hot weather. However, during the winter, temperature falls more in this area than the rest of the country. Thus, the region experiences climatic extremes that are clearly in contrast to the climatic condition to the rest of the country.

During the field visits, two FGDs with the local farmers, 5 KIIs with different agriculture officers in the upazila, local farmers and school teacher, and some informal interviews with the local farmers were held.

The main crops of the area are *boro* rice, T. *aman* rice and wheat. *Boro* rice is transplanted during January and harvested during mid-April to mid-May. T. *aman* is transplanted during mid-July to mid-August and harvested during mid-November to December. Wheat is broadcasted during mid-November and harvested during mid-March to the first week of April. The main varieties of *boro* rice are BRRI Dhan 28, BRRI Dhan 29, Pariza and hybrid SL-8H. Sarna, BR 11 and BR 24 are the main varieties of *aman* rice. Sourav, Gourav and Satabdi are the common varieties of wheat that are cultivated in the area. In recent years, the cultivation of wheat has become popular and wheat cultivated area is increasing day by day. The farmers informed that wheat cultivation required less irrigation compared to rice cultivation. Two to three irrigations were usually used for growing wheat. Besides this, wheat cultivation is easier than rice cultivation. The farmers also informed that the wheat yield was the highest in the year of 2010-11 among the past 12 years. The upazila agriculture officer informed that the temperature at the flowering stage of wheat was optimal and other climatic parameters were favorable for wheat growth in the year. Beside this, irrigation water was available in adequate quantity and the farmers could apply irrigations and fertilizers in time. For these reasons, wheat yield in the year surpassed the records of past 12 years.

This area usually faces shortage of irrigation water. The main source of irrigation water is deep tube-wells which are maintained and operated by the Barendra Multipurpose Development Authority. But, irrigation water is usually not sufficient and some areas remain fallow still now.

Climatic hazards, such as foggy environment, erratic rainfall and cold injury, affected the yield of *boro* rice, potato and wheat. The farmers said that extreme cold event damaged the seedlings of *boro* rice. Foggy environment caused the late blight diseases to potato and the leaves of *boro* rice to turn into yellow. During the field visit, the local people informed that the summer temperature has increased in recent years and an extreme hot weather condition has prevailed over the last few years. Moreover, the number of extreme cold days has decreased compared to the past. People also said that the temperature of the winter season has increased. They mentioned that high temperature during the wheat growing period had decreased the wheat yield. From the model analysis it is also found that wheat yield in the predicted years will be decreased because of increase in temperature.

8.5.4 Coastal area

The villages of Badoghata and Kathalbaria of Shyamnagar upazila in Satkhira district were visited from the coastal area. The area is located in the south-west coastal region. The greater part of this region has a smooth relief with salinity in large areas. Non-calcareous grey floodplain soil is the major component of general soil types.

During the field visits, one FGD with the local farmers, six KIIs with different agriculture officers in the upazila, local farmers and NGO worker and some informal interviews with the local farmers were held.

The main crop of the area is T. *aman* rice, which is transplanted during mid-July to mid-August and harvested during mid-November to December. About 75% of the net. cultivated area is under T. *aman* production. The varieties of T. *aman* rice cultivated are BR 10, BR 11, BR 22 and BRRI Dhan 30, BRRI Dhan 40 and BRRI Dhan 41. Among these, BR 10 and BRRI Dhan 30 are the dominant varieties. Many people become jobless after the harvesting of *aman* rice. They leave the area during November-December and come back again during June-July at the planting season of *aman*. The tropical cyclone 'Aila' hit the coastal zone on 25 May, 2009. The farmers reported that the T. *aman* production fell drastically in that year. But in the year of 2010, the T. *aman* production was remarkably high compared to the last 10 years. The reason behind this was that the soil salinity had reduced due to the occurrence of significant rainfall during October at the maturing stage of the T. *aman* rice. The farmers also mentioned that rainfall during the month of June-July is important for the transplanting of T. *aman* rice. *Boro* rice in the area is the second important crop transplanted during January and harvested during mid-April to mid-May. The varieties of the *boro* rice cultivated are BRRI Dhan 28, BRRI Dhan 29 and BRRI Dhan 47. Among these BRRI Dhan 47 is saline tolerant and its cultivation started a few years back. But it did not gain popularity among the farmers because of its susceptibility of grains loss before the ripening stage and the yield is low compared to other varieties.

Soil and water salinity, cyclone, storm surge, tidal flooding, haze, cold injury, irrigation water scarcity, increased temperature, shorter winter and erratic rainfalls are the main threats to the agricultural crops in the area. Among these, salinity is the main concern of the region. During the winter season, the crops are severely affected by the salinity problems. In the absence of appreciable rainfall, the soil of this area suffers from severe salinity problem. The farmers mentioned that salinity problem has increased severely since 1995 because of shrimp cultivation. For shrimp cultivation, one group of farmers enters the saline water while others resist and want to cultivate rice. This situation created social conflict among the farmers.

During the field visit, the upazila agriculture officer informed that seedlings of *boro* rice are sensitive to cold environment. Seedlings did not grow well and became twist when cold environment existed for a significant period during December-January. He also added that the yield of *boro* rice was also affected by higher temperature and rainfall. If the temperature in March-April was high, the evaporation from the soil also became high which further increased the soil salinity. A significant rainfall during this period could help mitigate this problem.

This area faced scarcity of irrigation water. Groundwater could not be used for irrigation purpose due to high salinity content. Only surface and reservoir water was used for irrigation. But during the winter season, available surface water was not adequate for irrigation. People of the area also suffered from scarcity of drinking water. They got their drinking water from pond and rain water harvesting.

CHAPTER 9

Conclusions and Recommendations

9.1 Conclusions

The trend in all-Bangladesh mean annual temperatures using the historical data (1948-2010) from 34 stations was found to be increasing at a rate of about 1.2^0C per century. This trend has become stronger in recent years. The trend in recent mean temperatures (1980-2010) was found to be the double (2.4^0C per century) of the historical trend. The spatial distribution of recent trends indicates that the mean annual temperature in the northern part of the country is increasing at a higher rate compared to the mid-western and eastern hilly regions. The winter (Dec-Feb), pre-monsoon (Mar-May), monsoon (Jun-Sep) and post-monsoon (Oct-Nov) trends in last 31 years of data were found to be 1.2, 3.2, 2.7 and 1.5^0C per century, respectively. The pre-monsoon, monsoon and winter trends were found to be becoming stronger and the post-monsoon trend was becoming weaker in recent times. The recent trends were also found to be higher for all months except for November-January. The trend in the month of May in the recent data was found to be a staggering 4^0C per century and in the month of January to be negative.

The all-Bangladesh annual normal rainfall was estimated for the period of 1980-2009 from 236 BWDB stations and was found to be 2306 mm. The annual rainfall at country level was found to be free of trend. However, there are some significant changes in regional scales. The seasonal rainfalls at country level have also remained unchanged except for the pre-monsoon season, when it has significant increasing trend. The post-monsoonal normal rainfalls have increased (not statistically significant) and the monsoonal normal rainfall has remained almost the same. The normal rainfalls in the months of June and August of the monsoon season have decreased and the rainfall of September has increased. The months of March and May of the pre-monsoon season have experienced increased rainfalls. The increases in May and September are statistically significant at country level. The chances of increased rainfalls in May, September and October were found to be about 66%, 73% and 71%, respectively, whereas those in June and August were only 34.5% and 29.4%, respectively. There are some regional variations in the monthly rainfall trends as well. The inter-annual variability in rainfalls for most months was found to be increasing. The number of rainy days in a year was found to be increasing. The longest duration of consecutive non-rainy days in a year was found to be decreasing. The 7-day, 3-day and 1-day maximum rainfalls in a year indicate that the rainfall intensity in the far north-western part of the country is increasing. The trend in number of days with more than 50 mm and 100 mm of rainfall in a year further supported this conclusion.

The sunshine duration has a decreasing trend at both annual and seasonal scales. The annual trend is 5.3% per decade, and the pre-monsoon, monsoon, post-monsoon and winter trends are 4.1%, 3.4%, 5.3% and 8.1%, respectively. All these trends were found to be statistically significant even at a confidence level of 99%. At a monthly scale, the decreases are higher during November-February and lower during June-August. The declining rate increases from the south to the north of the country.

The humidity has increasing trends of 1.0%, 0.4% and 1.1% per decade in the pre-monsoon, post-monsoon and winter seasons, respectively, and decreasing trend of 0.2% in the monsoon season. The winter and pre-monsoon trends are statistically significant at a confidence level of 99%, the monsoon trend at 95% and the post-monsoon trend at 80%. The humidity in all the months has increasing trends except for June-August. The trend is the highest in April, which is the warmest month of the year. The recent (1980-2010) trend was found to be much higher than the long-term (1948-2010) trend. The trends in the months of October-April have increased a lot in recent years. Furthermore, the decreasing trends in the months of June-August have become increasing in recent years.

The projected future climate with the PRECIS model indicates that the annual mean temperature may increase gradually at a rate of 4.6^{0}C per century. The increase could be more in the winter season compared to that of the monsoon season. The western and central parts of the country could experience more warming in future than the eastern part. The future annual precipitation could increase at a rate of 18 mm per decade, which is very low. The increase could be more in the north-eastern part of the country.

The results of the simulation studies conducted using a crop growth model indicate that the winter crop wheat will be highly vulnerable to climate change, followed by *boro* rice and *aman* rice. The wheat and *boro* yields might decrease by about 26% and 12%, respectively, by the end of this century. The effect of climate change on *aman* yield would be less and mixed depending on the years and locations. The south-western coastal region and the north-eastern haor basin would be more vulnerable than the central plain and high Barind area to predicated climatic changes.

The wheat yield at Chapai Nawabganj is found to be highly sensitive to increased temperature, decreased solar radiation, delayed sowing after 15 November, application of lower than 3 irrigations, increased soil pH and decreased soil organic carbon. *Boro* rice is also found to be sensitive to increased temperature and decreased solar radiation. Crop yield was found to respond positively to increase CO_2.

Foggy weather, increased temperature, shortening of winter and erratic pattern of rainfall appeared to be the climatic hazards in the four selected areas from local perception. Besides these, there are region specific hazards and crop vulnerabilities as well. Wheat, onion, vegetables, chili, lentil, mustard and different peas were identified by the local people are among the most susceptible crops to those climatic hazards.

In light of the experience gained during the course of this work, the following recommendations are made:

I. There are many levels of uncertainties in predicted future climates using the regional climate model PRECIS. The first level of uncertainty in modeling climate system comes from converting emissions into concentrations. The next level of uncertainty arises from the inadequate understanding of the processes and physics associated with carbon cycle and chemistry models. Though a very significant emphasis is given on improving our knowledge of climate system processes, yetthere remains uncertainty in how the climate responds to changes in atmospheric concentrations and compositions. There is considerable knowledge gap in developing the relationship between global and regional climate changes and impacts. There are also uncertainties in the implementation of numerics, representation of dynamics and sub-grid scale physical processes, natural climate variability and impact of atmospheric composition on radiative balance. Some of the results found from the PRECIS outputs in this study, as well as reported in various literatures from other modeling studies, appear to be inconsistent with the existing climatic trends in Bangladesh. Solar radiation and rainfall are among them. The reasons could be that all the processes, dynamics and feedbacks involved in the sun, atmosphere, land and ocean systems, as mentioned above, are not adequately represented in the climate models. We recommend such representation and calibration and validation of climate models, and updating of future projections in light of existing trends found in this study. This report may serve as a base document in that respect.

