Monsoon Rainfall Forecasting for Different Hydrological Regions of Bangladesh Using Climate Predictability Tool (CPT)

By

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MASTER OF SCIENCE IN WATER RESOURCES DEVELOPMENT

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A thesis submitted to the Institute of Water and Flood Management (IWFM) of Bangladesh University of Engineering and Technology, Dhaka in partial fulfillment of the requirements for the degree of **Master of Science in Water Resources Development**

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The thesis titled '**Monsoon Rainfall Forecasting for Different Hydrological Regions of Bangladesh Using Climate Predictability Tool (CPT)**'submitted by Satyajit Roy Das, Roll No. 1009282012 F, Session October 2009, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of M. Sc. in Water Resources Development on December 19, 2015.

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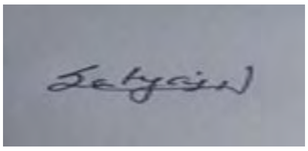
It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.



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Satyajit Roy Das

Dedicated
to
My Daughter
Smita Parthibi

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It is my pleasure to take the opportunity to thank those who made it possible for me to complete this thesis. First and foremost, I would like to show my deepest gratitude to Almighty God.

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ABSTRACT

This study aimed to use the Climate Predictability Tool (CPT) to analyse the monthly rainfall data over Bangladesh during 1981-2010. This technique based on a canonical correlation regressions to extract information from the large data sets.Long term changes of monsoon rainfall over Bangladesh have been studied using the available historical data collected by the Bangladesh Meteorological Department (BMD).Rainfall dataset were analyzed with Kriging interpolation method to calculate the aerial mean precipitation over Bangladesh. Correlation between observed and CPT- generated all-Bangladesh June-August (JJA) mean-rainfall during the period of 1981-2010 was found very strong (R^2=0.908). The JJA mean rainfall of observed datasets of 26 stations was 14.11 mm/d in 2011, whereas, CPT generated forecast was 13.82 mm/d. Mean monsoon (June-August) rainfall was calculated for the 8 hydrological regions of Bangladesh by taking average of the stations lies within them. In case of the northwest hydrological region, strong correlation (R^2=0.89) was found between observed and CPT-generated JJA mean rainfall during the period 1981-2010. Observed JJA mean rainfall (10.11 mm/d) in the northwest hydrological region in 2011 was higher compared to CPT-generated forecast (9.05 mm/d). The correlation between observed and CPT-generated JJA mean rainfall during the period 1981-2010 in the north central hydrological region was also found strong (R^2=0.84). Observed JJA mean rainfall (12.89 mm/d) in the north central hydrological region in 2011 was lower compared to CPT-generated forecast (13.84 mm/d). The correlation between observed and CPT-generated JJA mean rainfall during the period 1982-2009 in the northeast hydrological region was found moderately strong. Observed JJA mean rainfall (18.66 mm/d) in the northeast hydrological region in 2011 was lower compared to CPT-generated forecast (19.49 mm/d). The correlation between observed and CPT-generated JJA mean rainfall during the period 1981-2010 in the southwest hydrological region was found strong (R^2=0.8).In addition, the correlation between observed and CPT-generated JJA mean rainfall during the period of 1981-2010 in the eastern hilly hydrological region was also found strong (R^2=0.821). The monsoon rainfall during JJA season in the north central, and the eastern hilly hydrological region was in increasing trend whereas, in the northwest, the south central, and the southeast hydrological regions were in decreasing trend. Hence, it can be concluded that CPT is an affordable tool for monsoon rainfall forecasting over Bangladesh.

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Abbreviations and Acronyms

CPT Climate Predictability Tool

GCM General Circulation Models

LRF Long Range Forecast

MOS Model Output Statistics

NW North West Hydrological Region

NC North Central Hydrological Region

NE North East Hydrological Region

SW South West Hydrological Region

SC South Central Hydrological Region

SST Sea Surface Temperature

SW South West Hydrological Region

EH Eastern Hill Hydrological Region

RE River & Estuary Hydrological Region

CHAPTER I
INTRODUCTION

1.1 Background and Present State of the Problem

Hydrological cycle is one of the important subsystems which describe the continuous movement of water above, on, and below the Earth's surface. The cycle operates across all scales, from the global to the river catchment and connects the movement of water along rainfall, surface runoff, subsurface flow and groundwater. Rainfall is the most important atmospheric variable in water resource management and agriculture and associated with monsoons [1][2].

Monsoon rainfall, unlike any other hydrological parameters, is highly discontinuous both spatially and temporally. The variations of monsoon rainfall intensity with duration can be large from one rainfall event to another as well as from region to region. The monsoon is well organized spatially over seasons on a large scale domains but this is not accurate for smaller scale domains [1]. There are indications of changes in rainfall taking place both on the global and regional scales [3][4]. Changes in the patterns of monsoon rainfall and its impact on vegetation and animal life including humans, is an important climatic problem which need to be address on priority [5] [6].

Bangladesh, as a flood plain country located in the confluence of three major rivers namely the Padma, the Meghna and theJamuna, floods often recurring during the monsoon season [7][8][9]. Its climate is influenced primarily by monsoon [10]. Bangladesh is recognized worldwide as one of the most vulnerable countries to climate change due to extreme events and impact on hydrological cycle [11] [12] [9][13][14].

IPCC indicates that there would be drastic changes in monsoon rainfall patterns in the warmer climate. Bangladesh may experience 5-6% increase of rainfall by 2030, which may create frequent big and prolonged floods [15][16][17]. Regional projections revealed that climate changes would strengthen monsoon circulation, increase surface temperature, and increase the magnitude and frequency of extreme rainfall events [18][19][20]. Due to excess, untimely or deficit monsoon rainfall conditions, often crop failure occurred in Bangladesh [21][22][23]. Various studies have been carried out to assess the future monsoon rainfall of Bangladesh [4][6][11][12][19][24] [25] [26][27] [28][29].

An increasing frequency and magnitude of climate variability across the entire globe has focused the need for research onto the predictability of rainfall in Bangladesh [10][13][19][29].A challenging task for catchment management in particular is the provision of a quantitative rainfall forecast. Accurate forecasts of the spatial and temporal distribution of rainfall are useful for water quantity management [17].A reliable forecast of summer monsoon rainfall on seasonal time scales is also important for planning and implementing agricultural strategies [30].

Monsoon rainfall forecasting for different hydrological regions of Bangladesh using climate model is always a challenging task. According to [13], forecasting of non-linear variations has become extremely difficult in Bangladesh by any means of technique due to Chaotic nature of climate system.But demand for seasonal weather forecasts is getting higher as policymakers, planners and stakeholders of the vulnerable sectors such as agriculture, food security, water resources, etc. are keen enough to plan their activities a season ahead to minimize the losses due to weather hazards [18][31][32].Therefore, a reliable and user friendly seasonal weather forecasting technique is utmost urgency for taking proactive adaptation measures for sustainable management of agriculture by considering different hydrological regions of Bangladesh.

In the present day context, statistical techniques based on regression analyses are the best tools available for seasonal weather prediction though it applies linear relationship to predict the future state of atmospheric parameters [17]. Climate Predictability Tool (CPT), developed by International Research Institute of University of Columbia is a powerful tool for making efforts to forecast seasonal climate in the tropical and sub-tropical areas in the world. No systematic study has been done to forecast monsoon rainfall of all hydrological region of Bangladesh using CPT. So there is necessity for the forecast monsoon rainfall of all hydrological region of Bangladesh using CPT to plan a season ahead.

1.2 Objectives of the study

The main objectives of the project are as follows:

i. To forecast seasonal weather for different hydrological Regions in Bangladesh using CPT.

ii. To understand the regional differences in the context of forecasting seasonal rainfall pattern.

This study is expected to identify the seasonal forecast of rainfall pattern and to compare the regional differences. Moreover, regarding water management, this study will help to make a decision for development plan in the sector of agriculture.

1.3 Possible Outcomes of the study

Too much or too little monsoon rainfall has an influence the agricultural production by reducing yield. Additionally, the economic value associated with irrigating with the proper amount of water at the right time is considerable. If a farmer optimizes the use of irrigation scheduling a season ahead according to early forecast of monsoon rainfall, the amount of money that can be saved in water purchase and or well operation is significant. As climate differs with its regional settings, the monsoon rainfall will also differ for Bangladesh. For the upcoming environmental stresses on water, the early forecast of monsoon rainfall is very important to manipulate the water requirement regionally to manage the national water demands effectively.

This study is expected to forecast the monsoon rainfall and to compare the regional differences. Moreover, regarding farmers of Bangladesh, this study will help to make a decision for developing plan their activities a season ahead to minimize the losses due to weather hazards.

1.4 Limitations of the study

The main limitations of the study are

- The rainfall measurement system in Bangladesh is not adequate. Several traditional and a few auto recording rain gauges are available. The rainfall in nature has high variability in time and space for different topography, weather and climate condition.

- The representative stations were selected from different hydrological regions. The result of study would be more precise if all stations Bangladesh Water Development Board (BWDB) were taken in each region.
- The desired time series data were not found to predict long term changes of the climatic variables in each station.
- As the forecast of monsoon rainfall have been done based on model results, there is much uncertainty in the forecasted results. Further study can be done to cross-check the results.

1.5 Organization of the Chapters

The thesis contains six chapters. The organization of the chapters is as follows:

Chapter one provides the background of the study and present state of the problems. It also draws attention to the objectives of the study with limitations and organization of the chapters. Chapter two will examine the concept of monsoon rainfall and its factors in more detail and provide more details into the concept of different monsoon rainfall forecast tool. It also contains the general feature of CPT. The chapter also reviews the literature of monsoon rainfall and the effect of change in variables on monsoon rainfall. Chapter three presents the characteristics of the selected hydrologic regions. Chapter four discusses the methodology in detail used to forecast monsoon rainfall. Chapter five describes the results of forecast monsoon rainfall with regional differences using CPT. The findings from existing data and predicted data series are also analyzed. Finally, chapter six concludes the results of the study and provides recommendations for further study.

CHAPTER II
LITERATURE REVIEW

2.1 Introduction

This chapter provides a brief literature review of monsoon rainfall and its early forecast. The focus is on monsoon variability and predictability on time scales of great societal value, such as intraseasonal, interannual, decadal and longer including climate change.

The literature review has been aimed to the following aspects;

a) Studying the existing literatures in this field

b) Assessing the strength and weakness in literature and being able to find the gaps in knowledge.

c) Discussing the limitations of the existing methodologies, scopes, theories and constructing theoretical and analytical framework of the study,

2.2 Monsoon

Monsoon is traditionally defined as a seasonal reversing wind accompanied by corresponding changes in precipitation, but it is now used to describe seasonal changes in atmospheric circulation and precipitation associated with the asymmetric heating of land and sea [26],[33]. Usually, the term monsoon is used to refer to the rainy phase of a seasonally-changing pattern, although technically there is also a dry phase [7][15][34].

2.3 South East Asian Monsoon Climatology

The monsoon climate of South Asia including Bangladesh is due to the unique geographical layout of the region [27][30][35]. The Himalayas lie to the north while the warm Indian Ocean and Bay of Bengal lie to the south. These two features drive the atmosphere to produce the conditions that form the monsoon. In Bangladesh the onset of the summer monsoon starts in the south-eastern tip of the country at the beginning of June, progresses toward the northwest and reaches the north-western part by the middle of June. The withdrawal occurs in the opposite direction, starting in the northwestern part at the end of September and retreating from the entire country by mid-October [24], on average more than 70 % of Bangladesh's annual rainfall is concentrated in the 4 months from June to September.

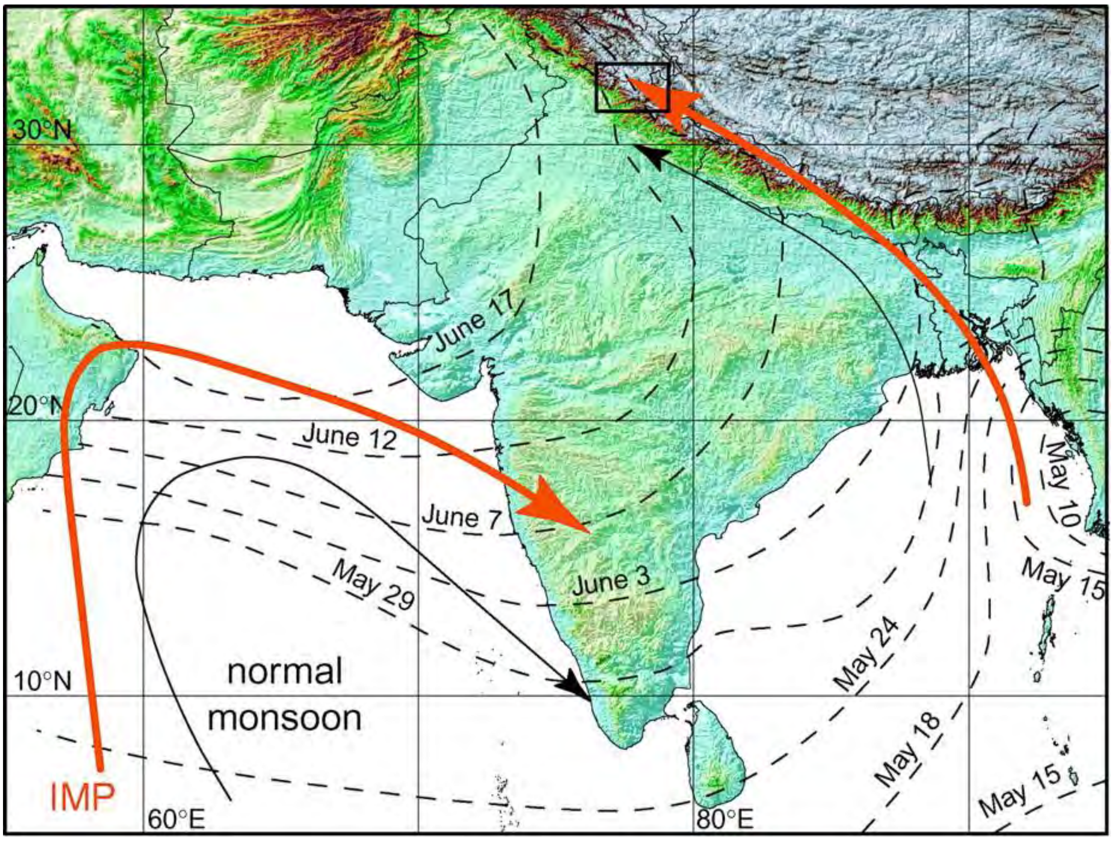

Fig 2.1: Pathway of Monsoon flow over Bangladesh.

The mean rainfall during the monsoon season from June to September ranges roughly from 1000 to 3000 mm in the country, with maximum near the north-eastern part and along the coast line in the southern part and with a minimum of west central part [1][22][32]. The rainfall over Bangladesh is basically dominated by the north-south oscillation of the monsoon trough. The rainfall increases when the monsoon trough is located at the foot of the Himalayas, because synoptic-scale convective activity is much more vigorous to the south of the monsoon trough axis than to the north of it [31][36].

2.4 Sources of Rainfall over Bangladesh

There are three main sources of rainfall in Bangladesh:

a. Western Depressions of Winter

The westerly depressions (anticyclones) form in the region of the Elburz Mountains, or even further west, in the Mediterranean region. They generally intensify as they move eastward and precipitate considerable amounts of snow on the western Himalayas. Continuing eastward they bring rain to the lower slopes of the eastern Himalayas, and as they are 'trapped' in the sea of the Assam Hills, to all parts of Bangladesh also.

b. Nor'westers

The Nor'westers are due to a varity of reasons, of which the main ones are the steady flow of cool dry air above 1800 metres altitudes from the north-west (anti-trades), and a warm moist current below 1800 meters from the south, intense evaporatranspiration in the Bengal Basin and Assam, and the katabatic winds from surrounding mountains [3][30[37]. The Nor'westers is usually of a short duration, but is intense, with a wind speed of 100 km/hr, and heavy rainfall.

c. Monsoon

The main rainy period begins with the coming of the moisture-laden south-west-trades popularly known as the monsoons, which are drawn to the Indian Sub-continent by the intense heat, and consequent low pressure over the Punjab and upper Ganges valley, which gives rise to a "tropical cell" with convection currents of massive proportions [5][34]. These winds blow across the North Indian Ocean and reach the Malabar Coast of Indian two weeks before they come up the Bay of Bengal to Bangladesh[18][28].

In this region the monsoon period is divided into three [25]: a) pre-monsoon (March-May), b) monsoon (June-September), and c) post-monsoon (October-November).

June to August is well known as peak-monsoon months. Bangladesh is one of the parts of tropical monsoon areas. Clouds and precipitation, particularly in the world's tropical regions, play an important role in driving the atmospheric circulation [4][12][14]. Therefore, accurate knowledge of the precipitation types and the period of maximum precipitation is the important issues to discuss.

Bangladesh Meteorological Department (BMD) has been issuing monthly weather forecasts every month, for the benefit of sector specific stakeholders and general public. There is a national committee for Long Range Weather Forecasting comprising of BMD, Space Research and Remote Sensing Organization (SPARRSO), Bangladesh Water Development Board (BWDB) and Department of Agriculture Extension (DAE). Forecast products from ECMWF, NCMRWF and JMA are collected and analyzed for making forecasts for the coming month [4].