II. The vulnerability of agricultural crops to climate change was assessed using the monthly average climatic data of 30 years. Such assessment does not reveal any information on year to year variability of vulnerability, which is equally important for proper policy and decision making to reduce crop vulnerability. Moreover, intra-month variability in climatic parameters is also important for proper assessment of crop vulnerability. Due to a number of uncertainties associated with the PRECIS predicted future climates, particularly at daily scale, we did not attempt to use the daily data. Further study can look into the vulnerability variability aspect as well as the vulnerability assessment using daily data.

III. The effect of climate change induced flooding (riverine, flash and tidal), foggy environment and humidity change on crop yield cannot be simulated using the DSSAT crop growth model. However, the changes in these parameters can have a major ramification on crop productivity and vulnerability than the gradual change in climatic parameters. Furthermore, the model does not have the provision to take into consideration the effect of salinity, which is particularly important for its application in coastal region. We suggest considering the findings of this study keeping these constraints in view.

IV. Tidal river water levels may have linkages to coastal flooding, salinity and drainage congestion and hence the crop vulnerability. A future study can look into the trends in the tidal river water levels.

ANNEXURE A

Rainfall Data Availability

Annexure A: List of available rainfall data used in this study

Station ID	Station name	Available period of records (years)	Starting date	Ending date
1	Atghoria	47	4/1/1962	6/30/2010
3	Atrai (Ahsanganj)	47	4/1/1962	9/30/2010
4	Bera	44	4/1/1962	6/30/2010
5	Bhaluka	47	4/1/1962	8/31/2010
6	Bogra	52	4/1/1957	7/31/2010
7	Chatmohar	44	4/1/1964	6/30/2010
9	Dhaka	50	4/1/1957	2/28/2010
10	Daulatpur	48	4/1/1962	10/31/2010
11	Dhunot	47	4/1/1962	9/30/2010
12	Faridpur (Banuaripara)	47	4/1/1962	9/30/2010
13	Gopalpur	47	4/1/1962	1/31/2010
14	Gurudaspur	47	4/1/1962	6/30/2010
15	Ishwardi	47	4/1/1961	6/30/2010
16	Joari	47	4/1/1962	6/30/2010
17	Joydebpur	47	4/1/1961	3/31/2010
18	Kalihati	45	4/1/1962	5/31/2010
19	Kushtia	47	4/1/1961	6/30/2010
20	Manikganj	49	4/1/1961	10/31/2010
21	Mirzapur	43	4/1/1962	4/30/2010
22	Nandigram	46	4/1/1962	9/30/2010
23	Natore	46	10/26/1961	9/30/2010
24	Nawkhila	37	4/1/1970	9/30/2010
27	Phulbaria	47	6/1/1962	7/31/2010
29	Raiganj	45	4/1/1962	6/30/2010
30	Rajbari	46	4/1/1961	7/31/2010
31	Savar	46	4/1/1962	2/28/2010
32	Sarishabari	46	4/1/1961	6/30/2010
33	Sherpur (Bogra)	48	4/1/1961	9/30/2010
34	Serajganj	47	4/1/1961	6/30/2010
35	Shazadpur	47	4/1/1961	6/30/2010
37	Sreepur	46	4/1/1962	7/31/2010
38	Sujanagar	45	4/1/1964	6/30/2010
39	Taras	44	4/1/1964	6/30/2010
40	Ullapara	48	4/1/1961	6/30/2010
41	Bheramara	47	4/1/1961	6/30/2010
61	Bajitpur	47	4/1/1962	7/31/2010
62	Dewanganj	48	4/1/1961	8/31/2010

Annexure A: (continued)

Station ID	Station name	Available period of records (years)	Starting date	Ending date
63	Durgapur	47	4/1/1961	8/31/2010
64	Gafargaon	47	4/1/1962	7/31/2010
65	Gouripur	43	4/1/1962	8/31/2010
67	Jamalpur	47	4/1/1961	8/31/2010
68	Jaria-jhanjail	38	4/1/1962	8/31/2010
71	Kishoreganj	47	4/1/1961	7/31/2010
72	Muktagacha	47	4/1/1962	8/31/2010
73	Mymensingh	47	4/1/1961	8/31/2010
74	Nalitabari	44	4/1/1964	7/31/2010
75	Nandail	47	6/12/1962	8/31/2010
76	Narsingdi	46	4/1/1961	2/28/2010
77	Phulpur	43	6/13/1962	8/31/2010
78	Sherpur Town	48	4/1/1961	10/31/2009
79	Shibpur	41	4/1/1962	1/31/2010
101	Bhairab Bazar	46	4/1/1962	8/31/2010
102	Bholaganj	40	4/1/1964	8/31/2010
103	Brahmanbaria	47	4/1/1961	8/31/2010
105	Chandpur Bagan	40	4/1/1969	8/31/2010
107	Chhatak	40	4/1/1967	8/31/2010
108	Dakhinbagh	47	8/8/1961	8/31/2010
109	Gobindaganj	45	4/1/1962	8/31/2010
110	Habiganj	44	4/1/1961	8/31/2010
111	Itakhola (Baikunthapur)	41	4/1/1964	8/31/2010
112	Itna	37	4/1/1962	2/28/2010
113	Khaliajuri	47	4/1/1962	8/31/2010
114	Kamalganj	47	4/1/1961	8/31/2010
115	Kendua	42	6/1/1962	8/31/2010
116	Lallakhal	43	4/1/1962	8/31/2010
117	Langla	42	4/1/1964	8/31/2010
118	Latu	42	4/1/1966	8/31/2010
119	Manumukh	45	4/1/1961	8/31/2010
120	Markuli	43	4/1/1962	8/31/2010
121	Mohanganj	47	4/7/1962	8/31/2010
122	Moulvi Bazar	46	4/1/1961	8/31/2010
123	Netrokona	44	4/1/1961	8/31/2010
125	Sheola	45	10/1/1962	8/31/2010
126	Srimangal	47	4/1/1961	8/31/2010
127	Sunamganj	46	4/1/1961	8/31/2010
128	Sylhet	51	4/1/1957	8/31/2010
129	Tajpur	47	4/1/1962	8/31/2010
130	Zakiganj	45	4/1/1964	8/31/2010
131	Sarail	42	4/1/1964	8/31/2010

Annexure A: (continued)

Station ID	Station name	Available period of records (years)	Starting date	Ending date
132	Nasirnagar	43	4/1/1964	8/31/2010
152	Badalgachi	47	9/1/1961	9/30/2010
153	Badarganj	42	5/29/1962	9/30/2010
154	Bagdogra (Nilphamari)	37	6/11/1961	6/30/2010
156	Bhawaniganj (Gaibandha)	40	6/15/1961	9/30/2010
157	Bithargarh	42	4/1/1963	9/30/2010
158	Bholahat	44	4/3/1962	9/30/2010
161	Boda	40	10/1/1962	9/30/2010
163	Chilmari	41	1/1/1963	9/30/2010
164	Ghoraghat	43	4/1/1965	9/30/2010
166	Debiganj	46	5/1/1961	4/30/2010
167	Dimla	39	4/1/1963	6/30/2010
168	Dinajpur	46	4/1/1961	9/30/2010
171	Gobindaganj	42	6/13/1961	9/30/2010
172	Godagari	45	4/1/1963	9/30/2010
174	Hatibandha	35	6/15/1962	9/30/2010
175	Hilli (Hakimpur)	43	4/1/1963	9/30/2010
177	Kaliganj	42	4/1/1961	5/31/2010
178	Kaunia	44	4/1/1962	9/30/2010
179	Khansama	42	5/21/1963	4/30/2010
180	Kantanagar	42	7/1/1962	9/30/2010
181	Khetlal	46	4/1/1962	9/30/2010
182	Kurigram	44	5/21/1961	9/30/2010
183	Lalmanirhat	43	4/19/1962	5/31/2010
184	Lalpur	46	7/15/1961	9/30/2010
185	Manda	42	10/22/1961	9/30/2010
186	Mithapukur	43	1/1/1963	5/31/2010
187	Mohadebpur	46	4/1/1962	9/30/2010
188	Mahipur	41	11/1/1962	8/31/2010
190	Nachol	42	1/1/1963	9/30/2010
191	Noagaon	46	4/1/1961	9/30/2010
192	Nazirpur (Patnitala)	45	4/1/1962	9/30/2010
193	Nekmard	39	1/1/1963	10/31/2009
194	Nithpur	43	4/1/1961	9/30/2010
195	Chapai Nawabganj	46	4/1/1962	10/31/2010
196	Nawabganj	43	4/1/1961	3/31/2010
197	Panchagarh	40	4/1/1963	9/30/2010
201	Phulbari	39	4/1/1962	9/30/2010
202	Pirgacha	43	4/17/1962	6/30/2010

Annexure A: (continued)

Station ID	Station name	Available period of records (years)	Starting date	Ending date
203	Pirganj	40	4/1/1962	9/30/2010
204	Puthia	45	4/1/1962	9/30/2010
205	Rajshahi	47	5/1/1961	10/31/2010
206	Rangpur	46	4/1/1961	9/30/2010
208	Rohanpur	47	5/1/1961	10/31/2010
209	Ruhea	39	4/1/1962	9/30/2010
210	Saidpur	42	4/1/1961	9/30/2010
211	Sapahar	45	11/1/1962	9/30/2010
212	Sardah	46	4/1/1962	9/30/2010
213	Setabganj	45	5/16/1961	9/30/2010
214	Amla	44	4/1/1961	7/31/2010
215	Shibganj (Rajshahi)	45	7/29/1961	9/30/2010
216	Shibganj (Bogra)	41	4/1/1963	9/30/2010
217	Shikarpur	38	5/26/1962	6/30/2010
218	Sundarganj	41	4/1/1962	6/30/2010
219	Tanore	46	4/1/1962	9/30/2010
220	Tentulia	41	11/1/1962	9/30/2010
221	Thakurgaon	42	6/1/1961	9/30/2010
222	Ulipur	43	4/1/1962	9/30/2010
223	Hogalbaria	43	1/1/1963	8/31/2010
224	Chuadanga	46	4/1/1961	9/30/2010
225	Meherpur	40	4/1/1961	7/31/2010
252	Bakerganj	46	4/1/1962	8/31/2010
253	Bamna	46	4/1/1962	8/31/2010
254	Banaripara	44	4/1/1962	8/31/2010
255	Bauphal	47	4/1/1961	8/31/2010
256	Barguna	45	4/1/1961	8/31/2010
257	Barhanuddin	42	4/1/1962	9/30/2009
258	Barisal	48	4/1/1959	8/31/2010
259	Bhandaria	45	4/1/1962	8/31/2010
260	Bhola	45	4/1/1962	8/31/2010
261	Daulatkhan	44	4/1/1961	8/31/2010
262	Galachipa	43	9/11/1961	8/31/2010
263	Gournadi	43	4/1/1961	8/31/2010
264	Jhalakati	47	9/18/1961	8/31/2010
265	Mathbaria	46	7/1/1962	6/30/2010
266	Patuakhali	45	4/1/1961	8/31/2010
267	Pirojpur	46	4/1/1961	8/31/2010
269	Khepupara	38	4/1/1968	8/31/2010

Annexure A: (continued)

Station ID	Station name	Available period of records (years)	Starting date	Ending date
271	Nazirpur	39	4/1/1968	8/31/2010
272	Patharghata	40	4/1/1968	8/31/2010
301	Amtali	40	4/1/1962	8/31/2010
302	Anwara	43	9/1/1962	7/31/2010
303	Bandarban	45	4/1/1961	7/31/2010
306	Chittagong	50	4/1/1957	9/30/2010
307	Cox's Bazar	35	4/1/1959	8/31/2009
310	Dulahazara	42	5/23/1962	6/30/2010
311	Fatikchari	37	4/1/1966	7/31/2010
313	Hathazari	43	4/1/1962	7/31/2010
315	Kaptai (Chowdhuri Chhara)	43	4/1/1961	11/30/2001
316	Kutubdia	43	4/1/1962	4/30/2010
317	Lama	47	4/1/1961	7/31/2010
319	Manikchari	35	4/1/1961	7/31/2010
320	Mirsarai	44	4/1/1961	8/31/2010
322	Nakhyangchari	41	9/11/1962	7/31/2010
323	Narayanhat	46	4/1/1962	7/31/2010
324	Nazirhat	40	4/1/1963	7/31/2010
325	Patia	44	4/1/1962	7/31/2010
327	Ramgarh	44	4/1/1961	9/30/2010
328	Rangamati	44	4/1/1961	9/30/2010
330	Rangunia	37	5/21/1961	7/31/2010
331	Sandwip	41	5/1/1961	7/31/2010
332	Satkania	41	4/1/1961	7/31/2010
334	Sitakunda	40	4/1/1966	5/31/2010
351	Bancharampur	45	4/1/1961	8/31/2010
352	Barura	43	4/1/1962	8/31/2010
353	Basurhat	42	10/14/1962	8/31/2010
354	Chandpur	45	4/1/1961	8/31/2010
355	Chhagalnaya	43	4/1/1961	8/31/2010
356	Comilla	44	4/1/1961	9/30/2010
357	Daudkandi	44	6/28/1961	8/31/2010
358	Feni	45	4/1/1961	7/31/2010
359	Gunabati	44	4/1/1962	8/31/2010
370	Parshuram	46	4/1/1962	8/31/2010
372	Raipur (Noakhali)	44	4/1/1962	7/31/2010
375	Ramgati	43	1/1/1963	6/30/2010
376	Senbag	4 5	4/1/1961	8/31/2010
377	Sonaimuri	45	10/1/1962	8/31/2010
402	Bhagyakul	42	4/1/1963	2/28/2010

Annexure A: (continued)

Station ID	Station name	Available period of records (years)	Starting date	Ending date
403	Bhanga	44	4/6/1961	7/31/2010
404	Boalmari	41	4/1/1961	8/31/2010
406	Faridpur	44	4/1/1961	8/31/2010
407	Fatehpur	45	4/1/1961	8/31/2010
409	Haridaspur	43	4/1/1961	8/31/2010
410	Madaripur	44	4/1/1961	8/31/2010
411	Modhukhali	44	4/1/1962	8/31/2010
412	Nawabganj	40	4/1/1961	2/28/2010
413	Palong	44	4/1/1961	8/31/2010
414	Shibchar	42	4/1/1962	8/31/2010
451	Rajghat	44	9/1/1962	8/31/2010
452	Alamdanga	44	10/1/1962	7/31/2010
453	Benapole	44	6/11/1962	8/31/2010
454	Chaugacha	41	6/1/1962	8/31/2010
455	Dattanagar	43	4/1/1961	6/30/2010
456	Jessore	47	4/1/1959	10/30/2010
457	Jhenaidah	44	4/1/1961	8/31/2010
458	Kaliganj (Jessore)	41	4/25/1962	4/30/2010
459	Keshabpur	43	7/22/1962	8/31/2010
460	Magura	43	4/1/1961	8/31/2010
461	Narail	45	4/1/1961	8/31/2010
462	Salikha	44	8/1/1962	8/31/2010
463	Sailkupa	45	7/25/1962	8/31/2010
501	Bagerhat	45	5/1/1961	8/31/2010
502	Benarpota	40	4/1/1961	4/30/2010
503	Chalna	41	6/14/1962	7/31/2010
504	Dumuria	45	5/21/1961	10/31/2009
505	Islamkati	44	5/18/1961	12/31/2009
506	Kaikhali	41	8/1/1962	5/31/2010
507	Kalaroa	43	6/22/1961	12/31/2009
508	Kaliganj (Khulna)	41	5/19/1961	6/30/2010
509	Kapilmuni	41	6/1/1962	6/30/2010
510	Khulna	46	4/1/1961	6/30/2010
511	Mollahha	41	5/21/1961	7/31/2008
512	Morrelganj	37	6/1/1961	11/30/2009
515	Paikgacha	41	5/23/1961	7/31/2007
518	Satkhira	46	4/1/1961	5/31/2010

ANNEXURE B

Sunshine Data Availability

Station ID	Station name	Available period of record (years)	Starting date	Ending date
10120	Dinajpur	21	1/1/1989	12/31/2010
10208	Rangpur	27	8/1/1979	12/31/2010
10320	Rajshahi	26	3/1/1979	12/31/2010
10408	Bogra	48	1/1/1961	12/31/2010
10609	Mymensingh	28	3/1/1979	12/31/2010
10705	Sylhet	47	1/1/1962	12/31/2010
10724	Srimangal	21	9/1/1989	12/31/2010
10910	Ishwardi	23	1/1/1985	12/31/2010
11111	Dhaka	43	1/1/1961	12/31/2010
11313	Comilla	24	3/1/1981	12/31/2010
11316	Chandpur	25	4/1/1977	12/31/2010
11407	Jessore	41	6/1/1967	12/31/2010
11505	Faridpur	23	1/1/1985	12/31/2010
11513	Madaripur	19	10/1/1985	12/31/2010
11604	Khulna	24	2/1/1984	12/31/2010
11610	Satkhira	24	1/1/1984	12/31/2010
11704	Barisal	39	2/1/1967	12/31/2010
11706	Bhola	28	1/1/981	12/31/2010
11805	Feni	20	1/1/1985	12/31/2010
11809	Maijdicourt	22	9/1/1985	12/31/2010
11814	Hatia	19	1/1/1985	12/31/2010
11912	Sitakundu	30	1/1/1979	12/31/2010
11916	Sandwip	21	1/1/1987	12/31/2010
11921	Chittagong	33	1/1/1961	12/31/2010
11925	Kutubdia	24	5/1/1984	12/31/2010
11927	Cox's Bazar	45	1/1/1961	12/31/2010
11929	Teknaf	31	1/1/1977	10 /31/2010
12007	Rangamati	22	1/1/1987	12/31/2010
12103	Patuakhali	22	9/1/1985	12/31/2010
12110	Khepupara	22	4/1/1988	1 2/31/2010
41858	Syedpur	16	3/1/1985	12/31/2010
41909	Tangail	22	10/1/1987	12/31/2010
41926	Chuadanga	17	11/1/1992	12/31/2010
41958	Mongla	8	1/1/2001	12/31/2010

ANNEXURE C

Humidity Data Availability

Annexure C: List of available relative humidity data used in this study

Station ID	Station name	Available period of record (year)	Starting date	Ending date
10120	Dinajpur	54	1/1/1948	12/31/2010
10208	Rangpur	51	4/1/1957	12/31/2010
10320	Rajshahi	46	1/1/1964	12/31/2010
10408	Bogra	59	2/1/1948	12/31/2010
10609	Mymensingh	61	1/1/1948	12/31/2010
10705	Sylhet	53	3/1/1956	12/31/2010
10724	Srimangal	46	1/1/1960	12/31/2010
10910	Ishwardi	49	3/1/1961	12/31/2010
11111	Dhaka	56	1/1/1953	12/31/2010
11313	Comilla	60	1/1/1948	12/31/2010
11316	Chandpur	41	1/1/1966	12/31/2010
11407	Jessore	61	1/1/1948	12/31/2010
11505	Faridpur	62	1/1/1948	12/31/2010
11513	Madaripur	32	1/1/1977	12/31/2010
11604	Khulna	59	1/1/1948	12/31/2010
11610	Satkhira	57	1/1/1948	12/31/2010
11704	Barisal	59	1/1/1949	12/31/2010
11706	Bhola	44	2/1/1966	12/31/2010
11805	Feni	36	1/1/1974	12/31/2010
11809	Maijdicourt	57	8/1/1951	12/31/2010
11814	Hatia	42	1/1/1966	12/31/2010
11912	Sitakundu	33	1/1/1967	12/31/2010
11916	Sandwip	41	1/1/196	6/30/2010
11921	Chittagong	61	1/1/1949	12/31/2010
11925	Kutubdia	28	1/1/1985	12/31/2010
11927	Cox's Bazar	62	1/1/1948	12/31/2010
11929	Teknaf	33	1/1/1977	10/31/2010
12007	Rangamati	51	4/1/1957	12/31/2010
12103	Patuakhali	34	8/1/1973	12/31/2010
12110	Khepupara	36	1/1/1974	12/31/2010
41858	Syedpur	19	1/1/1991	12/31/2010
41909	Tangail	23	1/1/1987	12/31/2010
41926	Chuadanga	21	1/1/1989	12/31/2010
41958	Mongla	9	1/1/1989	12/31/2010

ANNEXURE D

The PRECIS Model Predicted Climate

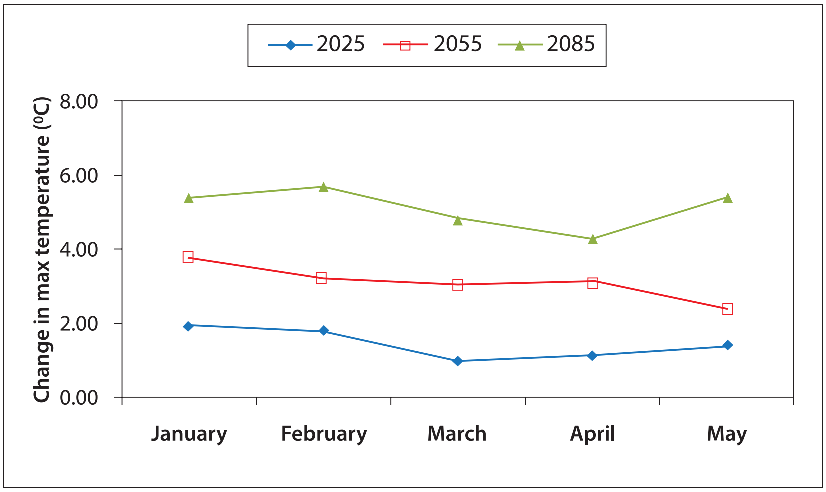


Figure D1: Climate model predicted change in monthly maximum temperature at Rajbari during the *boro* season