2.5 Long range forecast of Monsoon

Seasonal weather forecasting is conventionally done using statistical methods, in which several parameters are used with multiple or even multivariate regression techniques. With the new development of computing resources, seasonal weather forecasting is now tested using numerical methods for which meso-scale or limited area models are run for several months with the initial and boundary data from Global Circulation Models. Long range forecasting (LRF) of summer monsoon rainfall is a high priority in Bangladesh as there is no dynamic or statistical model to give the LRF for Bangladesh [28]. An accurate forecast of seasonal summer monsoon rainfall over the country is an increasing demand for decision makers and planners of the country in mitigating any kind of disaster like food crisis and water scarcity. Seasonal forecasting systems are usually categorized into two types, namely dynamical and hybrid (i.e., combination of dynamical and statistical forecasting). Dynamical techniques are based on forecasts made by combined atmosphere–ocean General Circulation Models (GCMs). A reliable seasonal weather forecasting technique is presented for taking proactive adaptation measures for sustainable management of agriculture, water resources and other vulnerable sectors in Bangladesh [15]. Climate Predictability Tool (CPT), developed by International Research Institute of University of Columbia is made use of making seasonal weather forecasts for Bangladesh. CPT is a powerful tool for making efforts to forecast seasonal climate in the tropical and sub-tropical areas in the world. This has been tested in many African countries for making seasonal weather outlook for their countries [4]. It is hoped that this method could be utilized in Bangladesh for early monsoon forecast

2.6 Monsoon Forecasting Tool

There had been many studies on prediction of Indian region monsoon rainfall by many researchers in the past. Gowariker *et al.* (1989) developed a sixteen parameter power regression model and it had been operational for forecasting of monsoon rainfall over India till 2002 [1]. As the model was not able to predict the all-India drought in 2002, Rajeevan *et al.* (2004) introduced a new ten parameter model for forecasting monsoon rainfall over India [17]. Further improved version of eight parameter model was introduced by Rajeevan *et al.* (2006) and it is being operational since then [6]. Monsoon rainfall forecasts are issued in two stages in April (with six parameters) and updated in June with all eight parameters. Seasonal Forecast Model (SFM) of Experimental Climate Prediction Centre (ECPC) of United States was adopted by the IMD for issuing experimental ensemble forecasts for the Indian region for 2005 and 2006 (IMD website www.imd.gov.in). It is a General Circulation Model (GCM) with model resolution T63 L28. Since GCM has the capacity to simulate large scale features over the region, statistical downscaling technique is being used to forecast rainfall over the desired regions. National Centre for Medium Range Weather Forecast (NCMRWF) of India has also been using GCM with statistical downscaling technique to issue seasonal weather outlook for Indian states for the benefit of farmers on experimental basis [17]. Statistical techniques based on regression analyses are the best tools available for seasonal weather prediction though it applies linear relationship to predict the future state of atmospheric parameters. Dynamical models are still far behind, as far as the prediction skill concerns, due to poor resolving lower boundary forcing of the model.

2.7 Climate Predictability Tool (CPT)

The CPT has shown some potential to predict June-July- August seasonal mean-rainfall and month of June mean-rainfall over Bangladesh as a whole and over different hydrological region of Bangladesh [4],[15]. It uses Canonical Correlation Analysis, in which predictors and predictands are involved in making forecasts using Model Output Statistics technique. Statistical techniques for long range forecasting make use of the past data especially relationship between the rainfall and other weather/climate related parameters. Sea Surface Temperature (SST) is a key indication because of its relatively gradual rate of change and the highly effective ocean atmosphere coupling. Multiple techniques usually apply an assortment of mathematical and dynamical techniques, for example, by using mathematical techniques to forecast SSTs which are then used as reviews to a dynamical atmosphere-only GCM to generate long range rainfall forecasts. The model is trained with 30 years of rainfall data retrieved from Meteorological observatories in Bangladesh and sea surface temperature data of Coupled General Circulation Model.

The CCA tool in CPT is in this category of regression, with the x's and the y's themselves being defined in a special way in order to need much fewer of each. The categorization identifies the PCR technique as a kind of multiple regression that uses a set of predictors to predict one predictand element at a time, and the CCA technique as a kind of multivariate regression, using a set of predictors collectively to predict a set of predictands collectively, such that both predictors and the predictands possess patterns amongst themselves as well as in their linkages with one another. In both techniques, the prediction rules are determined by analyzing the set of predictors and predictands over a historical period [28]. In climate diagnostics and prediction, often each case of corresponding predictors and predictand(s) come from one year for a specific season, so that there are as many cases as there are years. Short histories are less effective in identifying the best prediction rules, since every year contains extraneous or random variations; thus the more years that are available, the greater the likelihood that the consistent and robust relationships outweigh the random behaviors and appear clearly in the analysis results. To simplify the production of seasonal climate forecasts it can be used in any region, and for diagnostic research as well as forecasting. It can be used to perform CCA or PCR on any pair of data sets, for any application. SMRC has also been using Seoul National University (SNU) coupled GCM and APEC Climate Centre (APCC) Multi Model Ensemble (MME) products with statistical downscaling technique built in CPT for making seasonal weather forecasts (JJA and DJF) for Sri Lanka [28].

2.8 Key Local to Regional Processes Influencing Monsoon Variability and Predictability

A number of local- to regional-scale processes strongly influence the accuracy and utility of forecasting monsoon. These processes are all highly regional, involving complex interactions across a range of spatial and temporal scales, but are often fundamental to the specific development of each monsoon. Improvement in the understanding and prediction of such processes is crucial for progress in forecasting monsoon variability and change.

a. Surface Heterogeneity

Land surface processes and land use change play an important role in regional monsoon variability. When the soil is not too wet or not too dry, the soil conditions can control the amount of water being evaporated, and also can produce fundamental changes in the planetary boundary layer (PBL) structure that affects the development of convection and precipitation. A number of "hot spots" of land–atmosphere coupling identified, where sub-seasonal precipitation variability is modulated by regional soil water characteristics [33]. Regions and seasons that have large soil moisture memory predominate in both summer and winter monsoon regions in the period after the rainy season [16]. Soil moisture anomalies seem to have a significantly larger impact on rain rates in the South Asian monsoon.

b. Diurnal Cycle

An accurate representation of the diurnal cycle of convection over tropical lands remains an unresolved problem in monsoon rainfall forecast .Excessive triggering of convection over land contributes to models precipitating too frequently and at too low intensities, while an incorrect phase to the diurnal cycle of convection and associated precipitation can induce systematic biases in the diurnal cycle [16].

c. Low Level Jets

Low Level Jets' statistically significant relationships have been found between nocturnally-peaking LLJs and nocturnal precipitation extremes in numerous disparate regions of the world [33]. Widespread changes in the amplitude of near-surface diurnal heating cycles have been recorded as an important component of LLJ maintenance and that careful assessment of the impact of these changes on future LLJ activity is required.

d. Regional ocean-atmosphere coupling

Evaporation from the ocean is the primary source of water for monsoon rainfall. Processes influencing ocean thermocline depth and SSTs are therefore likely important for a good representation of monsoon precipitation [28]. Furthermore, it is well established that cyclone variability in the Bay of Bengal seems sensitive to a detailed representation of ocean mixed layer processes [4].

2.9 Present state of knowledge

Dynamical models may be the best suitable tool for making seasonal forecasts provided that the initial and boundary conditions are accurate enough. Due to the lack of data coverage over the vast ocean area, initial and boundary conditions are not much accurate and therefore global dynamical models do not have the credibility to simulate the salient feature of the mean monsoon and its variability. There are many global modeling centers, which produce global forecasts in adequate lead-time and therefore accurate and reliable forecasts may be developed in the future through improved data assimilation techniques. In the mean time, empirical / statistical methods need to be developed for generating seasonal weather forecasts to cater the demand.

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 etc., and the analytical soundness are often inadequate and not representative for the entire country. It is necessary to fill in this information and knowledge gap in order to devise appropriate policy and strategic measures and plan of action.

Mondal and Wasimi 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 [6]. SAARC Meteorological Research Center studied monthly and annual rainfalls for the period of 1961-90 [29]. However, they did not make any complete assessment of trend in rainfall in different time scales.

CHAPTER III

CHARACTERISTICS OF HYDROLOGICAL REGIONS

3.1 Introduction

To forecast monsoon rainfall over Bangladesh twenty six (26) stations of Bangladesh from eight different hydrological regions were selected. The stations with respect to hydrological region are as follows:

1. Bogra, Dinajpur, Ishurdi, Rajshahi, Rangpur, from North-West region
2. Dhaka, Mymensingh, from North-Central region
3. Sylhet, Srimongal from North-East region

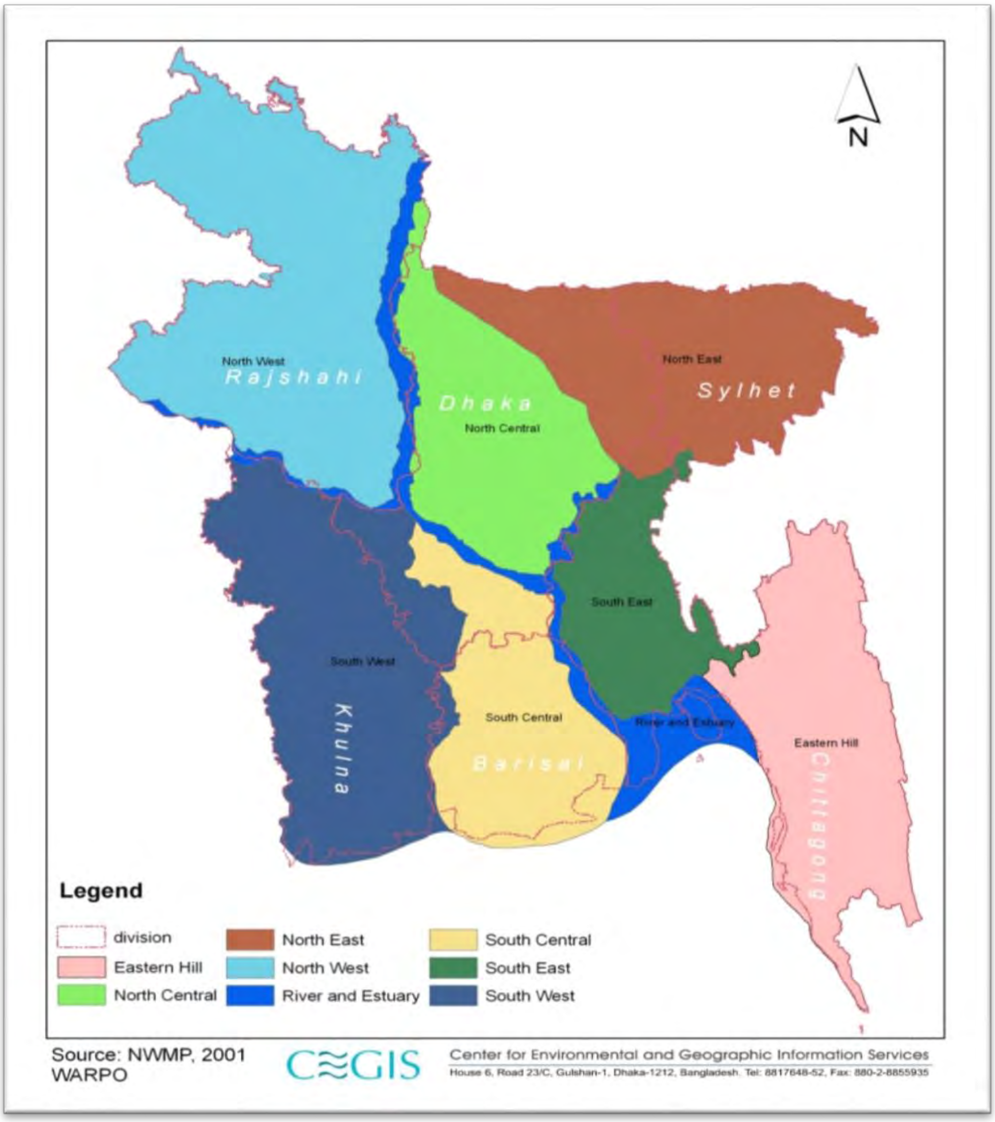

Figure 3.1: Study Area. [Source: NWMP, 2001, WARPO]

4. Faridpur, Jessore, Khulna, Satkhira from South-West region
5. Barisal, Khepurara, Madaripur, Patuakhali from South-Central region
6. Comilla, Feni, Chanpur, Maijdeecourt from South-East region
7. CoxsBazar, Rangamati, Sitakundu, Teknaf from East Hill Region
8. Bhola from River & Estuary

The above stations were selected based on availability of the station data. The representative stations from each hydrological region will give a contemporary study and regional differences regarding the monsoon rainfall in Bangladesh.

3.2 Climate of the study areas

3.2.1 Temperature and seasonality

The general characteristics of the seasons of Bangladesh have a subtropical monsoon climate characterized by wide seasonal variations in rainfall, moderately warm temperatures, and high humidity. Its climate is influenced primarily by monsoon and partly by pre-monsoon and post-monsoon circulations. The south-west monsoon originates over the Indian Ocean and carries warm, moist, and unstable air. The monsoon has its onset during the first week of June and ends in the first week of October, with some inter-annual variability in dates. Besides monsoon, the easterly trade winds are also active, providing warm and relatively drier circulation. In Bangladesh there are four prominent seasons, namely, winter, pre-monsoon, monsoon and post-monsoon. These are described below-

Winter (December to February)

Winter is relatively cooler and drier, with the average temperature ranging from a minimum of 7.2 to 12.8°C to a maximum of 23.9 to 31.1°C. In winter there is not usually much fluctuation in temperature which ranges from minimum of 7°C to 13°C to maximum of 24°C to 31°C. The minimum temperature occasionally falls below 5°C in the north though frost is extremely rare. There is a south to north thermal gradient in winter mean temperature: generally the southern districts are 5°C warmer than the northern districts. In general, maximum summer temperatures range between 37°C and 41°C. April is the warmest month in most parts of the country.

Pre-monsoon (March to May)

Pre-monsoon is hot with an average maximum of 36.7°C, predominantly in the west for up to 10 days, very high rate of evaporation, and erratic but occasional heavy rainfall from March to June. In some places the temperature occasionally rises up to 40.6°C or more. The peak of the maximum temperatures are observed in April, the beginning of pre-monsoon season. In pre-monsoon season the mean temperature gradient is oriented in southwest to northeast direction with the warmer zone in the southwest and the cooler zone in the northeast.

Monsoon (June to early-October)

Monsoon is both hot and humid, brings heavy torrential rainfall throughout the season. About four-fifths of the mean annual rainfall occurs during monsoon. The mean monsoon temperatures are higher in the western districts compared to that for the eastern districts. Warm conditions generally prevail throughout the season, although cooler days are also observed during and following heavy downpours.

Post-monsoon (late-October to November)

Post-monsoon is a short-living season characterized by withdrawal of rainfall and gradual lowering of night-time minimum temperature.

3.2.2 Wind Speed

Winds are mostly from the north and northwest in the winter, blowing gently at one to three kilometers per hour in northern and central areas and three to six kilometers per hour near the coast. From March to May, violent thunderstorms, called northwesters, produce winds of up to sixty kilometers per hour. During the intense storms of the early summer and late monsoon season, southerly winds of more than 160 kilometers per hour cause waves to crest as high as 6 meters in the Bay of Bengal, which brings disastrous flooding to coastal areas.

3.2.3 Rainfall & Humidity

Bangladesh is characterized by heavy rainfall in the monsoon. With the exception of the relatively dry western region of Rajshahi, where the annual rainfall is about 160 centimeters, most parts of the country receive at least 200 centimeters of rainfall per year. Because of its location just south of the foothills of the Himalayas, where monsoon winds turn west and northwest, the region of Sylhet in northeastern Bangladesh receives the greatest average precipitation (figure 3.2). About 80 percent of Bangladesh's rain falls during the monsoon season. The monsoons result from the contrasts between low and high air pressure areas that result from differential heating of land and water. During the hot months of April and May hot air raises over the Indian subcontinent, creating low-pressure areas into which rush cooler, moisture-bearing winds from the Indian Ocean.

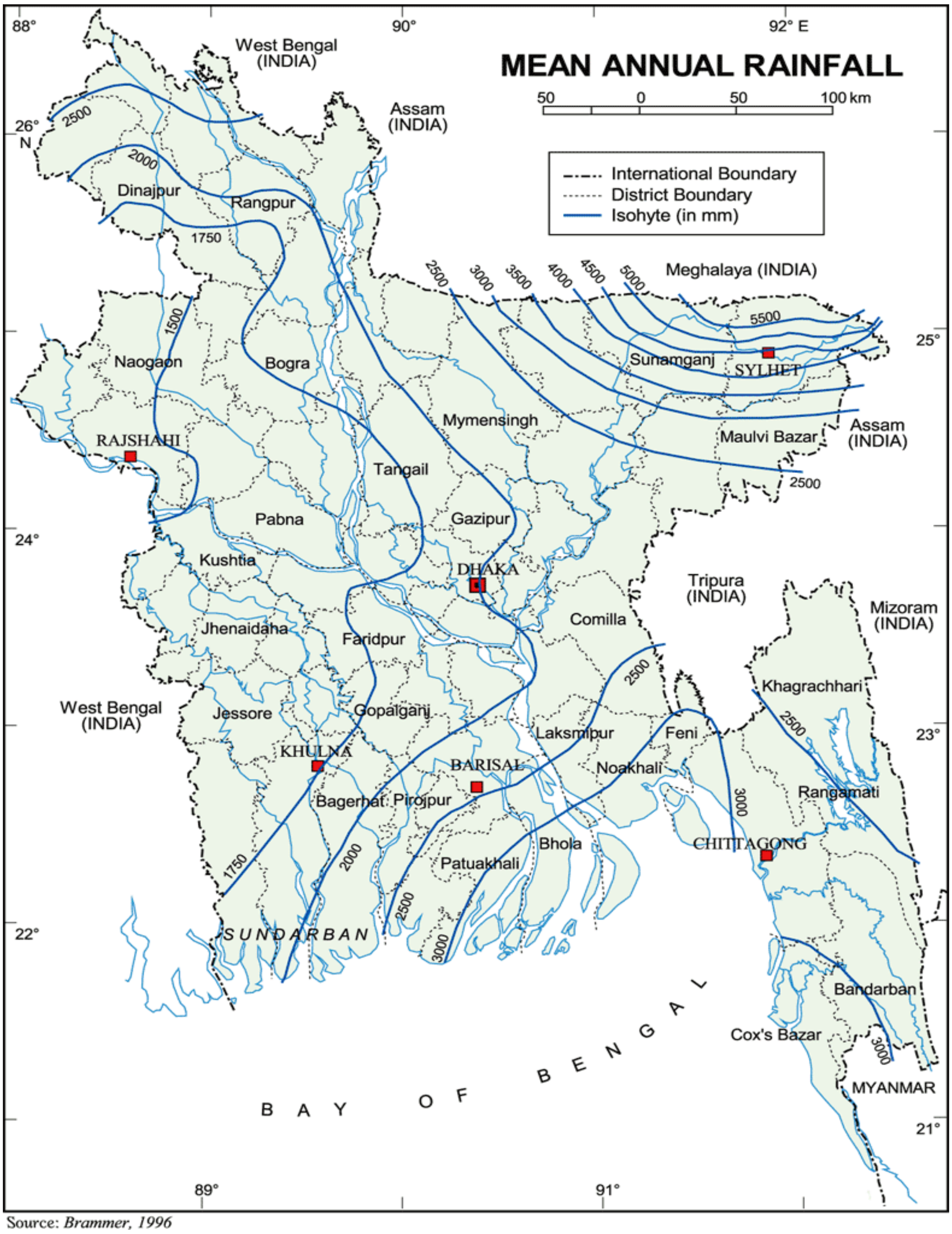

Figure 3.2: Annual Rainfall. (source: Brammer, 1996)

This is the southwest monsoon, commencing in June and usually lasting through September. Dividing against the Indian landmass, the monsoon flows in two branches, one of which strikes the western India. The other travels up the Bay of Bengal and over eastern India and Bangladesh, crossing the plain to the north and northeast before being turned to the west and northwest by the foothills of the Himalayas. The mean annual rainfall is about 2300mm, but there exists a wide spatial and temporal distribution. Annual rainfall ranges from 1200mm in the extreme west to over 5000mm in the east and north-east.