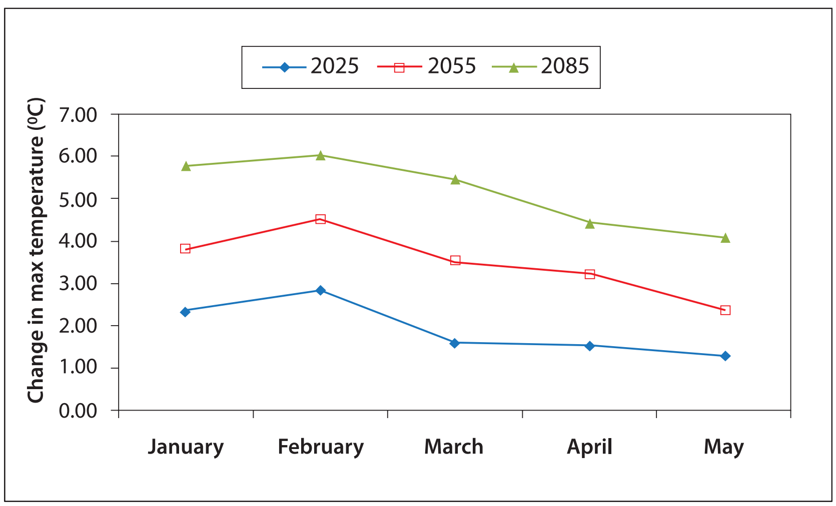


Figure D2: Climate model predicted change in monthly minimum temperature at Rajbari during the *boro* season

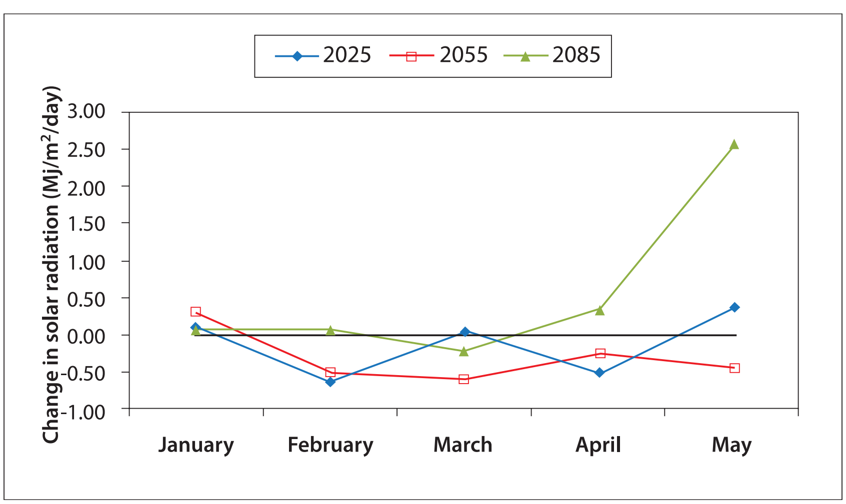


Figure D3: Climate model predicted change in monthly solar radiation at Rajbari during the *boro* season

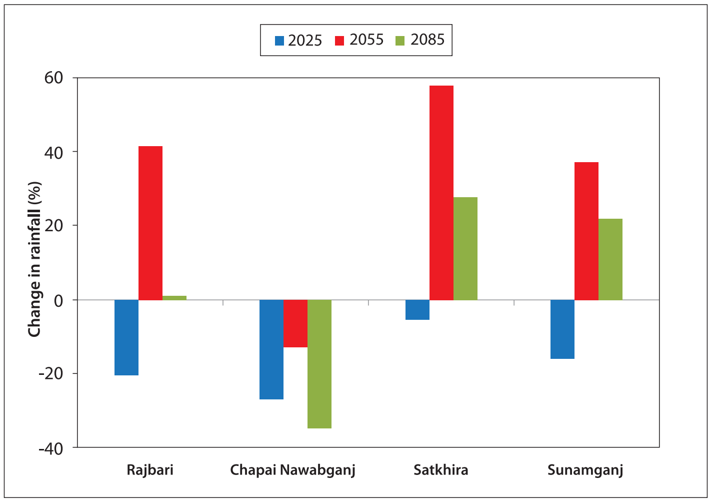


Figure D4: Climate model predicted change in total precipitation at different locations during the *boro* season

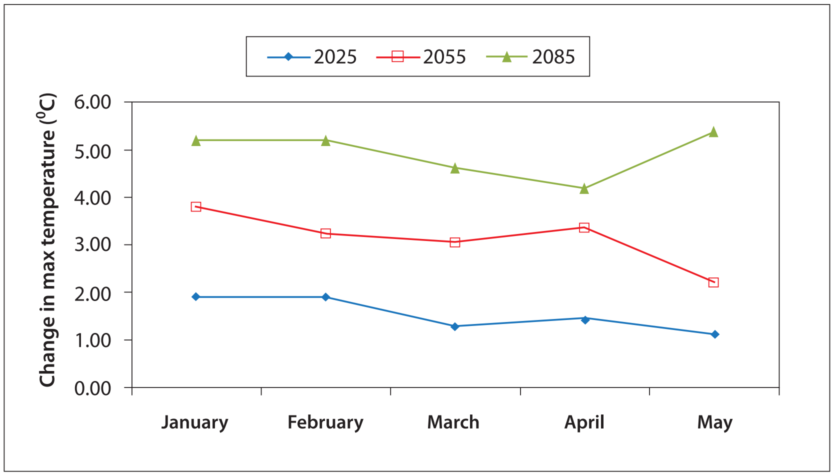


Figure D5: Climate model predicted change in monthly maximum temperature at Chapai Nawabganj during the *boro* season

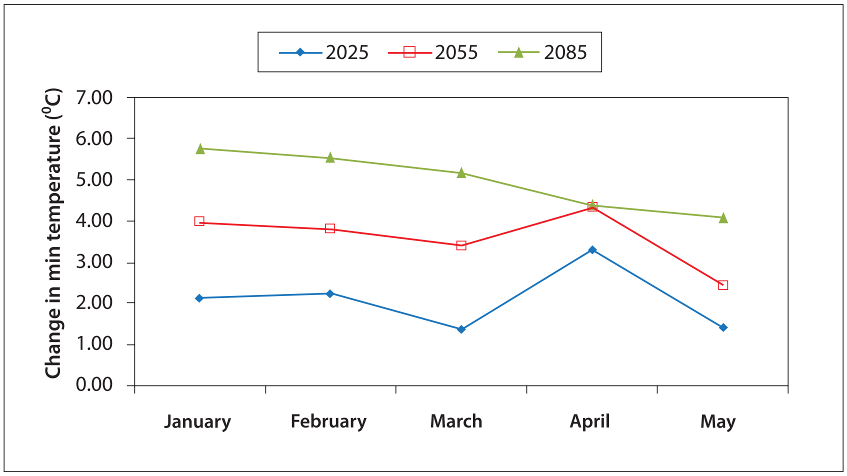


Figure D6: Climate model predicted change in monthly minimum temperature at Chapai Nawabganj during the boro season

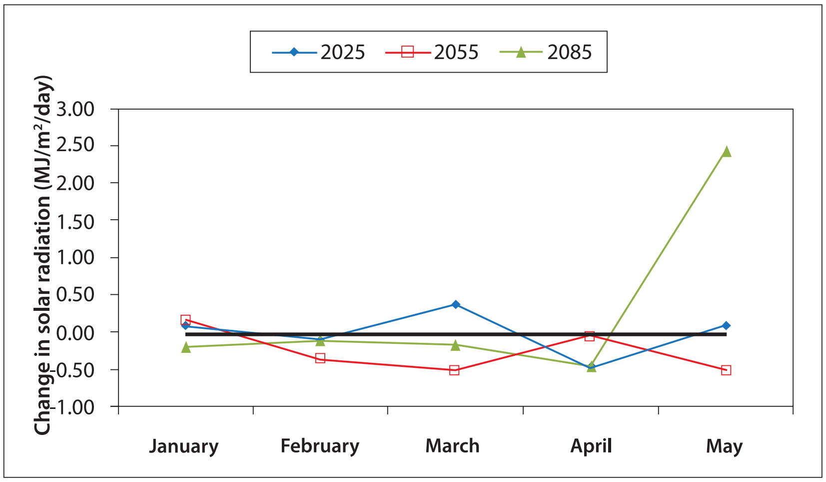


Figure D7: Climate model predicted change in monthly solar radiation at Chapai Nawabganj during the *boro* season

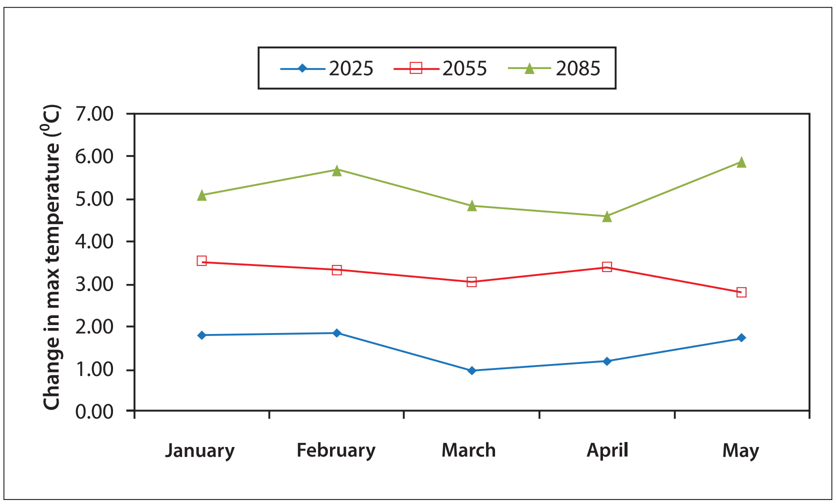


Figure D8: Climate model predicted change in monthly maximum temperature at Satkhira during the *boro* season