3.3 Climate Zone

On the basis of entire climatic condition Bangladesh can be divided into following seven distinct climatic zones (figure 3.3). The familiar pattern of northwest to southeast isopleths is revealed in this classification.

South-eastern zone (A): It comprises the Chittagong sub-region and a strip of land extending from southwest Sundarbans to the south of Comilla. The hills over 300m in height have north-eastern zone climate. The rest of the area has a small range of temperature, rarely goes over a mean of 32°C and below a mean of 13°C. Rainfall is heavy, usually over 2,540 mm. In winter dew fall is heavy.

North-eastern zone (B): This zone includes most of east and south Sylhet and a wedge shaped strip south of the Meghalaya Plateau. Here too, mean maximum temperature is rarely above 32°C but mean minimum is 10°C and below. Average humidity is even more than in south-eastern zone. In this zone winter rain is appreciable. Fog is very common in winter. This is the cloudiest part of Bangladesh. The higher hills and mountains of the Chittagong sub-region can also be classified under this zone.

Northern part of the northern region (C): This is an area of extremes. In summer the mean maximum temperature is well above 32°C whereas in winter the mean minimum is below 10°C. The summer is dry, with a scorching westerly wind, but the rainy season is very wet, with 2,000 to 3,000 mm of rainfall.

North-western (D): Except that the extremes are less and the rainfall is lower, this zone is similar to northern part of the northern region. The lower rainfall makes this area both atmospherically and pedologically drier.

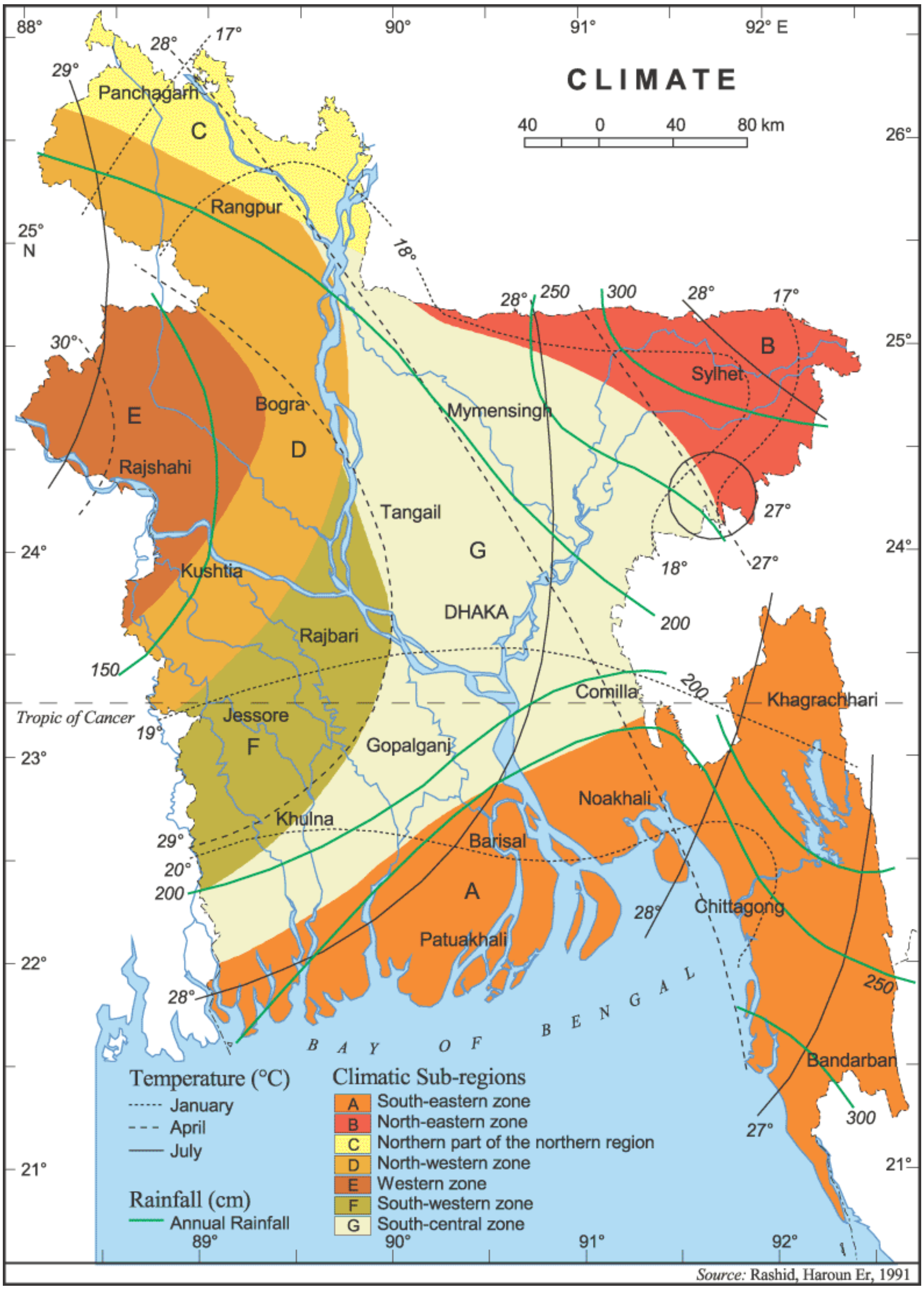

Figure 3.3: Climate Zone Map of Bangladesh. (source: Rashid, 1991)

Western zone (E): It comprises greater Rajshahi district and parts of adjacent districts. This is the driest area in Bangladesh with rainfall generally below 1,500 mm and summer humidity less than 50%. In summer, it is the hottest and driest of all climatic zones. Mean summer maximum temperature is over 35°C.

South-western zone (F): Here the extremes of the zones to the north are somewhat tempered. Rainfall is between 1,500 mm and 1,800 mm. The mean maximum temperature in summer is below 35°C. Dew-fall is heavier than in Western zone.

South-central zone (G): In this zone rainfall is abundant, being above 1,900 mm. The range of temperature is, as can be expected, much less than to the west, but somewhat more than in South-eastern zone. This is a transitory zone between the South-eastern, North-western and South-western zones and most of the severe hail storms, and tornadoes are recorded in this area.

CHAPTER IV
CLIMATE PREDICTABILITY TOOL (CPT)

4.1 Introduction

The depth of rainfall and its distribution in the temporal and spatial dimensions depends on many variables, such as pressure, temperature, and wind speed and direction. Due to the complexity of the atmospheric processes by which rainfall is generated and the lack of available data on the necessary temporal and spatial scales, it is not feasible generally to forecast rainfall using a physically based process model**.**

4.2 Data and Methodology

This study was carried out based on secondary data and field visits. The IRI Climate Predictability Tool (CPT) was used as a forecasting tool for this study. The CPT model was downloaded from http://iri.columbia.edu/outreach/software/ and installed on a computer. Thirty years (1981-2010) rainfall data was collected from 34 Meteorological Stations (BMD) allover Bangladesh. The sea-surface temperature data for use with the CPT was collected from the IRI data library. The monthly sea-surface temperatures from January 1970 to December 2011 were extracted from the IRI dataset library. Sea-surface temperatures were downloaded from http://iridl.ldeo.columbia.edu. Observed global (monthly) sea surface temperature (SST) data was obtained to use as predictor data in CPT.

Station data was collected from the BMD and processed to obtain JJA seasonal rainfall as the predictands for the CPT. All-Bangladesh and hydrological region wise aerial precipitation were calculated for JJA season and transform into a format (.txt), which suits for the CPT software. The SST data sets were used for finding correlation with observed rainfall (BMD) for all-Bangladesh; hydrological region level. It is mentioned that monsoon season consists of JJAS (June-September) in Bangladesh. But in the present study only June-August (JJA) data was considered for monsoon season in Bangladesh.

4.3 Climate Predictability Tool (CPT)

Principal Component Regression (PCR) and Canonical Correlation Analysis (CCA) methods were used in CPT. This involves data that represent predictors, and data that represent what is to be predicted i.e. predictands. Often, the predictor data was set up to occur earlier than the predictand data, with each spanning a historical period, so that predictive relationships become detectable and describable, and was used for real-time forecasts. However, the predictor and predictand data were also set up to occur at the same time, not staggered, so that the techniques describe diagnostic relationships between them.

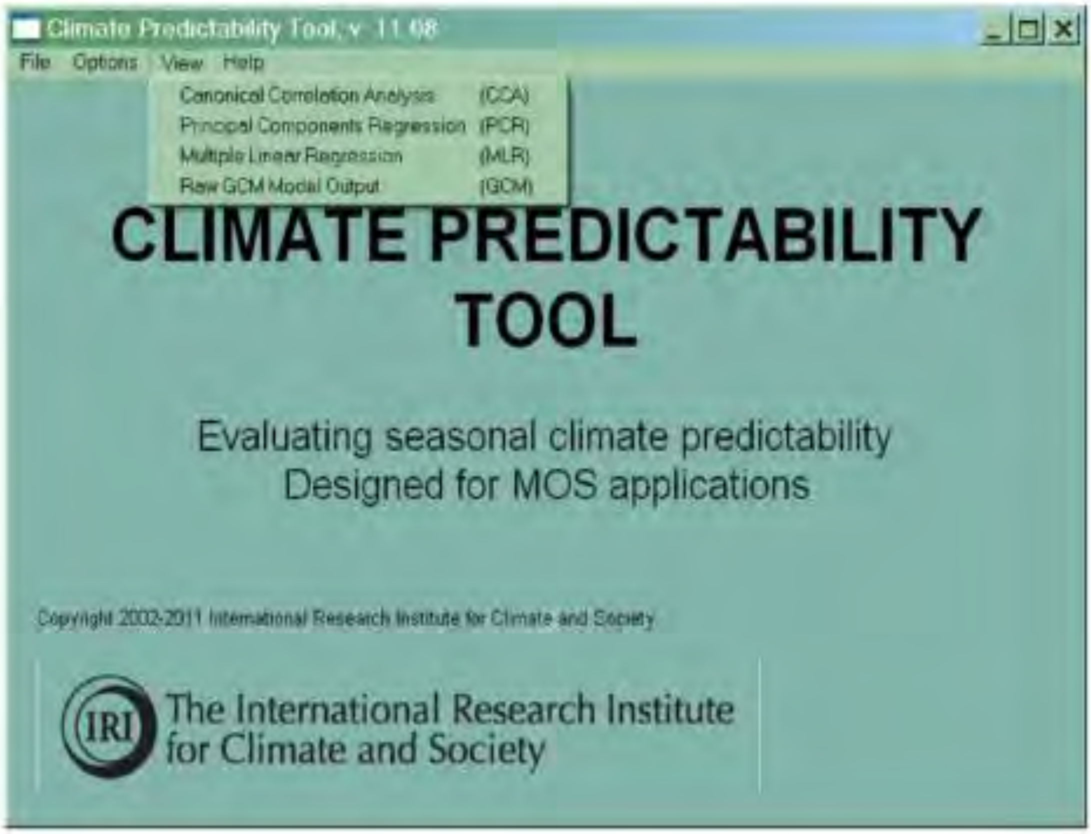

Fig-4.1: Aanalysis to perform: PCR, CCA, MLR or GCM

CPT cannot generate predictability where it does not exist. What it can do, however, is identify model errors that are characteristic, and correct the forecasts in such a way as to maximize their average accuracy over the long historical period for which there are samples of model forecast data along with the corresponding actually observed data. Thus, CPT calibrates, or corrects, model forecasts. This process is the same as what is commonly known as model output statistics, or MOS.

In this model correction design, and regardless of whether the CCA or the PCR tool was selected for the analysis, CPT did its job in the same basic manner. The way it works is that the predictand (the *y variable*) is related to the predictor (the *x variable*) linearly. The simplest case of a linear relationship is when there is one x and one y, such as the Southern Oscillation Index (SOI) for x, and the rainfall at a station (or the average rainfall over several stations) for y, and

$$y = bx + a \qquad (1)$$

Here y is predicted by getting the value of the predictor, x, multiplying it by some factor b, and then adding a constant number a. In general, the prediction of y from x is not perfect: in some instances y is over-predicted while in others it is under-predicted. In linear regression, upon which both CPT techniques are based, a and b were determined such that the sum of the squared errors over all of the historical cases used to make the equation is minimized. Squared errors rather than the absolute value of the errors were minimized because this nicely fitted the huge collection of linear statistical theory.

A number of different varieties of linear regression can be identified, and can be classified using various criteria. One criterion that helps to describe the two techniques used in CPT is the level of complexity of the predictor and predictand data. Three commonly recognized levels can be identified:

(a) *simple regression*: a single predictor and a single predictand

$$y = bx + a \qquad (1)$$

(b) *multiple regression*: two or more predictors, and a single predictand

$$y = b_1x_1 + b_2x_2 + ... + b_nx_n + a \qquad (2)$$

(case of n predictors; a is the accumulated constant)

The PCR tool in CPT is in this category of regression, with the x's themselves being defined in a special way in order to need much fewer of them.

(c) *multivariate (pattern) regression*: two or more predictors, two or more predictands

$\mathbf{Y} = \mathbf{BX} + a$ (3)

($\mathbf{Y}$, $\mathbf{B}$ and $\mathbf{X}$ are matrices; can be CCA)

The CCA tool in CPT is in this category of regression, with the x's and the y's themselves being defined in a special way in order to need much fewer of each.

The CPT software was initially designed for use in forecast development by national meteorological services, especially in Africa, to simplify the production of seasonal climate forecasts. It can be used in any region, and for diagnostic research as well as forecasting. It can be used to perform CCA or PCR on any pair of data sets, for any application.

4.4 Canonical-Correlation Analysis (CCA)

Canonical-Correlation Analysis (**CCA**) is a way of making sense of cross-covariance matrices. Canonical correlation analysis is a method for exploring the relationships between two multivariate sets of variables (vectors), all measured on the same individual.

One approach to studying relationship between the two sets of variables is to use canonical correlation analysis which describes the relationship between the first set of variables and the second set of variables. A typical use for canonical correlation in the experimental context is to take two sets of variables and see what is common amongst the two sets.

If we have two vectors $X = (X_1, ..., X_n)$ and $Y = (Y_1, ..., Y_m)$ of random variables, and there are correlations among the variables, then canonical-correlation analysis will find linear combinations of the X_i and Y_j which have maximum correlation with each other.

4.5 Calibration and validation of the trained model

In order for calibration of the trained model for JJA mean-rainfall, the following simple linear type regression equation was utilized for observed and CPT model generated JJA mean-rainfall data during the considering period.

$Y_{obs} = mX_{model} + C$ (4)

Where, $obs\ Y$ is the observed aerial mean-rainfall. X mod is the CPT generated mean-rainfall. m is the gradient of the regression and c is the intersect. Validation of CPT for mean-rainfall is carried out for the next year with the following equation.

$Y_{proj} = mX_{model} + C$ (5)

Where $proj\ Y$ is the calibrated mean-rainfall and X_{mod} is the CPT generated mean-rainfall for JJA period. m and c are gradient and intersect of the above linear equation used from the calibration process.

4.1 Rationality of Domain and Predictor Selection

Three domains (Somali Jet, Bay of Bengal, and Arabian Sea) were considered to get the best fit domain. Somali Jet (15º Northernmost and 8º Southernmost Latitude;52º Westernmost and 60º Easternmost Longitude) domain was selected for the study as it shows significant correlation in case of different predictors for Canonical correlation Analysis (CCA) compared to Bay of Bengal domain (20º Northernmost & 10º Southernmost Latitude and 60º Westernmost and 70º Easternmost Longitude) and Arabian Sea domain (20º Northernmost & 10º Southernmost Latitude and 80º Westernmost and 90º Easternmost Longitude). That's why, Somali jet was used as domain in CPT analysis.

Figure 4.2: Domain selection for CCA analysis

Several parameters (SST, ENSO, MSLP, Wind, GRCP Rainfall, GEO_850) were used as predictor to know which one is closely correlated with 3 domains (Somali Jet, Bay of Bengal, and Arabean Sea). Goodness Index of variables GEO_850, GRCP Rainfall and Wind were low for all 3 domains and very low correlation was observed. Though the variables MSLP and ENSO showed correlation ranges between -0.113 and -0.167 in 3 domains, still differed from SST. SST showed the maximum correlation ranges between -0.175 and -0.35 in all domains. However, highest correlation (-0.35) was observed between SST and Somali Jet to estimate the reliable forecast. SST showed almost same rainfall both for All Bangladesh observed and forecasted rainfall. That’s why, SST was used as predictor.

Table 4.1: Comparison of Correlation coefficient for selected parameter and domain

Parameter Name	Somali jet	Bay of Bengal	Arabian Sea
Sea Surface temperature (SST)	-0.35	-0.175	-220
ENSO	-0.142	-0.142	-0.142
Mean Sea Level Pressure (MSLP)	-0.144	-0.113	-0.167
Wind	-0.063	-0.024	0.024
GRCP Rainfall	-0.214	0.136	-0.206
GEO_850	-0.050	-0.150	-0.087

CHAPTER V

FORECAST SEASONAL WEATHER

5.1 All-Bangladesh Forecast

Daily rainfall data of different stations were collected from BMD for this study. The all-Bangladesh rainfall series for a given month, season or year was calculated from the average rainfall of different stations. The All-Bangladesh mean- monsoon rainfall was calculated with Kriging interpolation method using Surfer software, in which scattered rainfall station data was interpolated into pixel values, which in turn calculates aerial average of rainfall over the entire country.

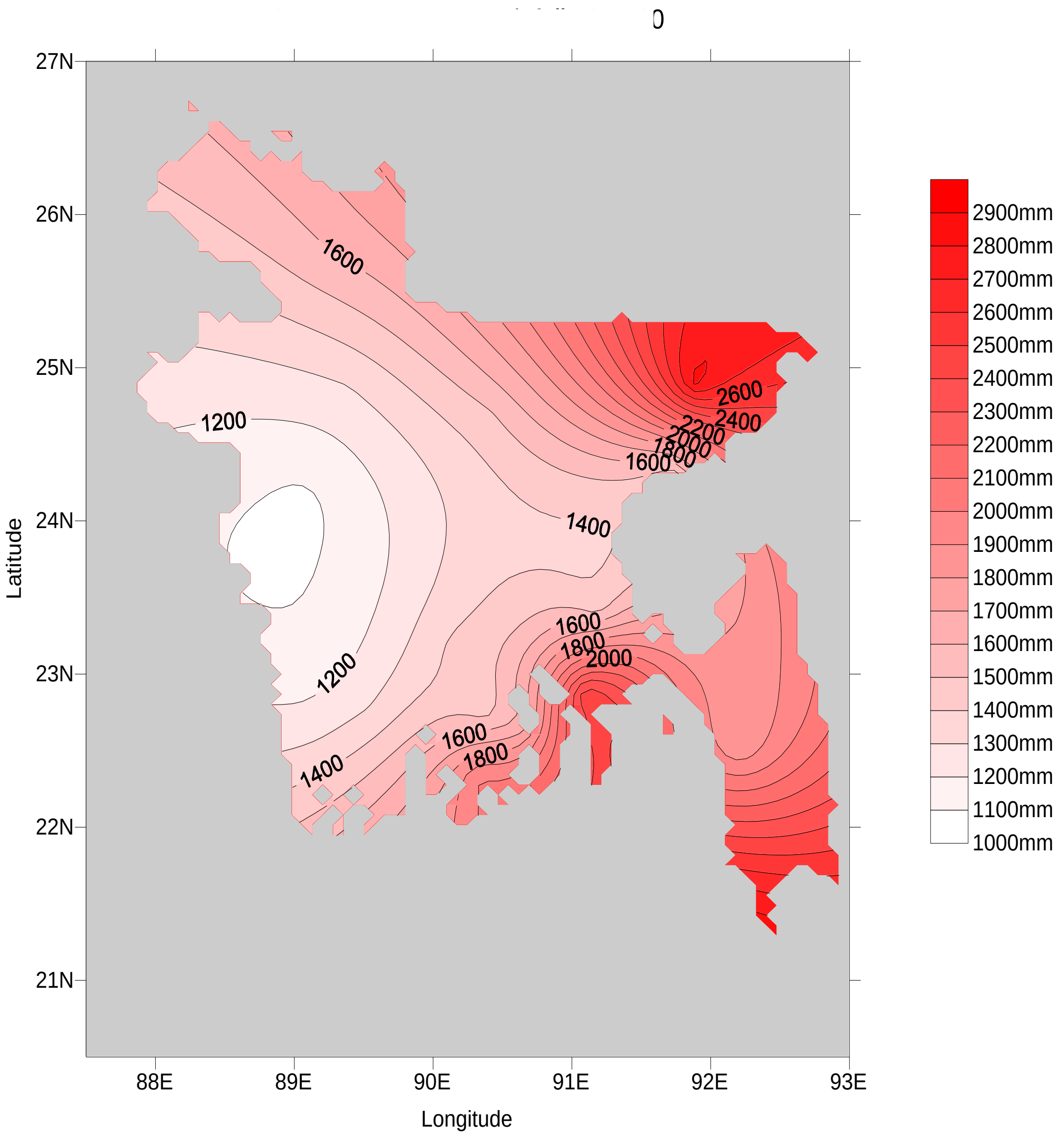

Fig. 5.1 Spatial distribution of monsoon rainfall over Bangladesh calculated with Kriging interpolation method using Surfer software

Sea surface temperature (SST) of Coupled General Circulation Model (CGCM) model data, during 1981–2010, was used as the predictors to make forecast for All-Bangladesh during for JJA. The CPT was trained, with Canonical Correlation Analysis (CCA) technique, for the period of 30 years. The domain of the predictor variables was selected as 15S°-8S° and 52E° to 60E°, which seems to be highly correlated with the predictand variables in Bangladesh. The model was optimized with 3 no. of Empirical Orthogonal Functions (EOF) modes of X-predictors, 3 no. of EOF modes of Y-predictand and 3 no. of CCA modes. The goodness of the model was reported as 0.355. Table 5.1 shows some statistics viz. Pearson's correlation, RMSE, Hit Score, Bias, etc. of the trained CPT model for All-Bangladesh JJA mean-rainfall.

Table 5.1 Some statistics of the 30 years trained model All-Bangladesh JJA mean-rainfall

	Pearson's Correlation	RMSE	Hit Score	Bias	Mean absolute error
All Bangladesh	- 0.6322	1.52	46.67%	-0.10	1.45

In order for calibration of the trained model for All-Bangladesh JJA mean-rainfall, the following simple linear type regression equation was utilized for observed and CPT model generated All-Bangladesh JJA mean-rainfall data during the period 1981-2010.

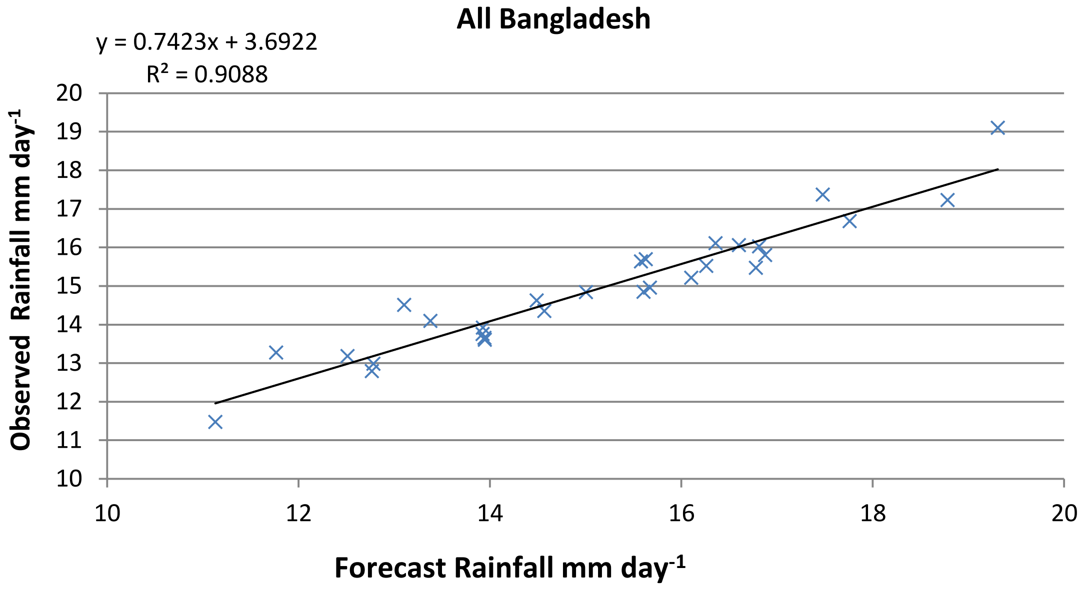

Fig. 5.2 Scatter plot of observed and CPT-generated All-Bangladesh JJA mean-rainfall during 1981-2010 period.

The scatter plot of observed and CPT-generated All-Bangladesh JJA mean-rainfall for selected BMD station during the period of 1981-2010 is shown in Fig. 5.3 The value of R^2 is found 0.986.

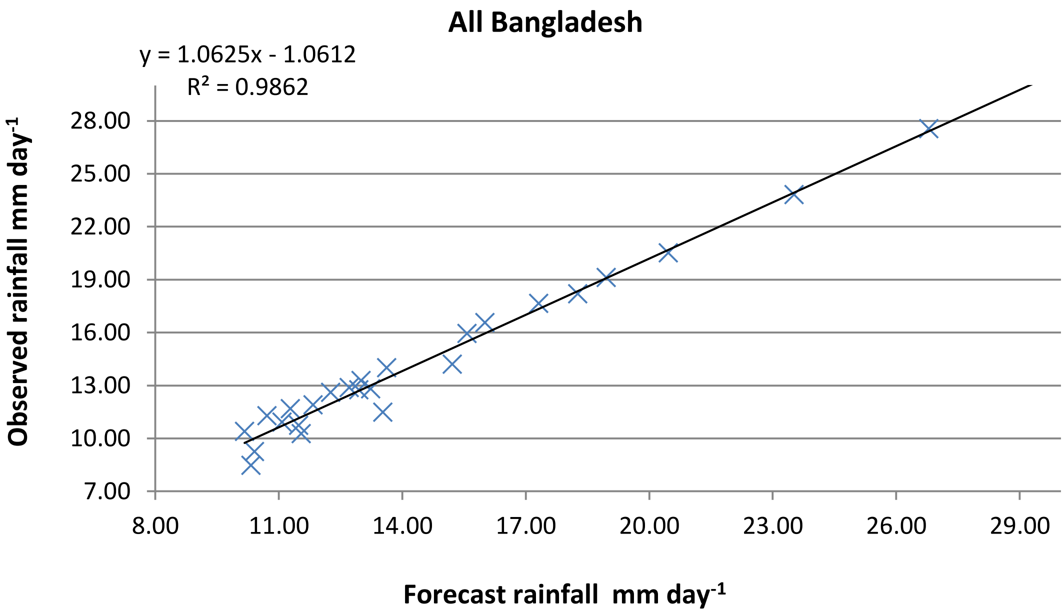

Fig 5.3 Scatter plot of observed and CPT-generated JJA mean-rainfall for selected BMD station during 1981-2010 period.

It was taken 27 stations mean rainfall out of these stations for all-Bangladesh. CPT generated forecast JJA mean rainfall 13.82 mm/d for 2011 and observed JJA mean rainfall 14.11 mm/d for 2011. CPT generated forecast JJA mean rainfall 0.29 mm/d (2.1 %) is underestimated is shown in Table 5.2.

Table 5.2 Coefficients of the linear regression model for JJA mean-rainfall for All Bangladesh with the forecast and observed rainfall of JJA 2011

	m (Gradient)	C (Intersect) mm day^{-1}	CPT-Generated JJA mean-rainfall for 2011 mm day^{-1}	Observed JJA mean rainfall for 2011 mm day^{-1}	Difference mm day^{-1}
All Bangladesh	1.062	-1.0621	13.82	14.11	0.29

The Fig.5.4 shows the observed All- Bangladesh JJA mean-rainfall during the period 1982-2009 together with the calibration during 1981-2009, validation for 2010 and projection for 2011. Variability of the area averaged All-Bangladesh rainfall during JJA season seems to be less as it reduces the noises of the signal with the spatial distribution.

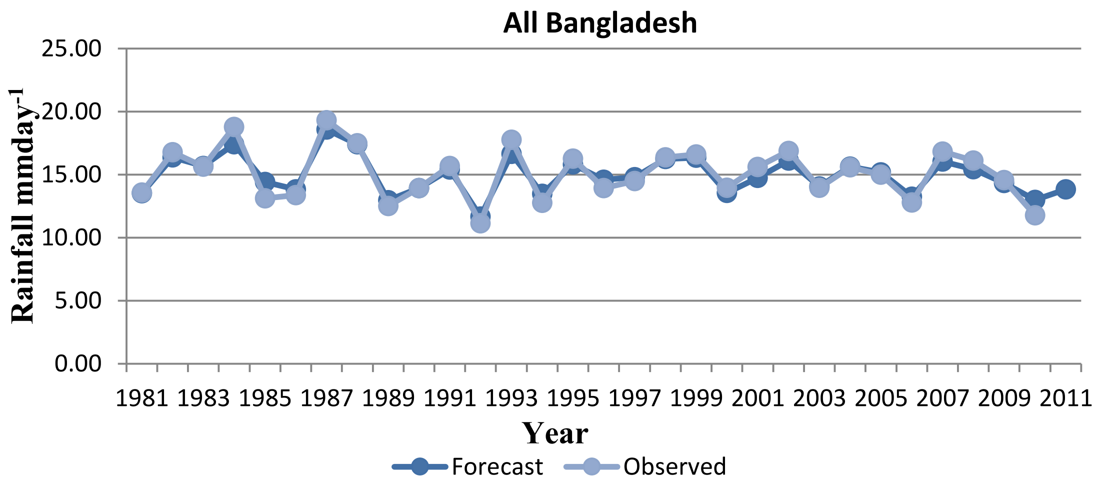

Fig.5.4 Observed All-Bangladesh mean-rainfall of JJA during 1981-2009 with calibration during 1981-2009, validation for 2010 and projection for 2011

5.2 Hydrological Region Based Forecasts

Eight hydrological regions, of which the monsoon rainfall mainly confines, were selected to make forecast for JJA period. From the daily values, monthly total rainfall was calculated for each month, for each station and for year. Then hydrological regions mean-monsoon rainfall was calculated from the average JJA rainfall of different station. Sea surface temperature fields (hindcast and forecast) of GCM model from 1981-2010 was used to train the model with Canonical Correlation Analysis (CCA) technique. Five-year period was set for cross-validation of the model. The domain of the predictor variables is selected as 15S°to 8S° and 500E° to 54E°, which seems to be highly correlated with the predictand variables in BMD station of Bangladesh.

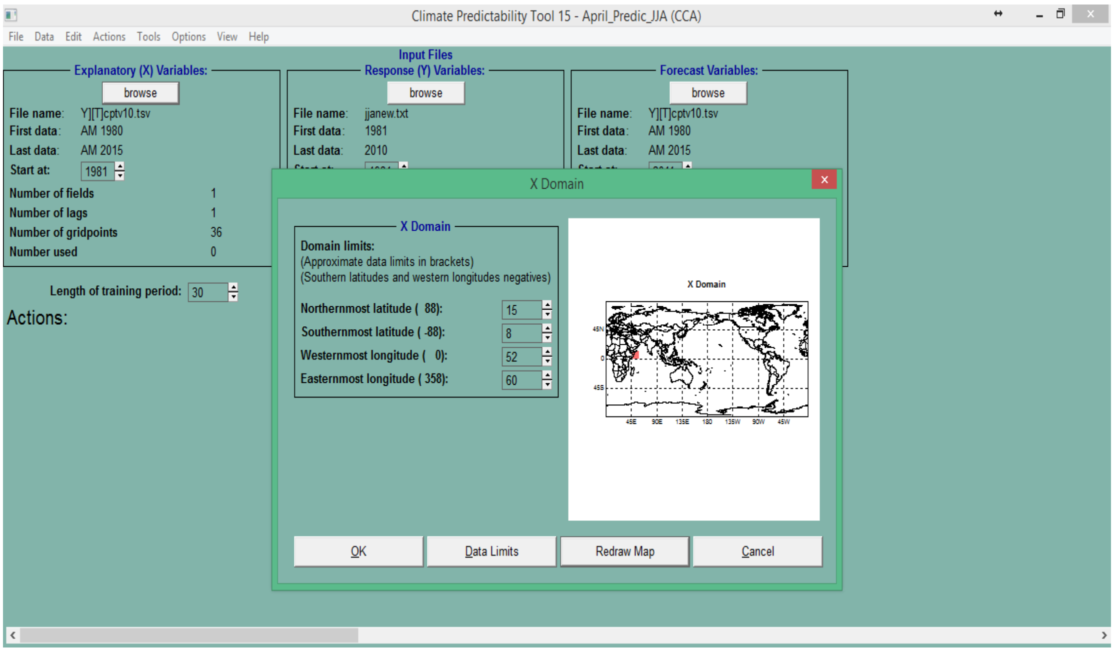

Fig. 5.5 Domain selection for CPT application

The model was optimized with 3 no. of Empirical Orthogonal Functions (EOF) modes of X-predictors, 3 no. of EOF modes of Y-predictand and 3 no. of CCA modes. The goodness of the model was reported as 0.35.

5.2.1 North West Hydrological Region

Table 5.3 shows some statistics viz. Pearson's correlation, RMSE, Hit Score, Bias, etc. of the trained CPT model for JJA mean-rainfall of North West Hydrological Region.

Table 5.3: Some statistics of the 30 years trained model North West Hydrologic Region JJA mean-rainfall

Hydrological Region	Pearson's Correlation	RMSE	Hit Score	Bias	Mean absolute error
North West	-0.62	0.9	50%	0.09	1.48

The scatter plot of observed and CPT-generated North West hydrological region JJA mean-rainfall for selected BMD station during the period of 1981-2010 is shown in Fig. 5.6. The value of R^2 is found 0.890.