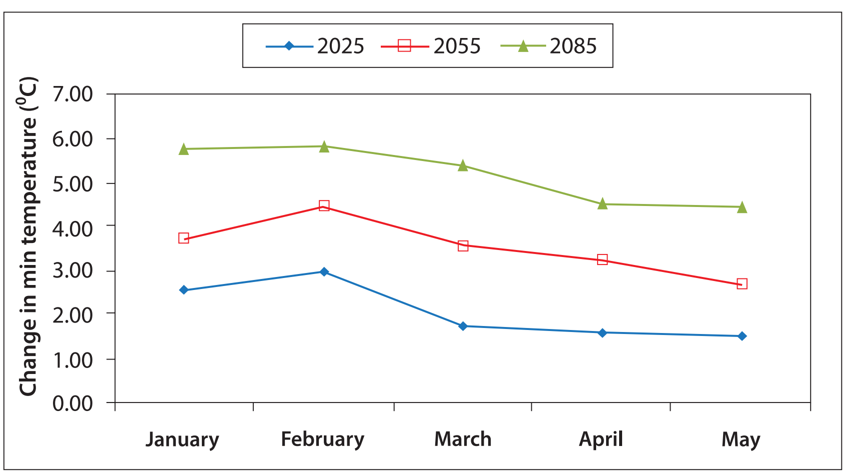


Figure D9: Climate model predicted change in monthly minimum temperature at Satkhira during the *boro* season

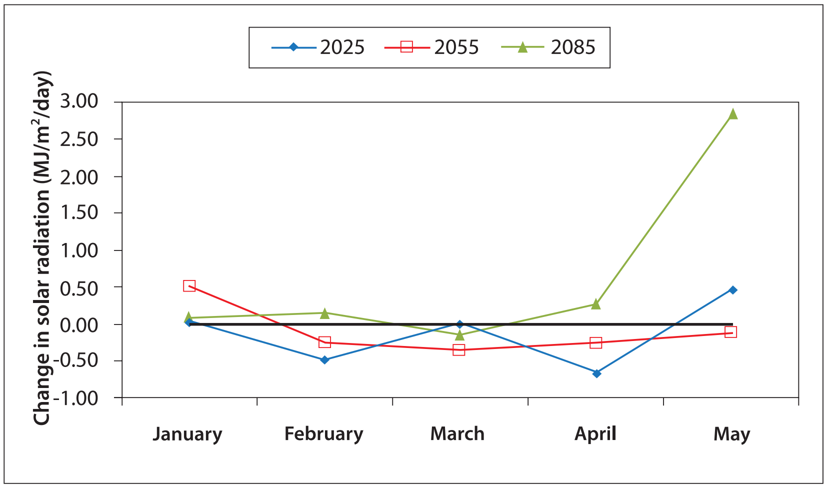


Figure D10: Climate model predicted change in monthly solar radiation at Satkhira during the *boro* season

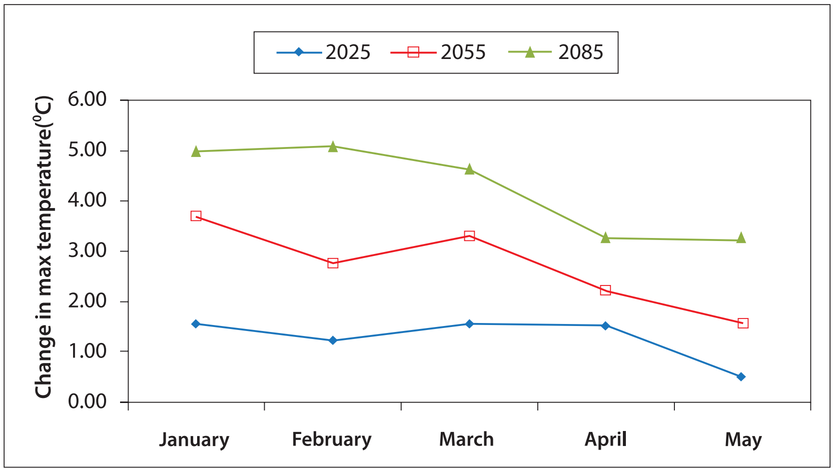


Figure D11: Climate model predicted change in monthly maximum temperature at Sunamganj during the *boro* season

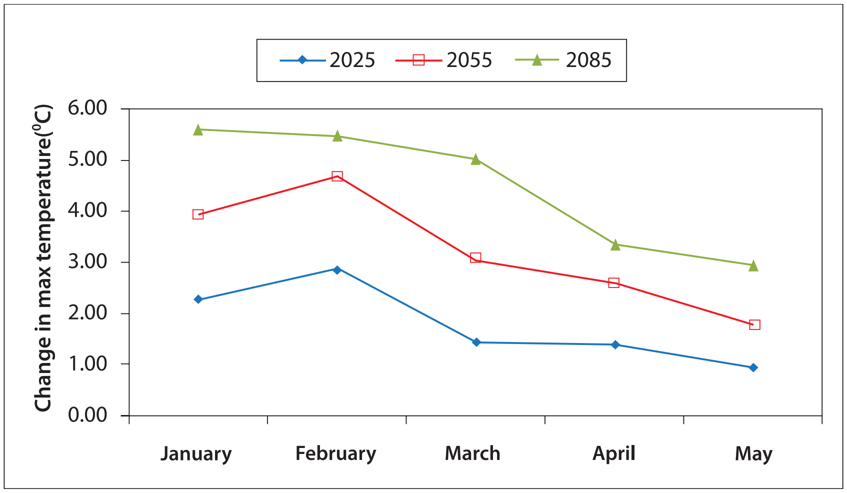


Figure D12: Climate model predicted change in monthly minimum temperature at Sunamganj during the *boro* season

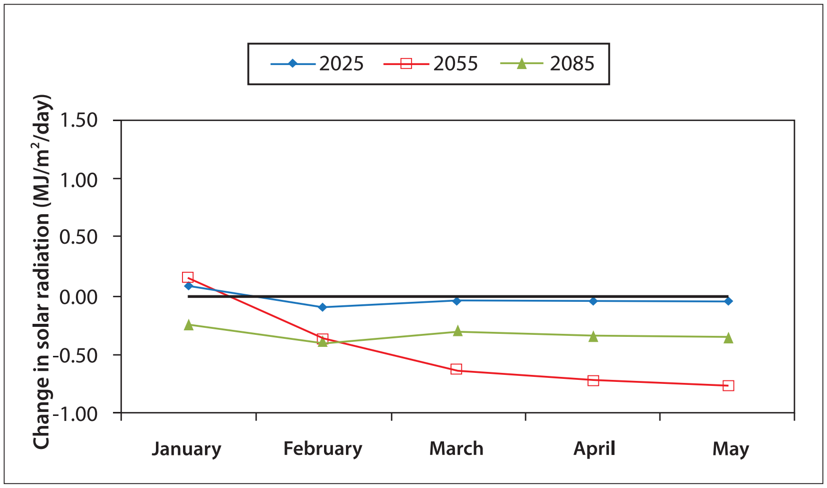


Figure D13: Climate model predicted change in monthly solar radiation at Sunamganj during the *boro* season

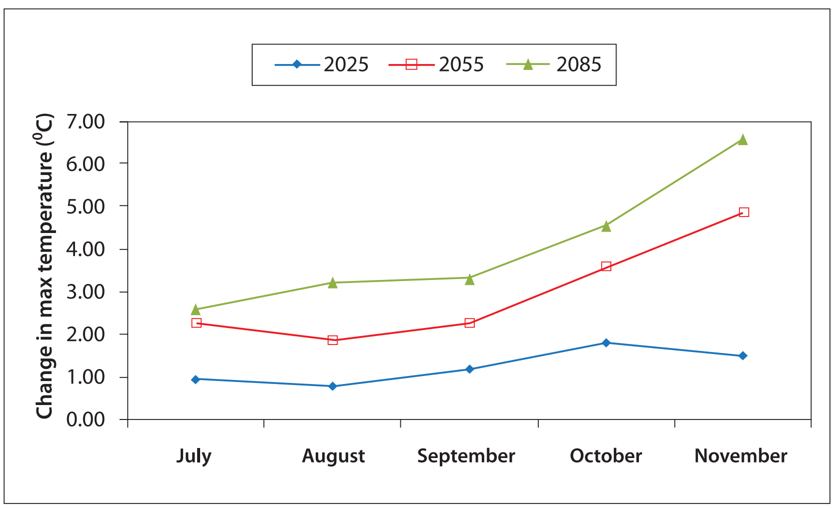


Figure D14: Climate model predicted change in monthly maximum temperature at Rajbari during the T. *aman* season

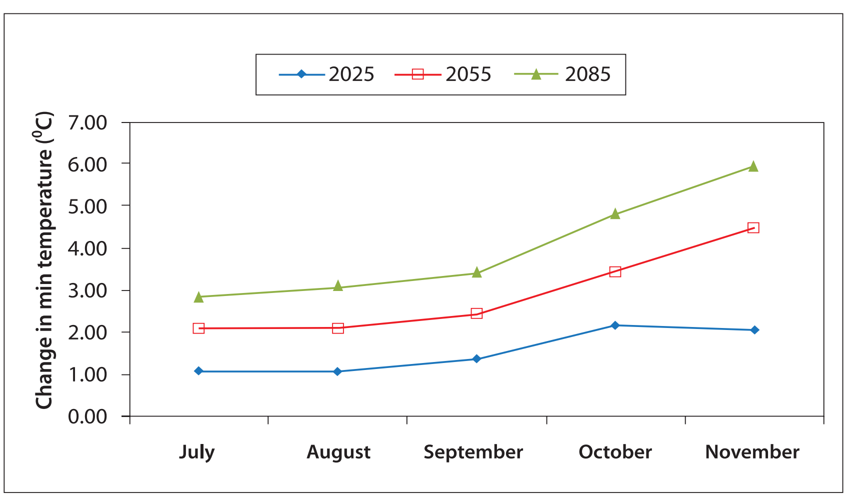


Figure D15: Climate model predicted change in monthly minimum temperature at Rajbari during the T. *aman* season

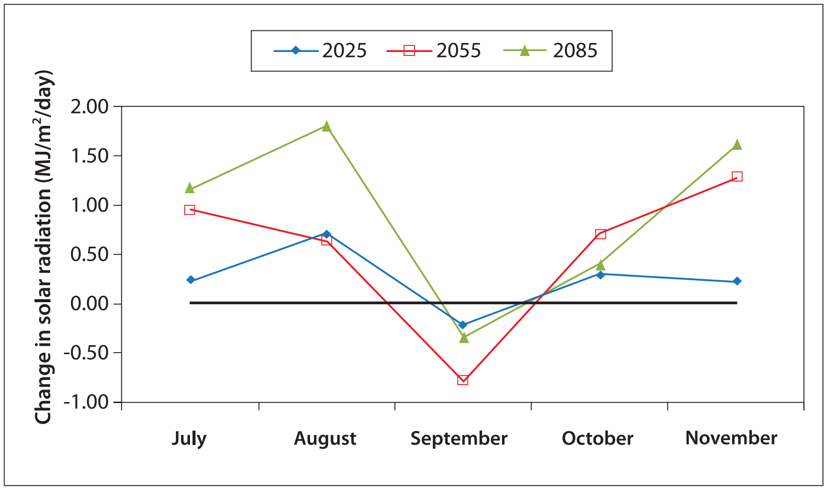


Figure D16: Climate model predicted change in monthly solar radiation at Rajbari during the T. *aman* season