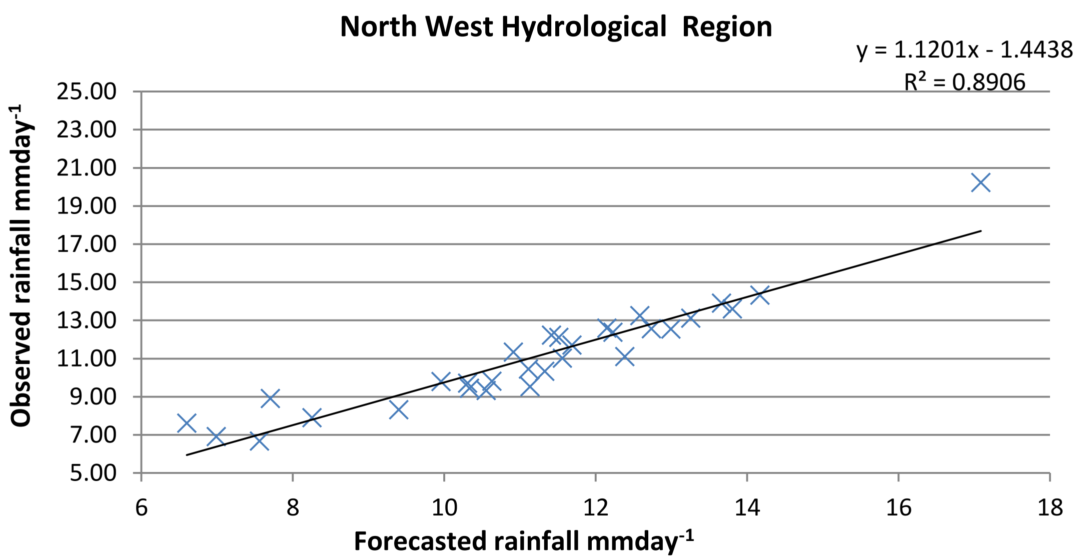

Fig. 5.6 Scatter plot of observed and CPT-generated North West Hydrological region JJA mean-rainfall during 1981-2010 period

Coefficients of linear regression model for calibration of CPT generated for North West Hydrological region JJA rainfall forecasts are tabulated in the Table 5.4. It also shows CPT generated and observed JJA rainfall for 2011. CPT generated forecast JJA mean rainfall 9.05 mm/d for 2011 and observed JJA mean rainfall 10.10 mm/d for 2011.

Table 5.4: Coefficients of the linear regression model for JJA mean-rainfall for North West Hydrological Region with the forecast and observed rainfall of JJA 2011

Hydrological Region	m (Gradient)	C (Intersect) mm day^{-1}	CPT-Generated JJA mean-rainfall for 2011 mm day^{-1}	Observed JJA mean rainfall for 2011 mm day^{-1}	Difference mm day^{-1}
North West	1.120	-1.443	9.05	10.10	1.05

The Fig. 5.7 shows the observed JJA mean-rainfall for North West hydrological rainfall during the period 1982-2009 together with the calibration during 1981-2009, validation for 2010 and projection for 2011. Decreasing trend of North West Hydrological Region monsoon rainfall during JJA season was found in Fig. 5.7.

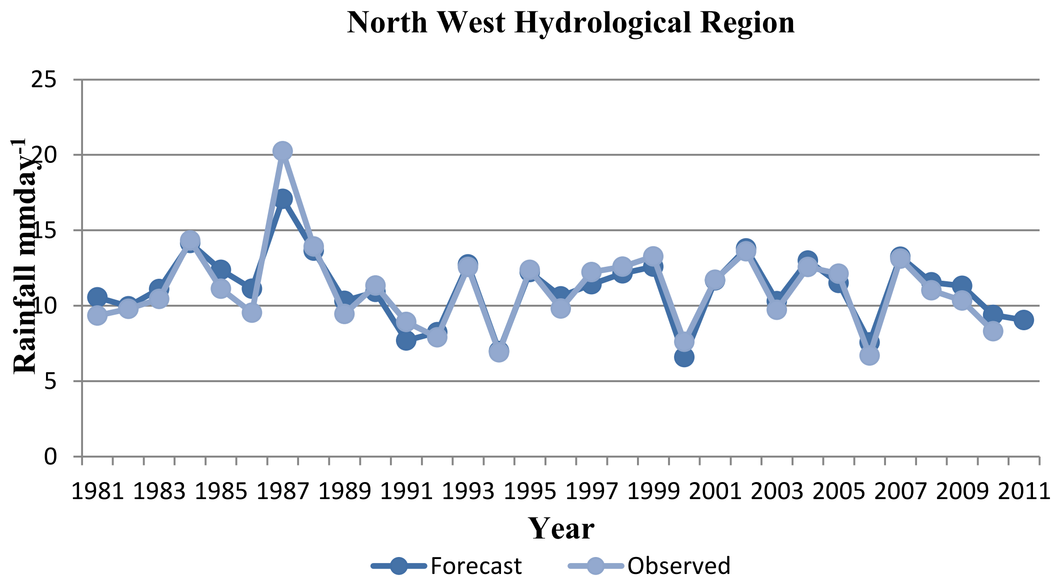

Fig. 5.7 Observed North West Hydrological Region mean-rainfall of JJA during 1981-2009 with calibration during 1981-2009, validation for 2010 and projection for 2011

5.2.2 North Central Hydrological region

Table 5.5 shows some statistics viz. Pearson's correlation, RMSE, Hit Score, Bias, etc. of the trained CPT model for JJA mean-rainfall of North Central Hydrological Region.

Table 5.5 Some statistics of the 30 years trained model North Central Hydrological Region JJA mean-rainfall

Hydrological Region	Pearson's Correlation	RMSE	Hit Score	Bias	Mean absolute error
North Central	-0.70	0.86	60%	0.04	1.34

The scatter plot of observed and CPT-generated North Central hydrological region JJA mean-rainfall for selected BMD station during the period of 1981-2010 is shown in Fig. 5.8. The value of R^2 is found 0.838.

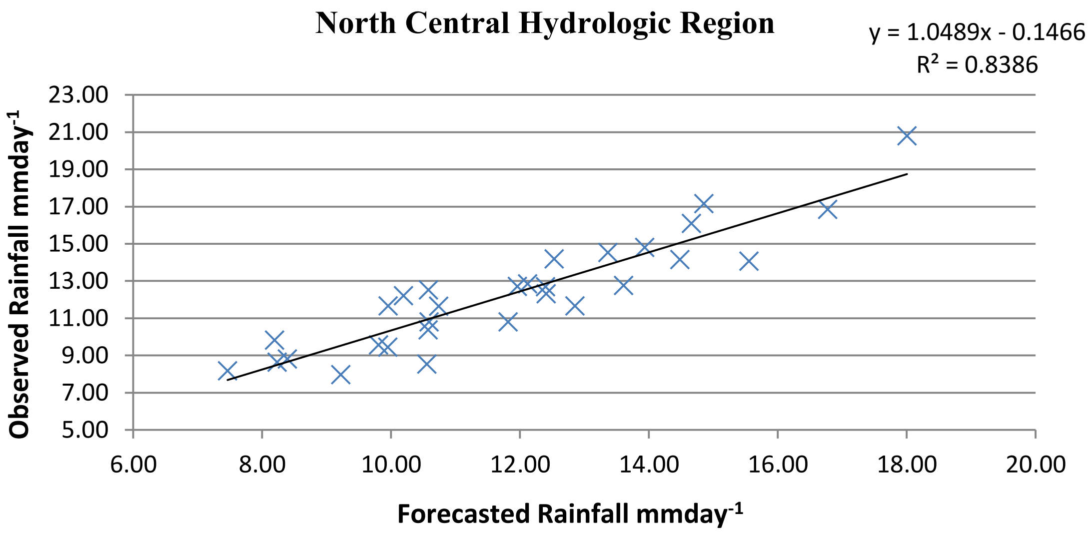

Fig. 5.8 Scatter plot of observed and CPT-generated North Central Hydrological region JJA mean-rainfall during 1981-2010 period

Coefficients of linear regression model for calibration of CPT generated for North Central Hydrological region JJA rainfall forecasts are tabulated in the Table 5.6. It also shows CPT generated and observed JJA rainfall for 2011. CPT generated forecast

JJA mean rainfall 13.84 mm/d for 2011 and observed JJA mean rainfall 12.89 mm/d for 2011.

Table 5.6 Coefficients of the linear regression model for JJA mean-rainfall for North West Hydrological Region with the forecast and observed rainfall of JJA 2011

Hydrological Region	m (Gradient)	C (Intersect) mm day^{-1}	CPT-Generated JJA mean-rainfall for 2011 mm day^{-1}	Observed JJA mean rainfall for 2011 mm day^{-1}	Difference mm day^{-1}
North West	1.048	-0.146	13.84	12.89	-0.95

The Fig. 5.9 shows the observed JJA mean-rainfall of North Central hydrological region during the period 1982-2009 together with the calibration during 1981-2009, validation for 2010 and projection for 2011. Increasing trend of North Central Hydrological Region monsoon rainfall during JJA season was found in Fig. 5.9.

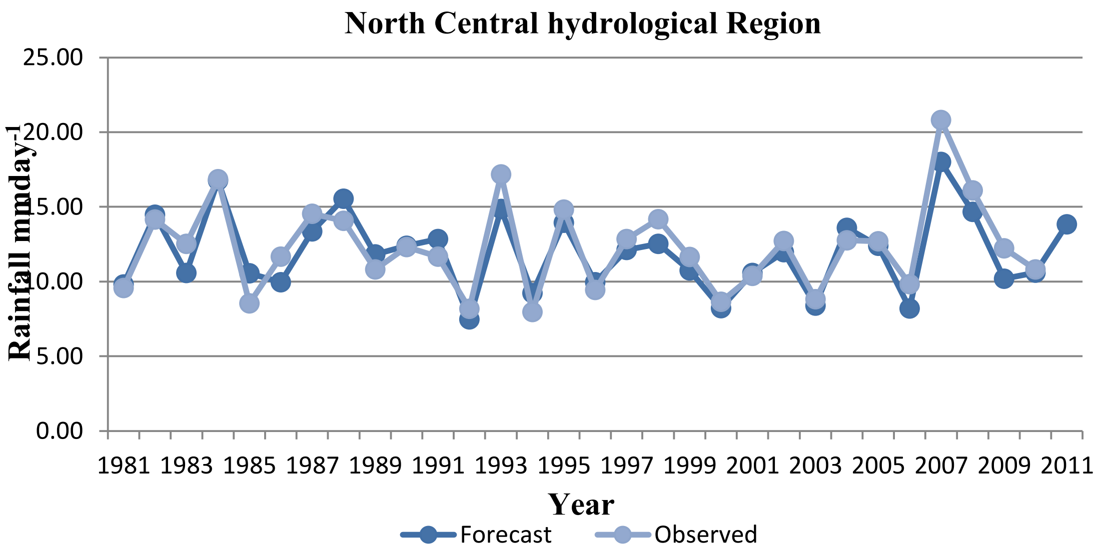

Fig. 5.9 Observed North Central Hydrological Region mean-rainfall of JJA during 1981-2009 with calibration during 1981-2009, validation for 2010 and projection for 2011

5.2.3 North East Hydrological Region

Some statistics viz. Pearson's correlation, RMSE, Hit Score, Bias, etc. of the trained CPT model for JJA mean-rainfall of North East Hydrological Region is shown in Table 5.7.

Table 5.7: Some statistics of the 30 years trained model North East Hydrologic Region JJA mean-rainfall

Hydrological Region	Pearson's Correlation	RMSE	Hit Score	Bias	Mean absolute error
North East	-0.56	1.34	55%	0.065	2.255

The scatter plot of observed and CPT-generated North East hydrological region JJA mean-rainfall for selected BMD station during the period of 1981-2010 is shown in Fig. 5.10. The value of R^2 is found 0.693.

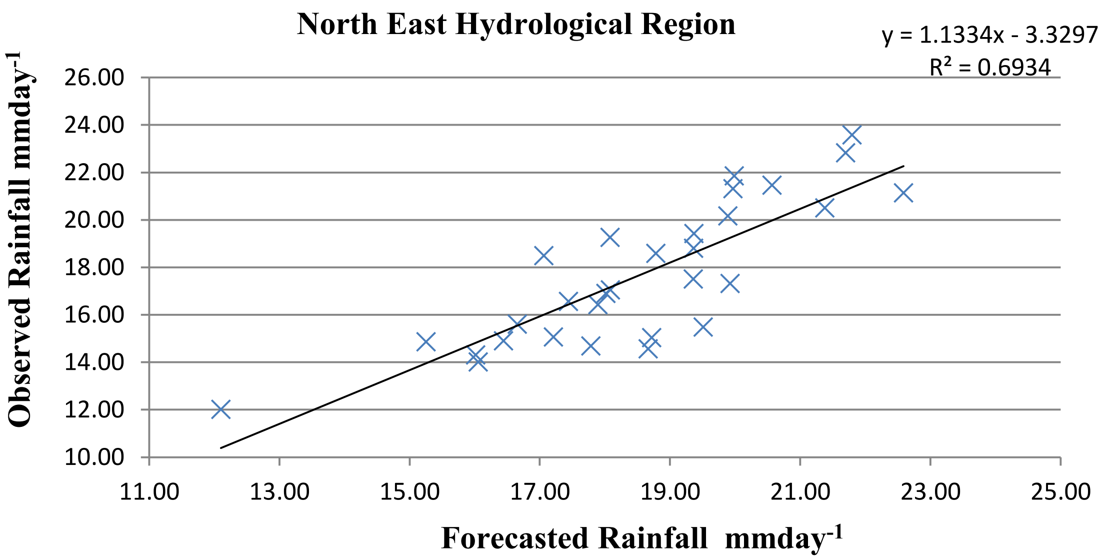

Fig. 5.10 Scatter plot of observed and CPT-generated North East Hydrological Region JJA mean-rainfall during 1981-2010 period

Coefficients of linear regression model for calibration of CPT generated for North East Hydrological region JJA rainfall forecasts are tabulated in the Table 5.8. It also shows CPT generated and observed JJA rainfall for 2011. CPT generated forecast JJA mean rainfall 19.49 mm/d for 2011 and observed JJA mean rainfall 18.66 mm/d for 2011.

Table 5.8: Coefficients of the linear regression model for JJA mean-rainfall for North East Hydrological Region with the forecast and observed rainfall of JJA 2011

Hydrological Region	m (Gradient)	C (Intersect) mm day^{-1}	CPT-Generated JJA mean-rainfall for 2011 mm day^{-1}	Observed JJA mean rainfall for 2011 mm day^{-1}	Difference mm day^{-1}
North West	1.133	-3.329	19.49	18.66	-0.83

The Fig. 5.11 shows the observed JJA mean-rainfall of North East hydrological region during the period 1982-2009 together with the calibration during 1981-2009, validation for 2010 and projection for 2011. Decreasing trend of North East Hydrological Region monsoon rainfall during JJA season was found in Fig. 5.11.

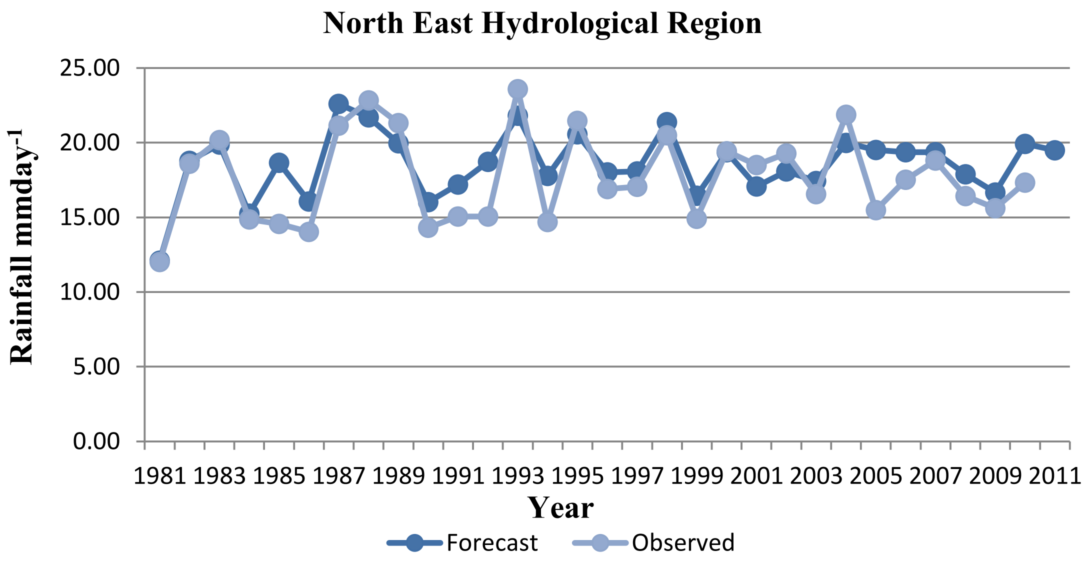

Fig.5.11: Observed North East Hydrological Region mean-rainfall of JJA during 1981-2009 with calibration during 1981-2009, validation for 2010 and projection for 2011

5.2.4 South West Hydrological region

Some statistics viz. Pearson's correlation, RMSE, Hit Score, Bias, etc. of the trained CPT model for JJA mean-rainfall of South West Hydrological Region is shown in Table 5.9.

Table 5.9: Some statistics of the 30 years trained model South West Hydrological Region JJA mean-rainfall

Hydrological Region	Pearson's Correlation	RMSE	Hit Score	Bias	Mean absolute error
South West	-0.756	0.8275	65%	-0.08	1.45

The scatter plot of observed and CPT-generated South West hydrological region JJA mean-rainfall for selected BMD station during the period of 1981-2010 is shown in Fig. 5.12. The value of R^2 is found 0.795.