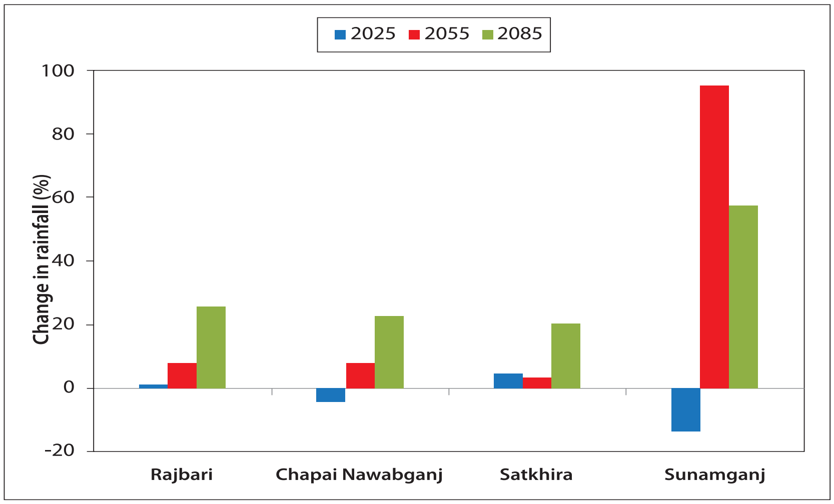


Figure D17: Climate model predicted change in total precipitation at different locations during the T. *aman* season

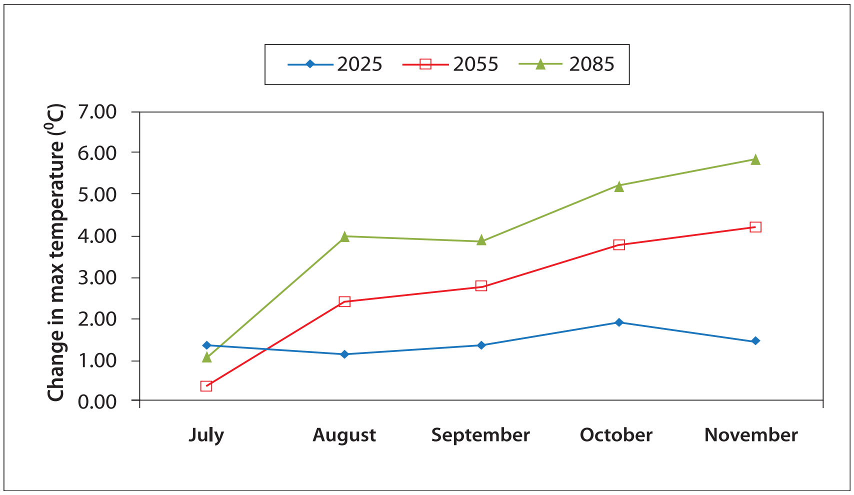


Figure D18: Climate model predicted change in monthly maximum temperature at Chapai Nawabganj duringthe T. *aman* season

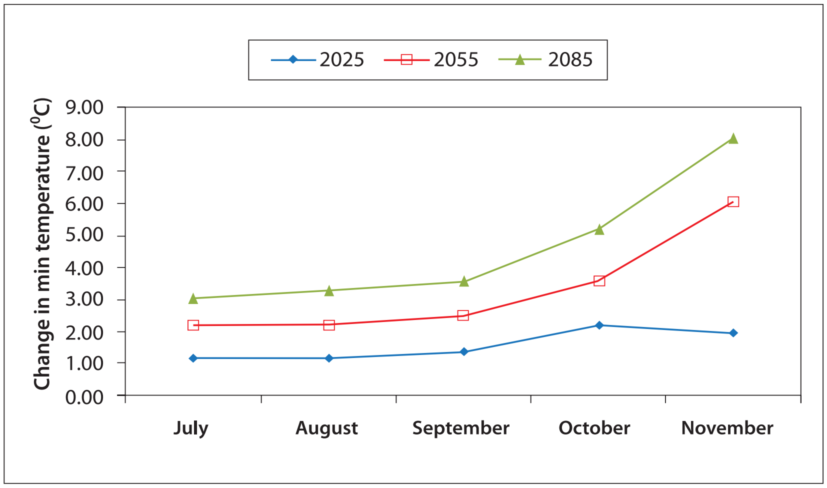


Figure D19: Climate model predicted change in monthly minimum temperature at Chapai Nawabganj during the T. *aman* season

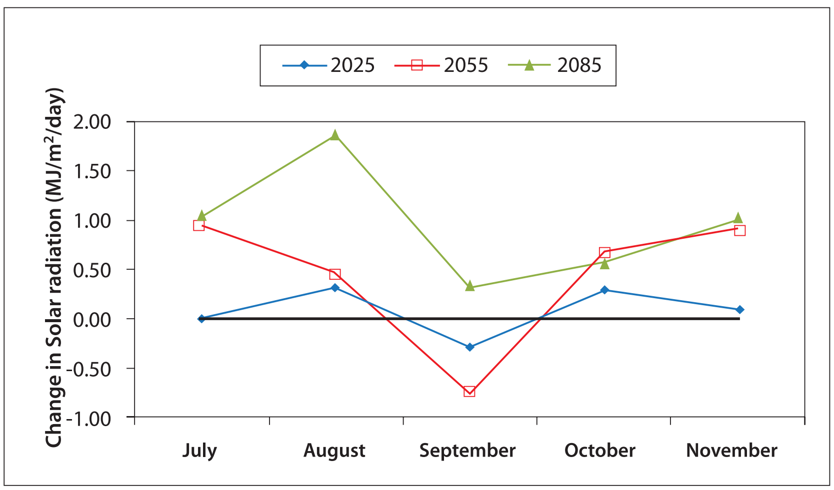


Figure D20: Climate model predicted change in monthly solar radiation at Chapai Nawabganj during the T. *aman* season

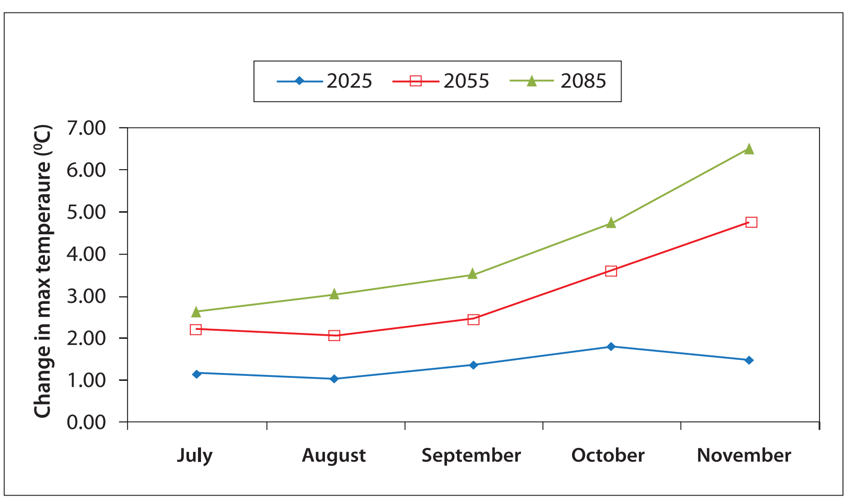


Figure D21: Climate model predicted change in monthly maximum temperature at Satkhira during the T. *aman* season

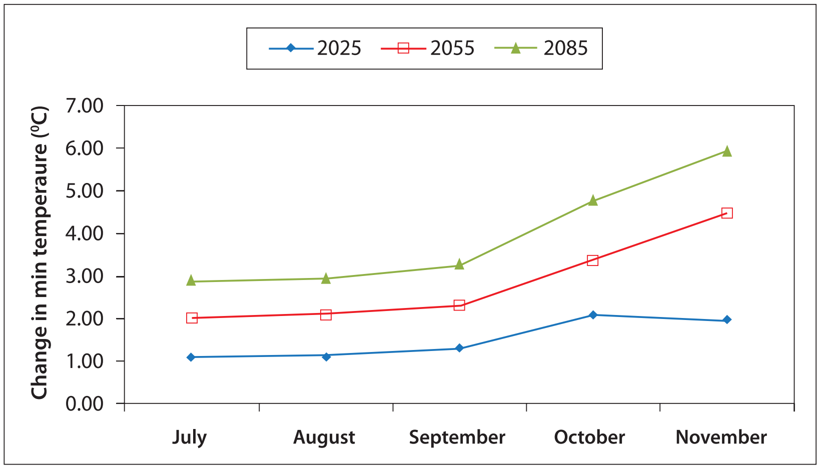


Figure D22: Climate model predicted change in monthly minimum temperature at Satkhira during the T. *aman* season

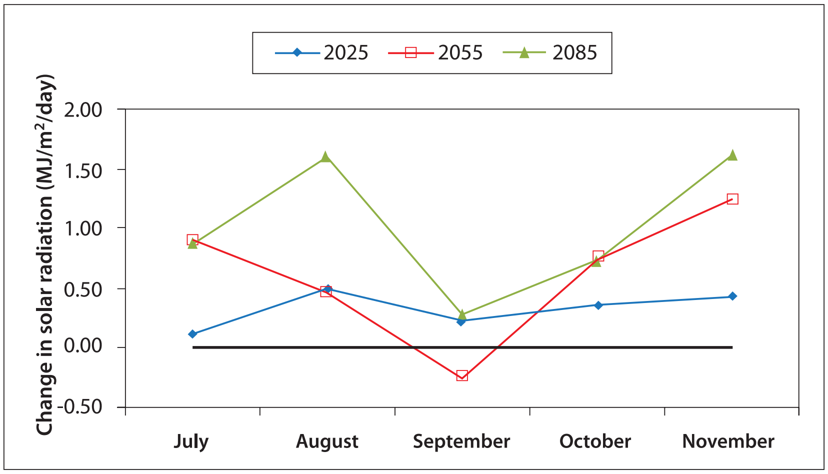


Figure D23: Climate model predicted change in monthly solar radiation at Satkhira during the T. *aman* season

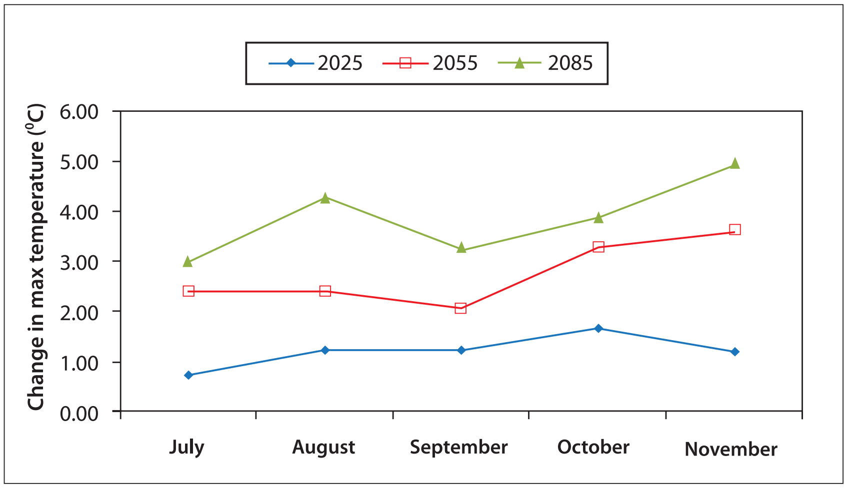


Figure D24: Climate model predicted change in monthly maximum temperature at Sunamganj during the T. *aman* season

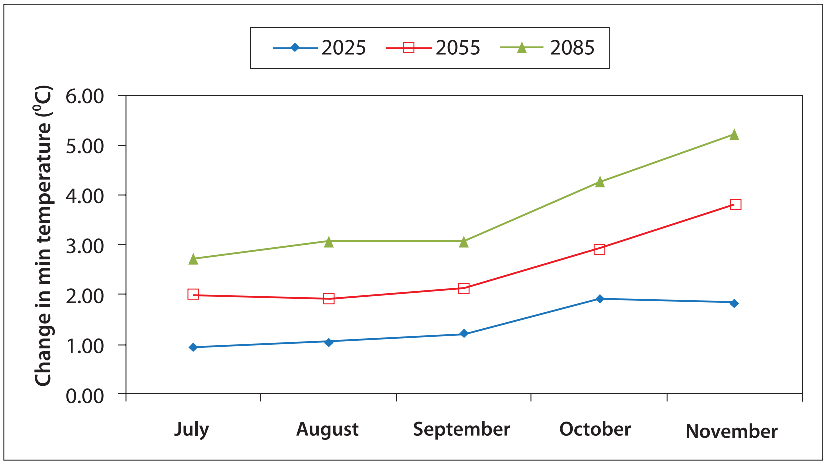


Figure D25: Climate model predicted change in monthly minimum temperature at Sunamganj during the T. *aman* season

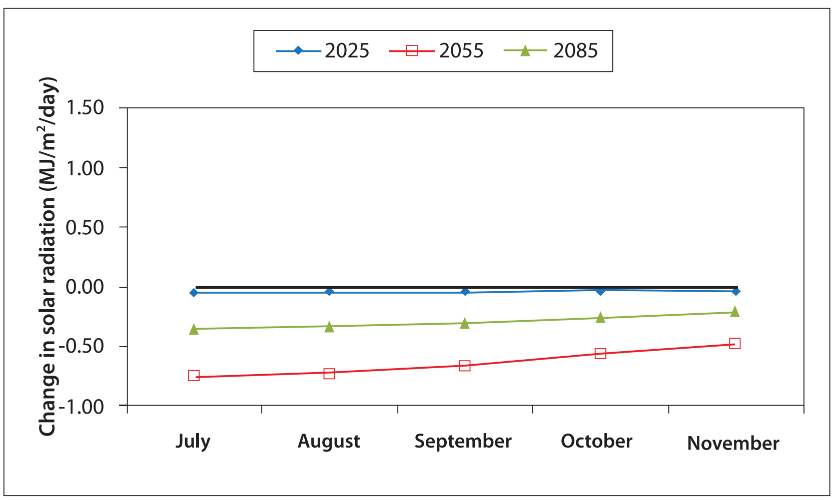


Figure D26: Climate model predicted change in monthly solar radiation at Sunamganj during the T. *aman* season

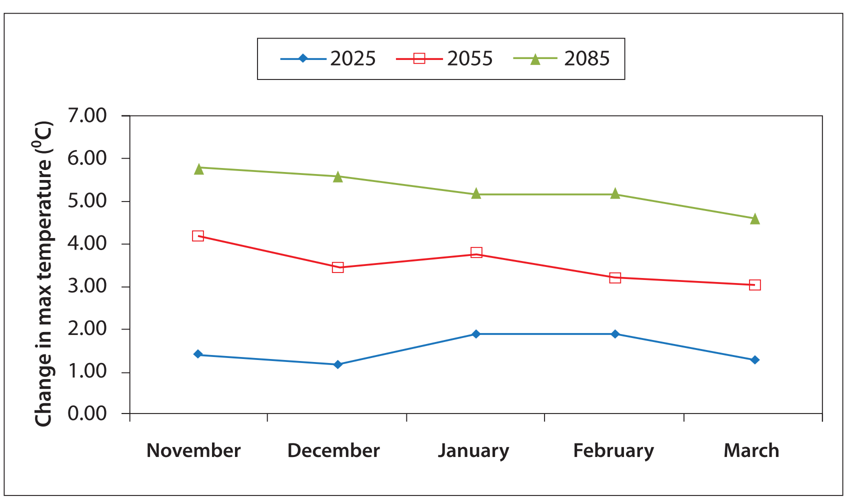


Figure D27: Climate model predicted change in monthly maximum temperature at Rajbari during the wheat season

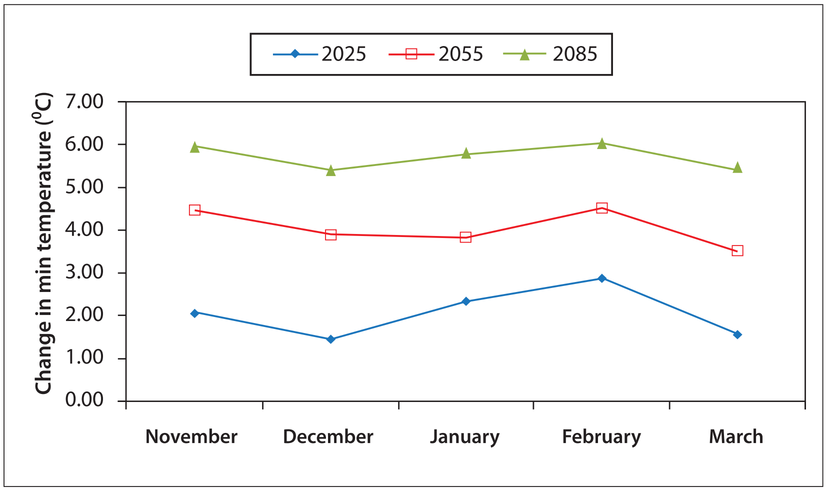


Figure D28: Climate model predicted change in monthly minimum temperature at Rajbari during the wheat season

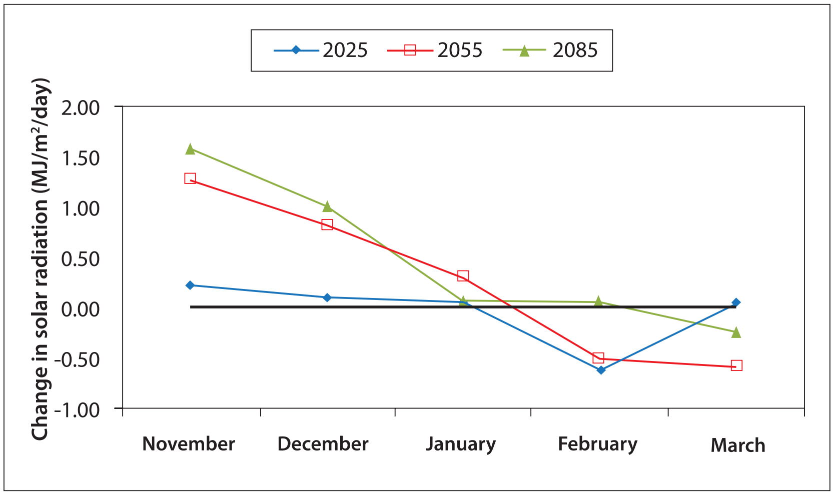


Figure D29: Climate model predicted change in monthly solar radiation at Rajbari during the wheat season

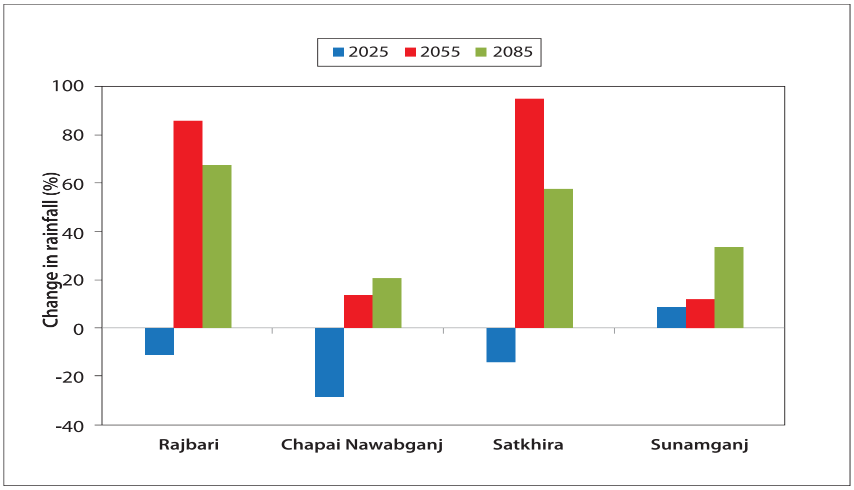


Figure D30: Climate model predicted change in total precipitation at different locations during the wheat season

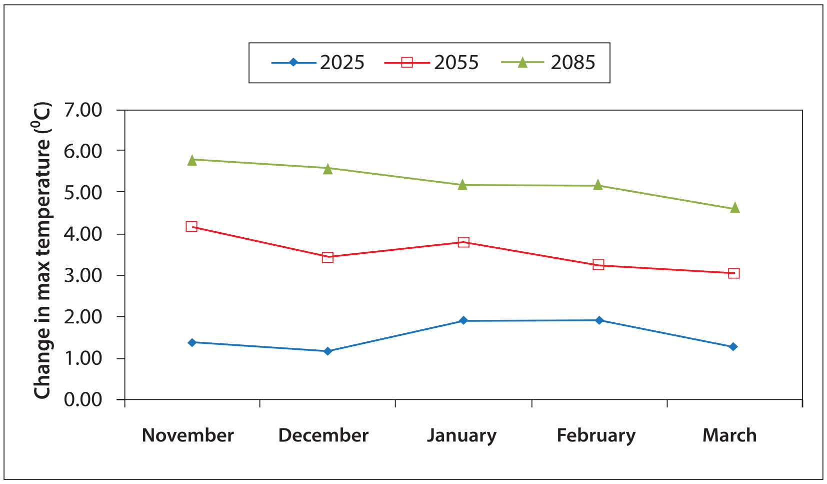


Figure D31: Climate model predicted change in monthly maximum temperature at Chapai Nawabganj during the wheat season