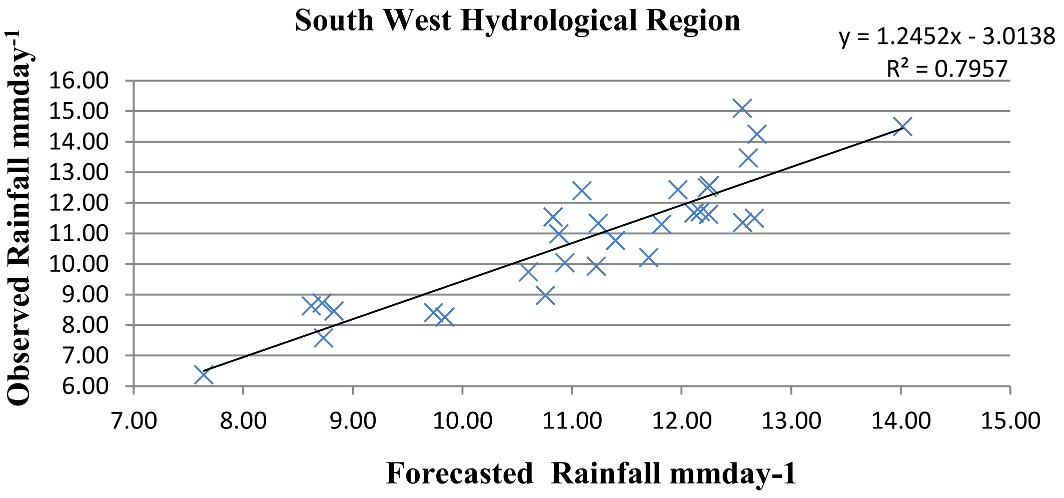

Fig. 5.12: Scatter plot of observed and CPT-generated South West Hydrological region JJA mean-rainfall during 1981-2010 period

Coefficients of linear regression model for calibration of CPT generated for South West Hydrological region JJA rainfall forecasts are tabulated in the Table 5.10. It also shows CPT generated and observed JJA rainfall for 2011. CPT generated forecast JJA mean rainfall 9.01 mm/d for 2011 and observed JJA mean rainfall 9.88 mm/d for 2011.

Table 5.10: Coefficients of the linear regression model for JJA mean-rainfall for South West Hydrological Region with the forecast and observed rainfall of JJA 2011

Hydrological Region	m (Gradient)	C (Intersect) mm day^{-1}	CPT-Generated JJA mean-rainfall for 2011 mm day^{-1}	Observed JJA mean rainfall for 2011 mm day^{-1}	Difference mm day^{-1}
South West	1.245	-3.013	9.01	9.88	0.87

The Fig. 5.13 shows the observed JJA mean-rainfall of South West Hydrological Region during the period 1982-2009 together with the calibration during 1981-2009, validation for 2010 and projection for 2011. Decreasing trend of South west Hydrological Region monsoon rainfall during JJA season was found in Fig. 5.13.

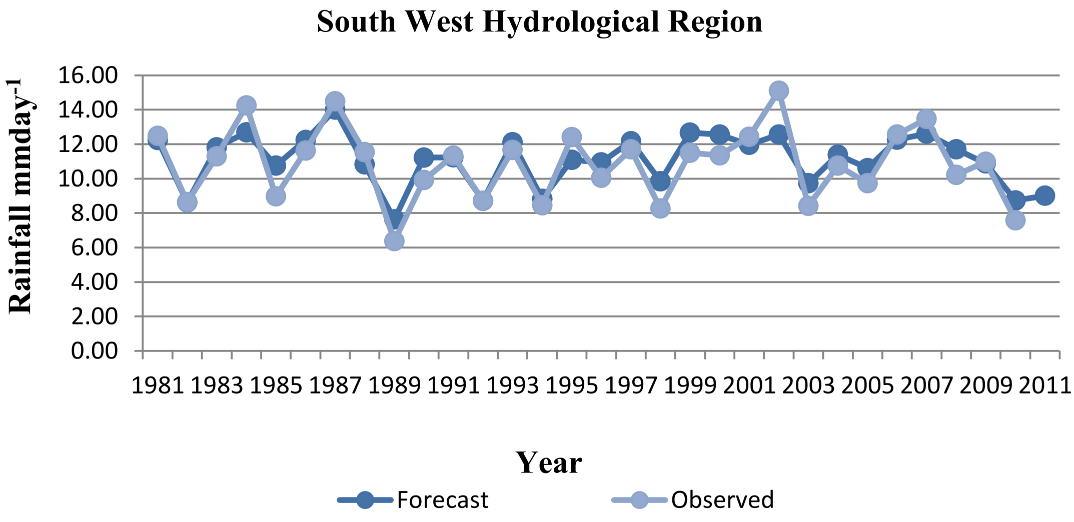

Fig. 5.13 Observed South West Hydrological Region mean-rainfall of JJA during 1981-2009 with calibration during 1981-2009, validation for 2010 and projection for 2011

5.2.5 South Central Hydrological Region

Some statistics viz. Pearson's correlation, RMSE, Hit Score, Bias, etc. of the trained CPT model for JJA mean-rainfall of South Central Hydrological Region is shown in Table 5.11.

Table 5.11: Some statistics of the 30 years trained model South Central Hydrological Region JJA mean-rainfall

	Pearson's Correlation	RMSE	Hit Score	Bias	Mean absolute error
South Central	-0.67	0.1475	77%	0.19	1.16

The scatter plot of observed and CPT-generated South Central hydrological region JJA mean-rainfall for selected BMD station during the period of 1981-2010 is shown in Fig. 5.14. The value of R^2 is found 0.892.

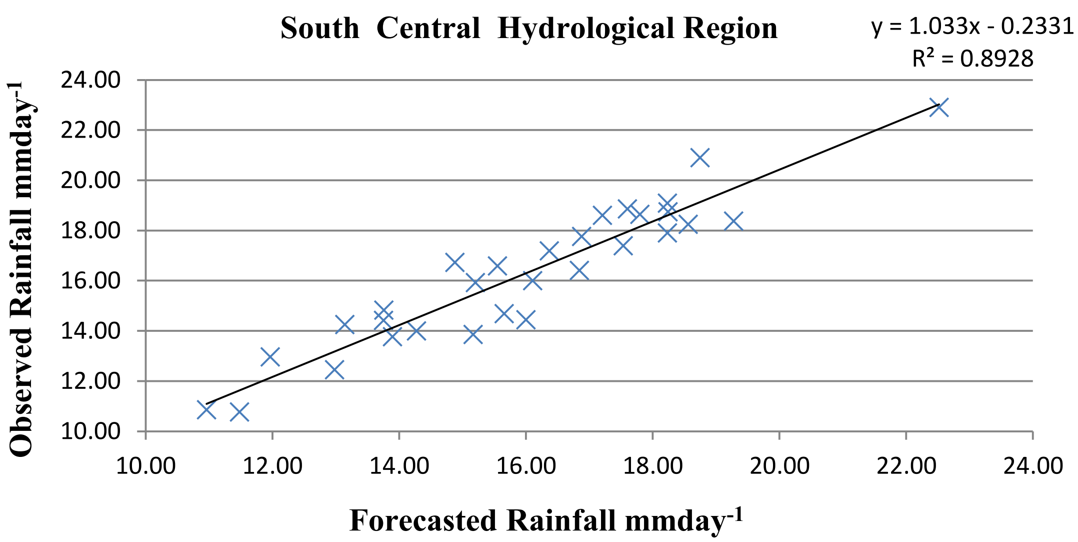

Fig. 5.14 Scatter plot of observed and CPT-generated South Central Hydrological region JJA mean-rainfall during 1981-2010 period

Coefficients of linear regression model for calibration of CPT generated for South Central Hydrological region JJA rainfall forecasts are tabulated in the Table 5.12. It also shows CPT generated and observed JJA rainfall for 2011. CPT generated forecast

JJA mean rainfall 12.91 mm/d for 2011 and observed JJA mean rainfall 13.88 mm/d for 2011.

Table 5.12: Coefficients of the linear regression model for JJA mean-rainfall for South Central Hydrological Region with the forecast and observed rainfall of JJA 2011

Hydrological Region	m (Gradient)	C (Intersect) mm day^{-1}	CPT-Generated JJA mean-rainfall for 2011 mm day^{-1}	Observed JJA mean rainfall for 2011 mm day^{-1}	Difference mm day^{-1}
South Central	1.033	-0.233	12.91	13.88	0.97

The Fig. 5.15 shows the observed JJA mean-rainfall of South Central Hydrological Region during the period 1982-2009 together with the calibration during 1981-2009, validation for 2010 and projection for 2011. Decreasing trend of South Central Hydrological Region monsoon rainfall during JJA season was found in Fig. 5.15.

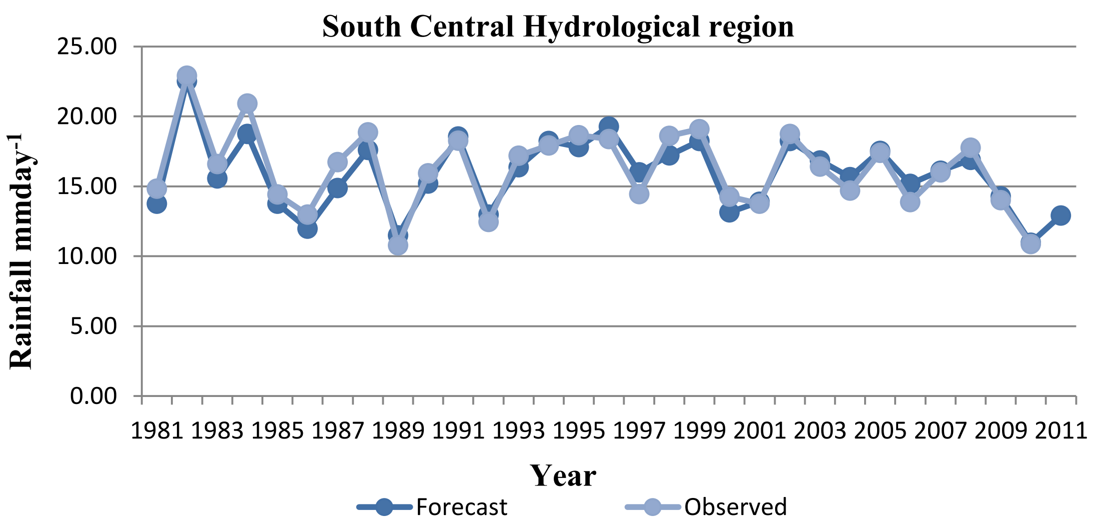

Fig. 5.15 Observed South Central Hydrological Region mean-rainfall of JJA during 1981-2009 with calibration during 1981-2009, validation for 2010 and projection for 2011.

5.2.6 South East Hydrological Region

Some statistics viz. Pearson's correlation, RMSE, Hit Score, Bias, etc. of the trained CPT model for JJA mean-rainfall of South East Hydrological Region is shown in Table 5.13.

Table 5.13: Some statistics of the 30 years trained model South East Hydrologic Region JJA mean-rainfall

Hydrological Region	Pearson's Correlation	RMSE	Hit Score	Bias	Mean absolute error
South East	-0.8	0.94	74%	0.06	1.425

The scatter plot of observed and CPT-generated South East hydrological region JJA mean-rainfall for selected BMD station during the period of 1981-2010 is shown in Fig. 5.16. The value of R^2 is found 0.895.

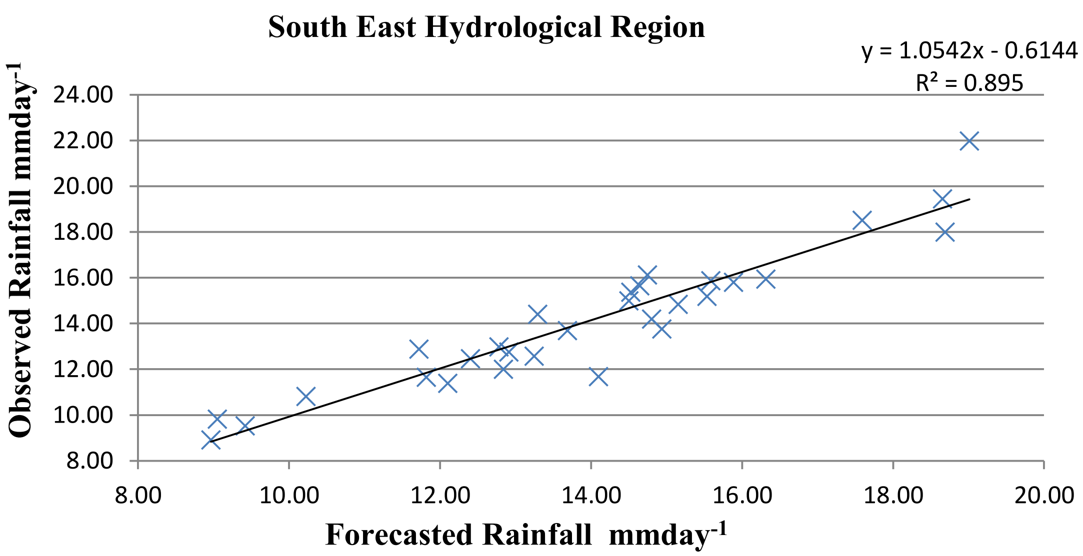

Fig. 5.16: Scatter plot of observed and CPT-generated South East JJA mean-rainfall during 1981-2010 period.

Coefficients of linear regression model for calibration of CPT generated for South East Hydrological region JJA rainfall forecasts are tabulated in the Table 5.14. It also shows CPT generated and observed JJA rainfall for 2011. CPT generated forecast JJA mean rainfall 14.73 mm/d for 2011 and observed JJA mean rainfall 14.11mm/d for 2011.

Table 5.14 Coefficients of the linear regression model for JJA mean-rainfall for South East Hydrological Region with the forecast and observed rainfall of JJA 2011

Hydrological Region	m (Gradient)	C (Intersect) mm day^{-1}	CPT-Generated JJA mean-rainfall for 2011 mm day^{-1}	Observed JJA mean rainfall for 2011 mm day^{-1}	Difference mm day^{-1}
South East	1.054	0.614	14.73	14.11	-0.62

The Fig. 5.17 shows the observed JJA mean-rainfall of South East Hydrological Region during the period 1982-2009 together with the calibration during 1981-2009, validation for 2010 and projection for 2011. Decreasing trend of South East Hydrological Region monsoon rainfall during JJA season was found in Fig. 5.17.

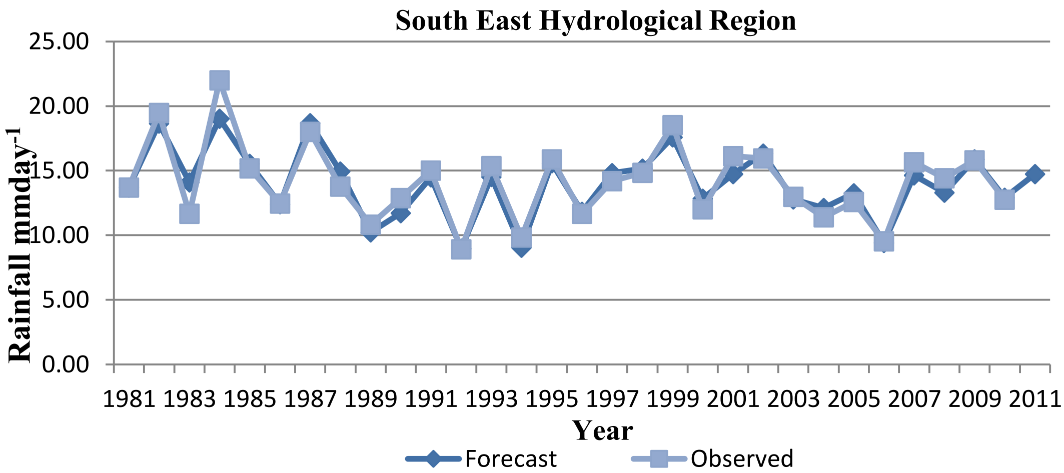

Fig.5.17 Observed South East Hydrological Region mean-rainfall of JJA during 1981-2009 with calibration during 1981-2009, validation for 2010 and projection for 2011.

5.2.7 Eastern Hill Hydrological Region

Some statistics viz. Pearson's correlation, RMSE, Hit Score, Bias, etc. of the trained CPT model for JJA mean-rainfall of Eastern Hill Hydrological Region is shown in Table 5.15.

Table 5.15: Some statistics of the 30 years trained model Eastern Hill Hydrologic Region JJA mean-rainfall

Hydrological Region	Pearson's Correlation	RMSE	Hit Score	Bias	Mean absolute error
Eastern Hill	-0.73	1.47	70%	0.19	1.12

The scatter plot of observed and CPT-generated Eastern Hill Hydrological Region JJA mean-rainfall for selected BMD station during the period of 1981-2010 is shown in Fig. 5.18. The value of R^2 is found 0.821.

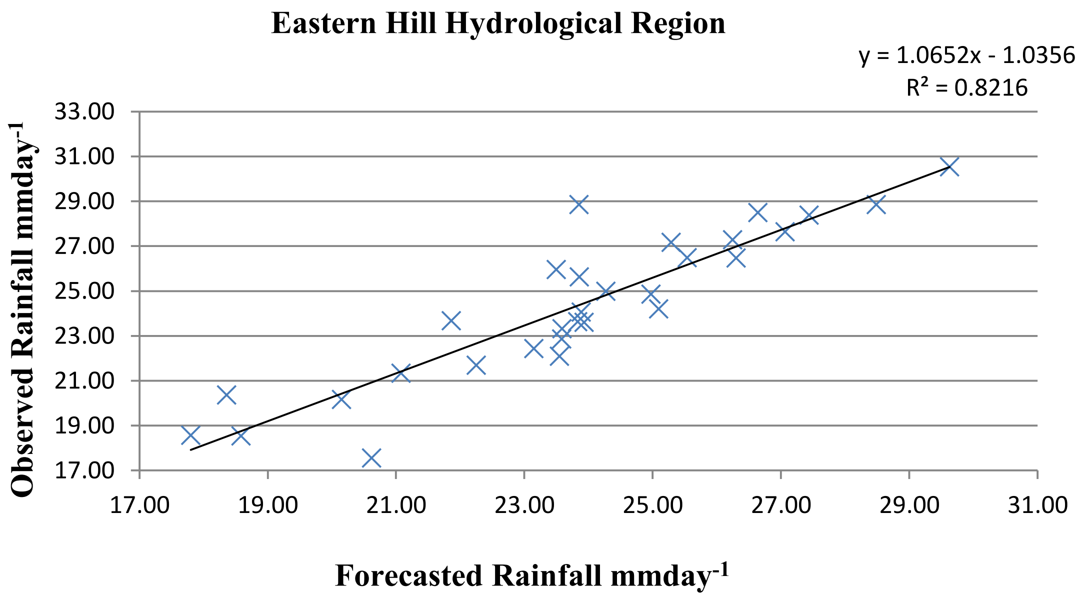

Fig. 5.18 Scatter plot of observed and CPT-generated Eastern Hill JJA mean-rainfall during 1981-2010 period

Coefficients of linear regression model for calibration of CPT generated for Eastern Hill Hydrological region JJA rainfall forecasts are tabulated in the Table 5.16. It also shows CPT generated and observed JJA rainfall for 2011. CPT generated forecast JJA mean rainfall 21.50 mm/d for 2011 and observed JJA mean rainfall 21.33 mm/d for 2011.

Table 5.16 Coefficients of the linear regression model for JJA mean-rainfall for Eastern Hill Hydrological Region with the forecast and observed rainfall of JJA 2011

Hydrological Region	m (Gradient)	C (Intersect) mm day^{-1}	CPT-Generated JJA mean-rainfall for 2011 mm day^{-1}	Observed JJA mean rainfall for 2011 mm day^{-1}	Difference mm day^{-1}
Eastern Hill	1.054	0.614	21.50	22.37	0.87

The Fig. 5.17 shows the observed JJA mean-rainfall of Eastern Hill Hydrological Region during the period 1982-2009 together with the calibration during 1981-2009, validation for 2010 and projection for 2011. Increasing trend of Eastern Hill Hydrological Region monsoon rainfall during JJA season was found in Fig. 5.19.

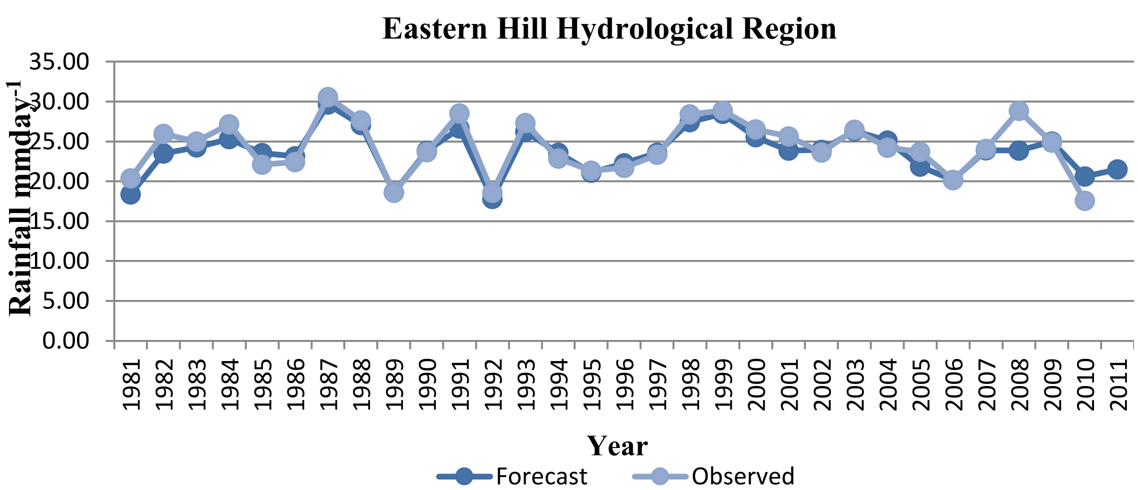

Fig. 5.19 Observed Eastern Hill Hydrological Region mean-rainfall of JJA during 1981-2009 with calibration during 1981-2009, validation for 2010 and projection for 2011.

5.2.8 River & Estuary Hydrological Region

Some statistics viz. Pearson's correlation, RMSE, Hit Score, Bias, etc. of the trained CPT model for JJA mean-rainfall of River & Estuary Hydrological Region is shown in Table 5.17.

Table 5.17 Some statistics of the 30 years trained model River & Estuary Hydrologic Region JJA mean-rainfall

Hydrological Region	Pearson's Correlation	RMSE	Hit Score	Bias	Mean absolute error
River & Estuary	-0.56	1.29	55%	0.05	1.56

The scatter plot of observed and CPT-generated River & Estuary Hydrological Region JJA mean-rainfall for selected BMD station during the period of 1981-2010 is shown in Fig. 5.20. The value of R^2 is found 0.730.

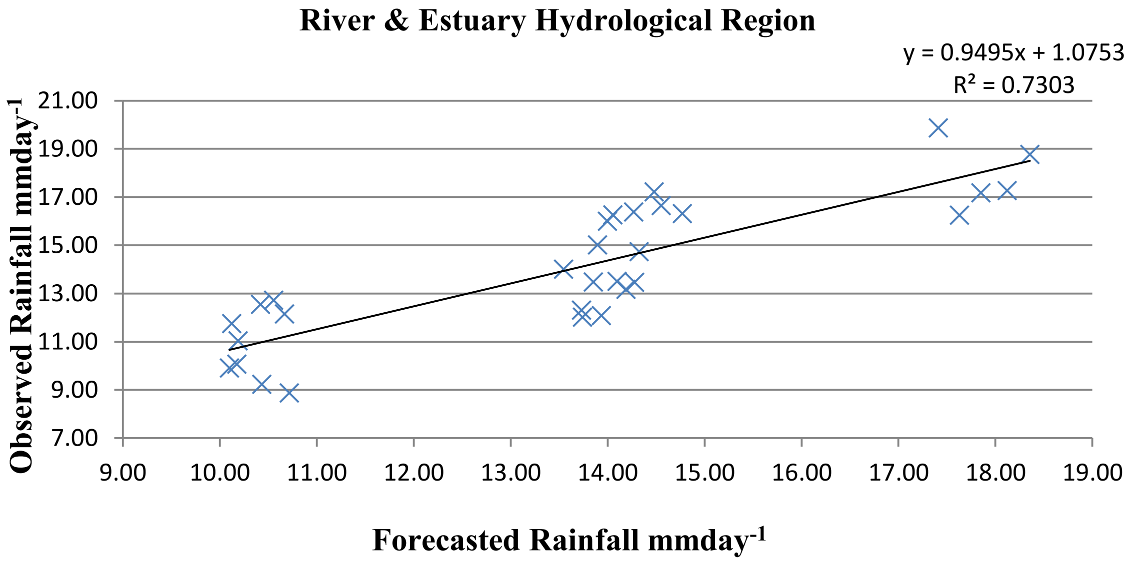

Fig. 5.20 Scatter plot of observed and CPT-generated River & Estuary JJA mean-rainfall during 1981-2010 period.

Coefficients of linear regression model for calibration of CPT generated for River & Estuary Hydrological region JJA rainfall forecasts are tabulated in the Table 5.18. It also shows CPT generated and observed JJA rainfall for 2011. CPT generated forecast

JJA mean rainfall 10.04 mm/d for 2011 and observed JJA mean rainfall 12.33 mm/d for 2011.

Table 5.18 Coefficients of the linear regression model for JJA mean-rainfall for River & Estuary Hydrological Region with the forecast and observed rainfall of JJA 2011

Hydrological Region	m (Gradient)	C (Intersect) mm day^{-1}	CPT-Generated JJA mean-rainfall for 2011 mm day^{-1}	Observed JJA mean rainfall for 2011 mm day^{-1}	Difference mm day^{-1}
River & Estuary	0.949	1.075	10.04	12.33	2.29

The Fig. 5.21 shows the observed JJA mean-rainfall of River & Estuary Hydrological Region during the period 1982-2009 together with the calibration during 1981-2009, validation for 2010 and projection for 2011. Decreasing trend of River & Estuary Hydrological Region monsoon rainfall during JJA season was found in Fig. 5.21.

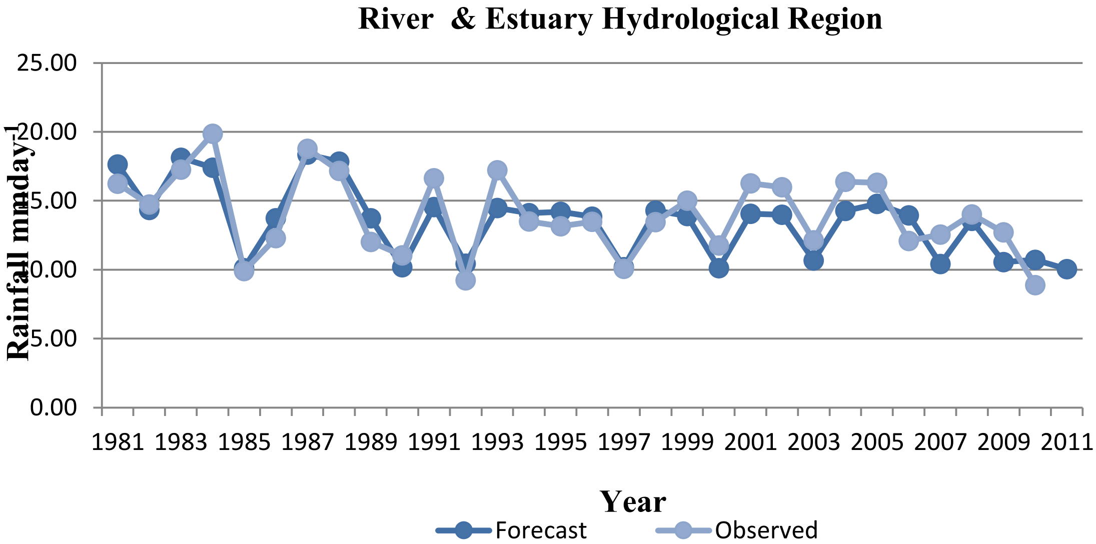

Fig.5.21: Observed River & Estuary Hydrological Region mean-rainfall of JJA during 1981-2009 with calibration during 1981-2009, validation for 2010 and projection for 2011.

5.3 Comparison of Different Hydrological Regions

Rainfall dataset was collected from BMD, which was analyzed with Kriging interpolation method to calculate the aerial mean precipitation over Bangladesh. The predictor variables of CGCM model was found highly correlated with predictand variables, where the goodness of the model was 0.355.

Correlation between observed and CPT- generated all-Bangladesh JJA mean-rainfall during the period of 1981-2010 was strong (R^2=0.908) (Fig 5.2). The study findings are consistent with the findings of SMRC (2010), who also found strong correlation (R^2=0.9) between observed and CPT-generated all-Bangladesh JJA mean rainfall [14]. In addition, very strong correlation (R^2=0.986) was found between observed and CPT-generated all-Bangladesh JJA mean rainfall during the period of 1981-2010. JJA mean rainfall of observed datasets of 27 stations was 14.11 mm/d in 2011, whereas, CPT generated forecast was 13.82 mm/d (Table 5.2). The study findings are in agreement with the findings of SMRC (2010), who found very less difference (-0.08 mm/d) between observed and forecast JJA mean rainfall [14].

Hydrological regions based mean-monsoon rainfall was calculated from daily values followed by monthly, yearly total at each station and average of different stations. In case of North West hydrological region, strong correlation (R^2=0.89) was found between observed and CPT-generated JJA mean rainfall during the period of 1981-2010. Observed JJA mean rainfall (10.11 mm/d) in North West hydrological region in 2011 was higher compared to CPT-generated forecast (9.05 mm/d).

The correlation between observed and CPT-generated JJA mean rainfall during the period of 1981-2010 in North Central Hydrological region was also found strong (R^2=838) (Fig. 5.8). Observed JJA mean rainfall (12.89 mm/d) in North Central hydrological region in 2011 was lower compared to CPT-generated forecast (13.84 mm/d) (Table 5.6). The monsoon rainfall during JJA season in North Central hydrological region was in increasing trend whereas, in North West hydrological region decreasing trend observed.

The correlation between observed and CPT-generated JJA mean rainfall during the period of 1982-2009 in North East Hydrological region was found strong (R^2=0.693) (Fig. 5.10). Observed JJA mean rainfall (18.66 mm/d) in North East hydrological region in 2011 was lower compared to CPT-generated forecast (19.49 mm/d) (Table 5.8).

The correlation between observed and CPT-generated JJA mean rainfall during the period of 1981-2010 in South West Hydrological region was found strong (R2=0.795) (Fig. 5.12). Observed JJA mean rainfall (9.88 mm/d) in South West hydrological region in 2011 was higher compared to CPT-generated forecast (9.01 mm/d) (Table 5.10).

Observed and CPT-generated forecast of JJA mean rainfall in South Central Hydrological region during the period of 1981-2010 was highly correlated (R^2=0.892) (Fig. 5.14). Observed JJA mean rainfall (13.88 mm/d) in South Central hydrological region in 2011 was higher compared to CPT-generated forecast (12.91 mm/d) (Table 5.12). Monsoon rainfall during JJA season in South Central hydrological region was in decreasing trends over the study period (Fig. 5.15).

Observed and CPT-generated forecast of JJA mean rainfall in South East Hydrological region during the period of 1981-2010 was highly correlated (R^2=0.895) (Fig. 5.16). Observed JJA mean rainfall (14.11 mm/d) in South East hydrological region in 2011 was lower compared to CPT-generated forecast (14.73 mm/d) (Table 5.14). Monsoon rainfall during JJA season in South East hydrological region was in decreasing trends over the study period (Fig. 5.17).

The correlation between observed and CPT-generated JJA mean rainfall during the period of 1981-2010 in Eastern Hill Hydrological region was found strong (R^2=0.821) (Fig. 5.18). Observed JJA mean rainfall (21.33 mm/d) in Eastern Hill hydrological region in 2011 was slightly lower compared to CPT-generated forecast (21.50 mm/d) (Table 5.16). Monsoon rainfall during JJA season in Eastern Hill hydrological region was in increasing trends over the study period (Fig. 5.19).

The correlation between observed and CPT-generated JJA mean rainfall during the period of 1981-2010 in River & Estuary Hydrological region was found strong (R^2=0.730) (Fig. 5.20). Observed JJA mean rainfall (12.33mm/d) in River & Estuary hydrological region in 2011 was higher compared to CPT-generated forecast (10.04 mm/d) (Table 5.18). Monsoon rainfall during JJA season in Eastern Hill hydrological region was in decreasing trends over the study period (Fig. 5.21).

Table 5.19: The regional differences in the context of forecasting seasonal rainfall pattern

Hydrological Region	CPT- Generated JJA mean-rainfall for 2011 mm day^{-1}	Observed JJA mean rainfall for 2011 mm day^{-1}	Difference mm day^{-1} (%)
North West	9.05	10.10	1.05 (10.4%)
North Central	13.84	12.89	-0.95 (7.37%)
North East	19.49	18.66	-0.83 (4.45%)
South West	9.01	9.88	0.87 (8.80%)
South Central	12.91	13.88	0.97 (6.99%)
South East	14.73	14.11	-0.62 (4.39%)
Eastern Hill	21.50	22.37	0.87 (3.89%)
River & Estuary	10.04	12.33	2.29 (18.57%)

5.4 Conclusion

Calibrated JJA mean-rainfall during 1981-2011 is shown in Fig. 3-4 for eight hydrological region of Bangladesh. It also shows the observed JJA mean-rainfall during 1981-2011 together with forecast for the year 2011. Results reveal that forecasted rainfall of five stations is underestimated and three stations are overestimated over Bangladesh. All-Bangladesh observed and forecasted rainfall is almost same, where the forecasts are within the acceptable range.

CHAPTER VI
CONCLUSION AND RECOMMENDATION

6.1Conclusion

In the present study, sea surface temperature over the Indian Ocean region has shown potential to predict JJA mean-rainfall over Bangladesh as a whole and all hydrologic region of Bangladesh. Developing accurate and acceptable seasonal forecasts is a challenging task with any conventional method as the end users are much keen on site specific locations. Seasonal forecasting using high resolution dynamical downscaling technique is very much costly as it consumes very high computing resources. Therefore, this study attempts to utilize Model Output Statistics (MOS) technique for CGCM field variables to develop regression based statistical interface for providing economical seasonal weather forecasts for all hydrological region of Bangladesh.

In general, predictions are made in different time scales utilizing corresponding predictability sources. For an example, initial state of the atmosphere is of vital importance in predicting day-to-day weather forecasts in which predictability loses within a week or two due to chaotic nature of the atmosphere. Therefore, seasonal forecasts are conventionally done in detecting predictable signals of the concerned variables by avoiding associated noises. In some parts of the world, especially over the tropical region, inter-annual variability is very much influenced by the ENSO events in which sea surface temperature over the eastern equatorial Pacific plays a crucial role.

Bangladesh seems to be higher predictability skills for JJA monsoon prediction than the other seasons. The all Bangladesh annual monsoon rainfall was estimated for the period of 1980-2011 from eight hydrological Regions (27 BMD Stations) and was found 14.11mmday^{-1} .The annual monsoon rainfall at country level was found to be free of trend. However there are some significant changes in regional scales. The normal rainfalls in the months of JJA of monsoon have decreased. There are some regional variations in the monthly rainfall trends as well. It also shows the observed JJA mean-rainfall during 1981-2011 together with forecast for the year 2011. Results reveal that forecasted rainfalls of three hydrological regions are overestimated and five hydrological regions are underestimated over Bangladesh. All-Bangladesh observed and forecasted rainfall is almost same, where the forecasts are within the acceptable range.