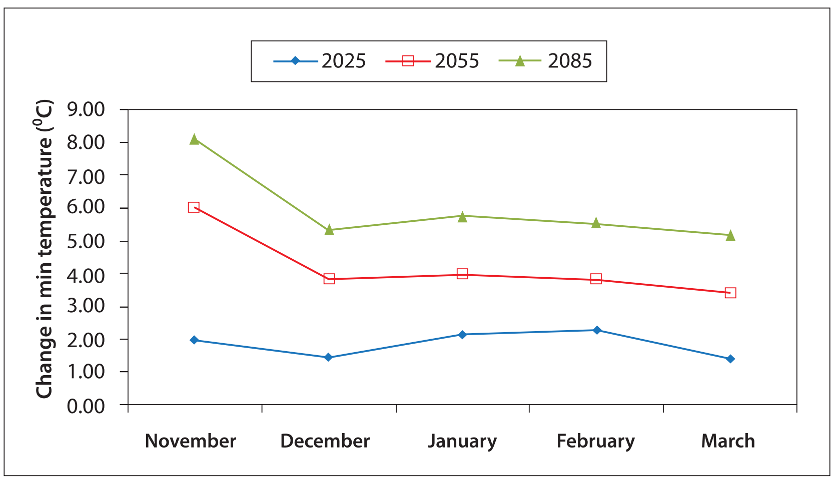


Figure D32: Climate model predicted change in monthly minimum temperature at Chapai Nawabganj during the wheat season

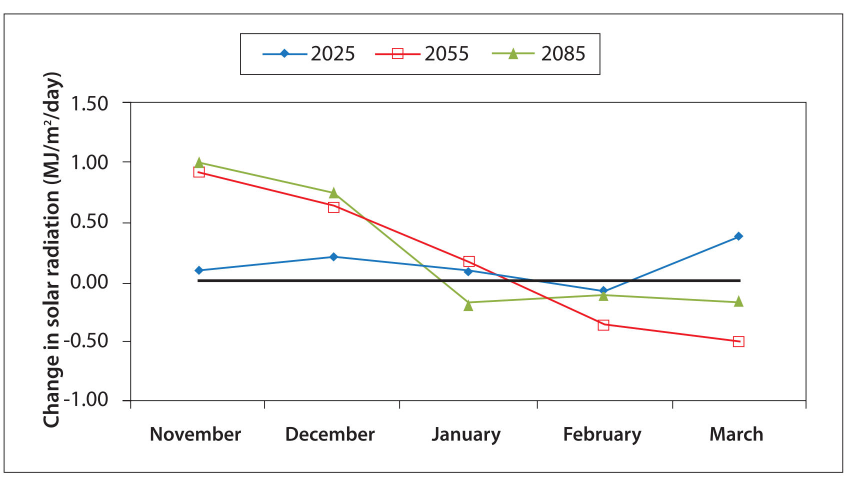


Figure 33: Climate model predicted change in monthly solar radiation at Chapai Nawabganj during the wheat season

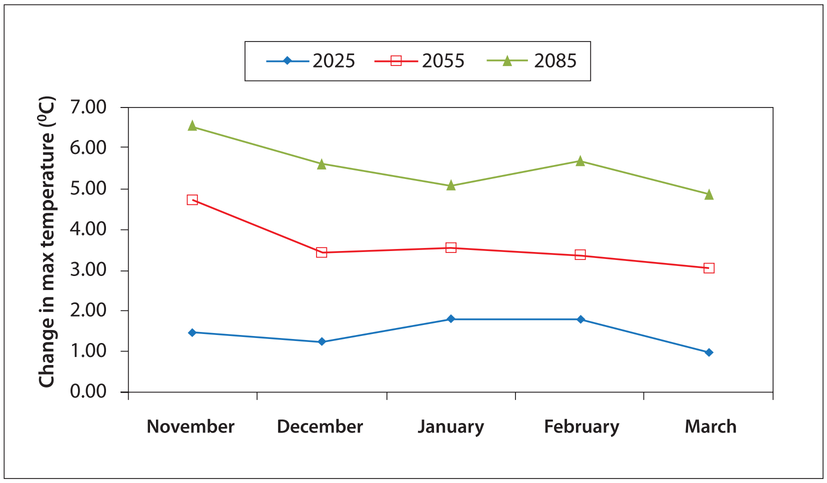


Figure D34: Climate model predicted change in monthly maximum temperature at Satkhira during the wheat season

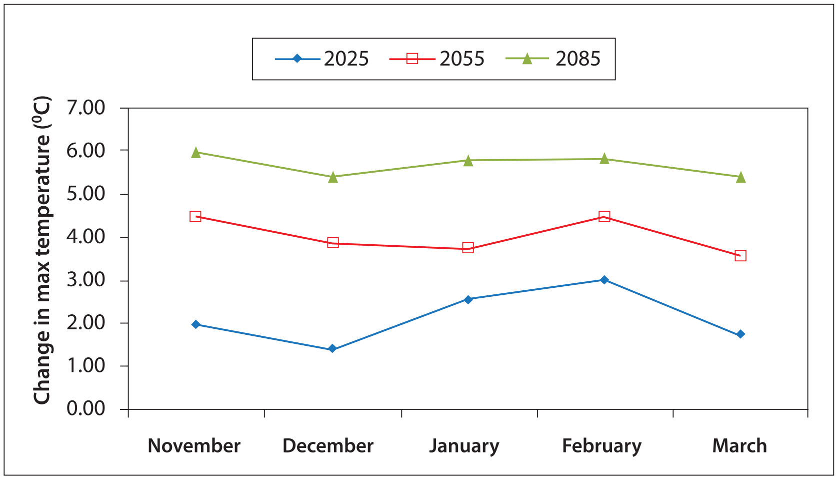


Figure D35: Climate model predicted change in monthly minimum temperature at Satkhira during the wheat season

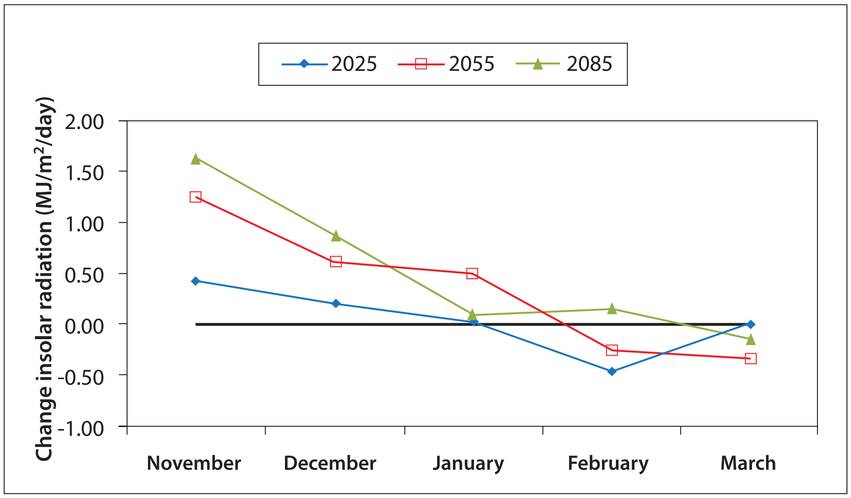


Figure D36: Climate model predicted change in monthly solar radiation at Satkhira during the wheat season

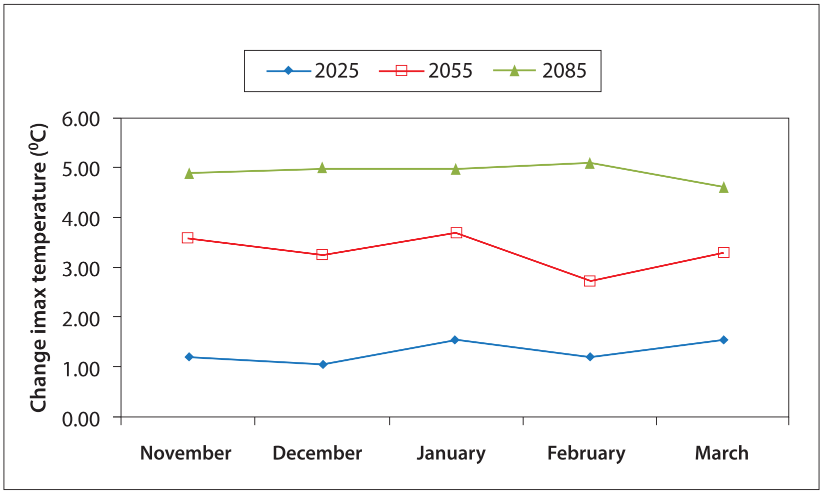


Figure D37: Climate model predicted change in monthly maximum temperature at Sunamganj during the wheat season

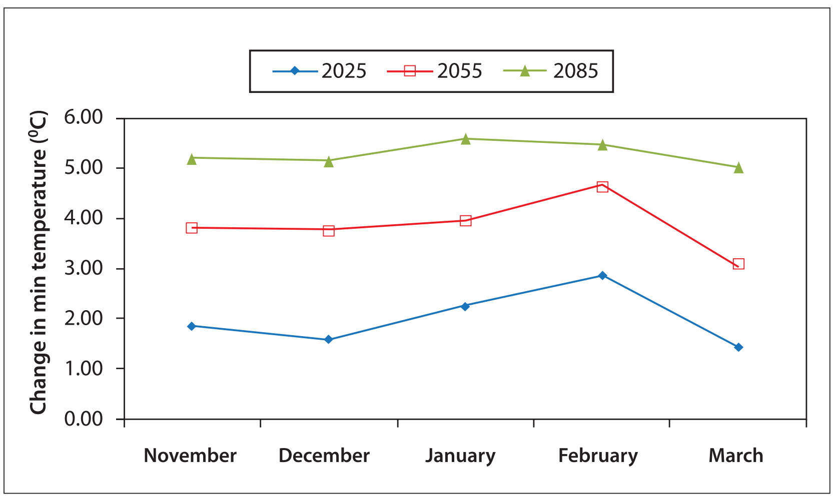


Figure D38: Climate model predicted change in monthly minimum temperature at Sunamganj during the wheat season

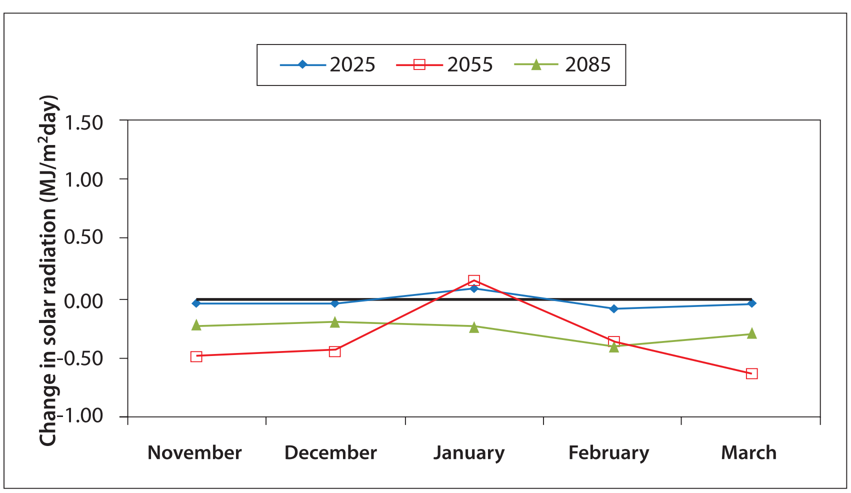


Figure D39: Climate model predicted change in monthly solar radiation at Sunamganj during the wheat season

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