Main findings of the study listed below:

1) Correlation between observed and CPT- generated all-Bangladesh JJA mean-rainfall during the period of 1981-2010 was strong (R^2=0.908).
2) JJA mean rainfall of observed datasets of 26 stations was 14.11 mm/d in 2011, whereas, CPT generated forecast was 13.82 mm/d.
3) In case of northwest hydrological region, strong correlation (R^2=0.89) was found between observed and CPT-generated JJA mean rainfall during the period of 1981-2010. Observed JJA mean rainfall (10.11 mm/d) in northwest hydrological region in 2011 was higher compared to CPT-generated forecast (9.05 mm/d).
4) The correlation between observed and CPT-generated JJA mean rainfall during the period of 1981-2010 in north central hydrological region was also found strong (R^2=0.84). Observed JJA mean rainfall (12.89 mm/d) in north central hydrological region in 2011 was lower compared to CPT-generated forecast (13.84 mm/d).
5) The correlation between observed and CPT-generated JJA mean rainfall during the period of 1982-2009 in north east hydrological region was found moderately strong. Observed JJA mean rainfall (18.66 mm/d) in north east hydrological region in 2011 was lower compared to CPT-generated forecast (19.49 mm/d).
6) The correlation between observed and CPT-generated JJA mean rainfall during the period of 1981-2010 in south west hydrological region was found strong (R^2=0.795).
7) In addition, the correlation between observed and CPT-generated JJA mean rainfall during the period of 1981-2010 in eastern hilly hydrological region was found significant (R^2=0.821).
8) The correlation between observed and CPT-generated JJA mean rainfall during the period of 1981-2010 in river & estuary hydrological region was found moderately strong (R^2=0.730) (Fig. 5.20). Observed JJA mean rainfall (12.33mm/d) in river & estuary hydrological region in 2011 was higher compared to CPT-generated forecast (10.04 mm/d) .

9) The monsoon rainfall during JJA season in north central, and eastern hilly hydrological region was in increasing trend whereas, in northwest, south central, and south east hydrological region decreasing trend observed.

6.2 Recommendations

Based on the aforementioned result and the experience gained during the study, the following recommendations are made.

a) There are many levels of uncertainties in forecast monsoon using CPT. Some of the results found from the CPT outputs in the study, as well reported in various literatures from others studies, appear to be inconsistent with existing monsoon trends in Bangladesh.
b) Monsoon depends on multidimensional variables. So if we can consider all other variables (such as surface temperature at 2m height, zonal winds of 850mb and 200mb, meridianal wind of 850mb, geopotential height of 500mb etc) during studies it may be possible to estimate more bias free JJA monsoon forecast for different hydrological region.
c) CPT seems to be an affordable tool for any Meteorological service, especially in the developing nations like Bangladesh.

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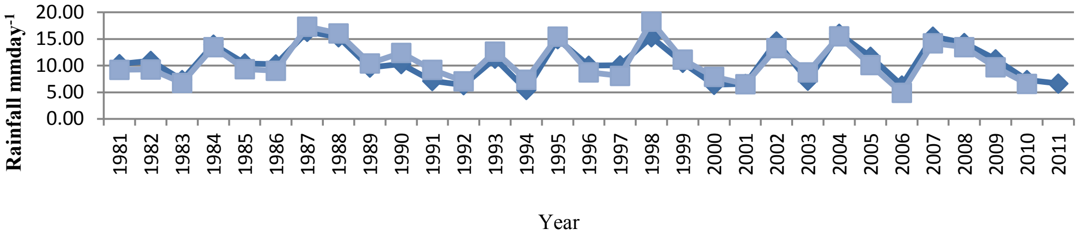
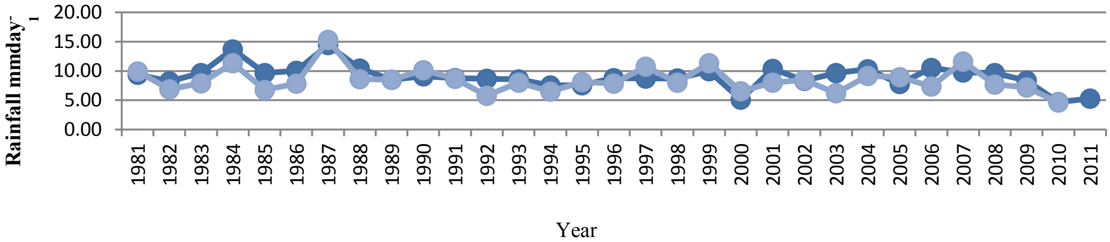
APPENDIX-1

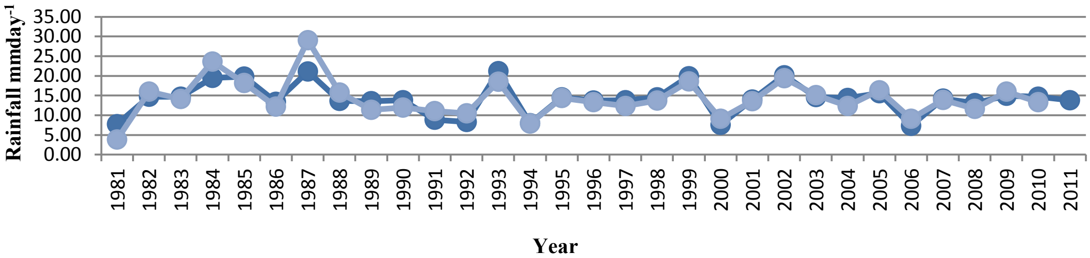
1) Observed **North-West** Hydrological Region BMD station based mean-rainfall of JJA during 1981-2009 with calibration during 1981-2009, validation for 2010 and projection for 2011



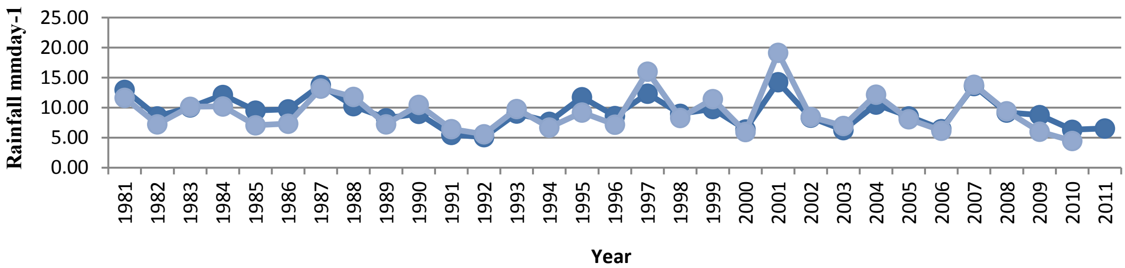
a) Bogra



b) Ishurdi

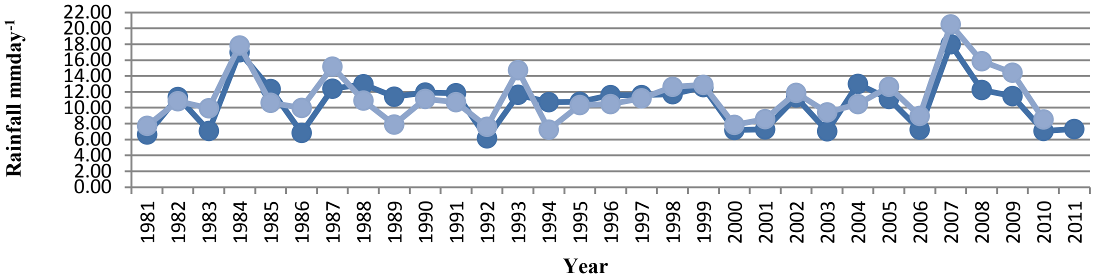


c) Rangpur

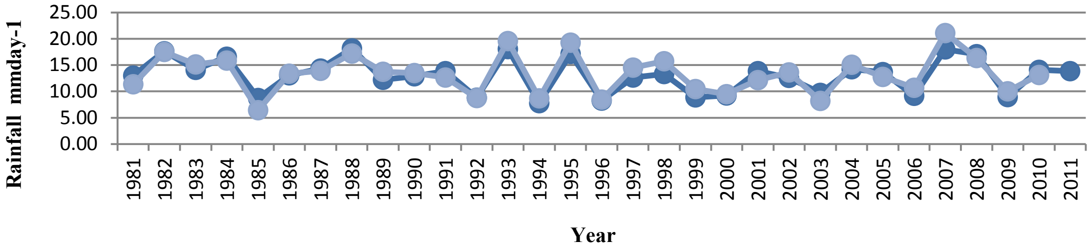


d) Rajshahi

2) Observed **North-Central** Hydrological Region BMD station based mean-rainfall of JJA during 1981-2009 with calibration during 1981-2009, validation for 2010 and projection for 2011

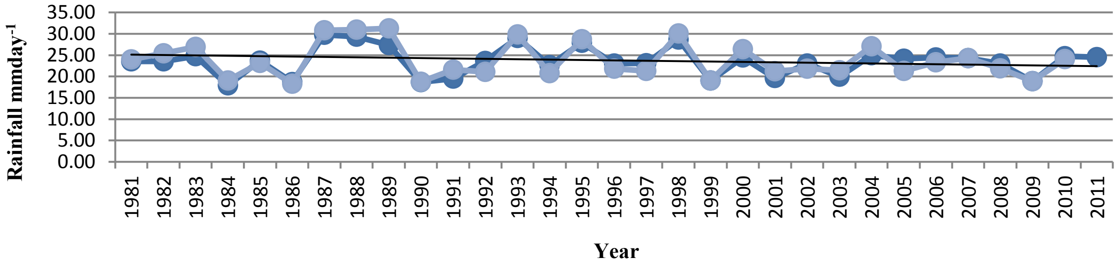


a) Dhaka

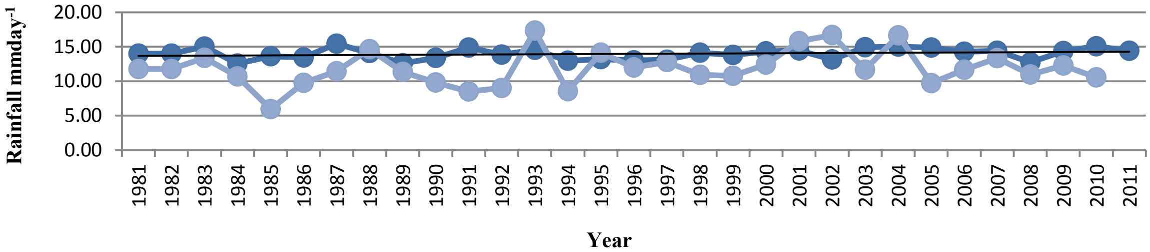


b) Mymensing

3) Observed **North-East** Hydrological Region BMD station based mean-rainfall of JJA during 1981-2009 with calibration during 1981-2009, validation for 2010 and projection for 2011



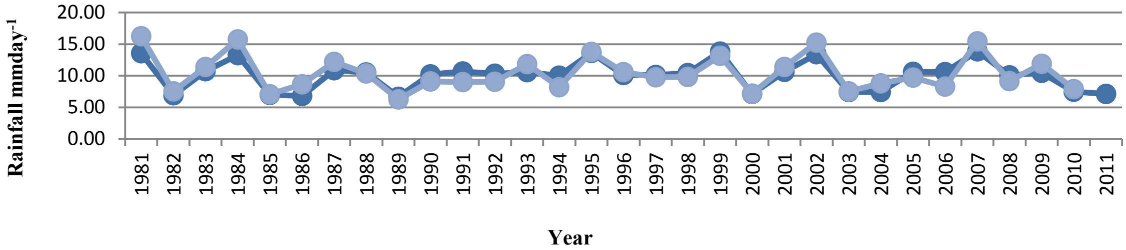
a) Shylet



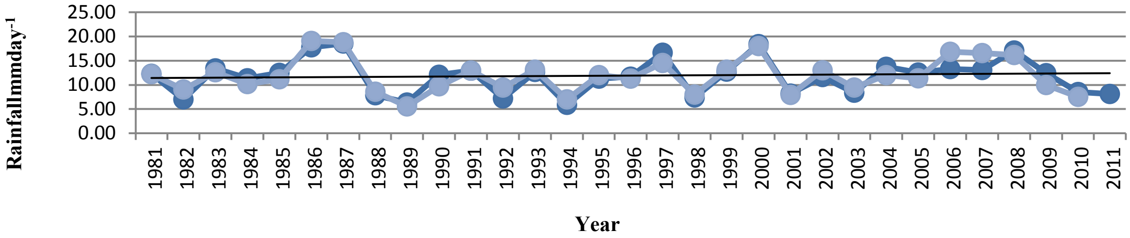
b) Srimongal

Forecast Observed

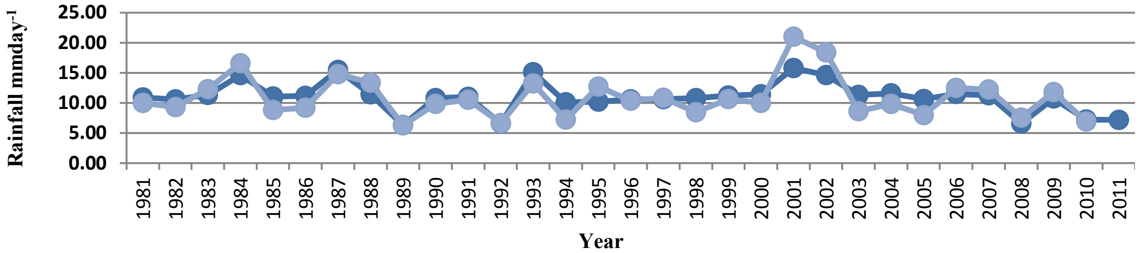
4) Observed **South-West** Hydrological Region BMD station based mean-rainfall of JJA during 1981-2009 with calibration during 1981-2009, validation for 2010 and projection for 2011



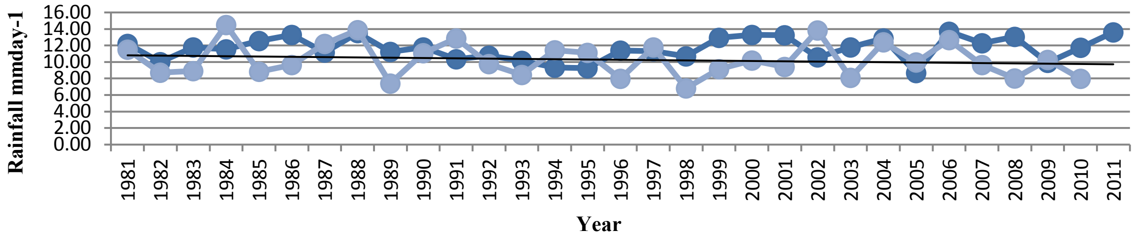
a) Faridpur



b) Jessore



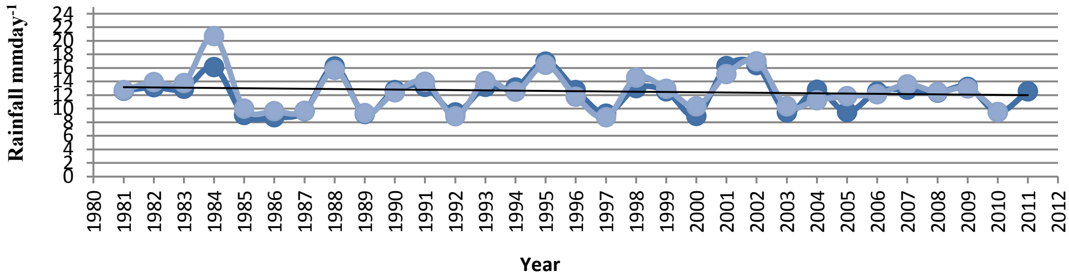
c) Khulna



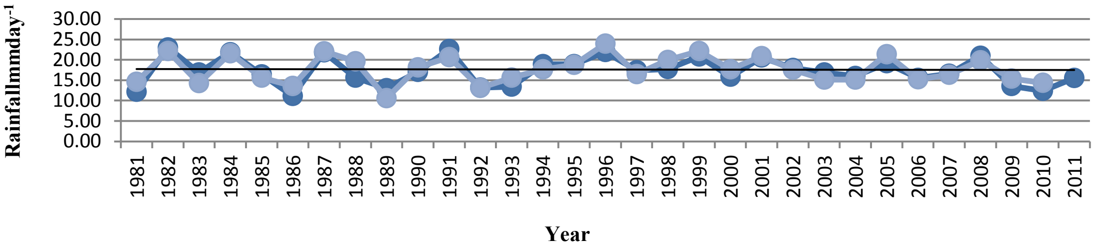
d) Satkhira

Forecast   Oberserved

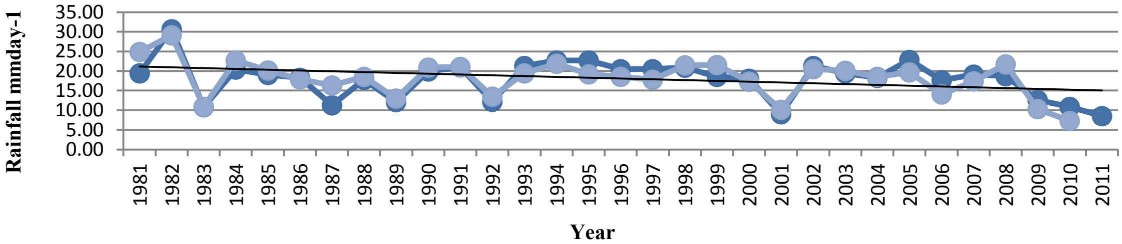
5) Observed **South-Central** Hydrological Region BMD station based mean-rainfall of JJA during 1981-2009 with calibration during 1981-2009, validation for 2010 and projection for 2011



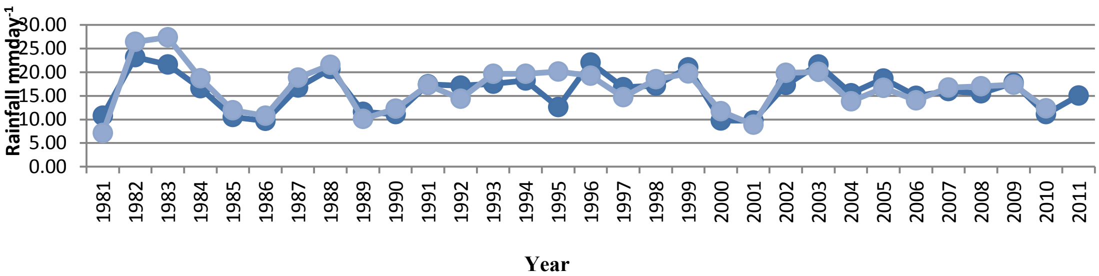
a) Barisal



b) Khepupara

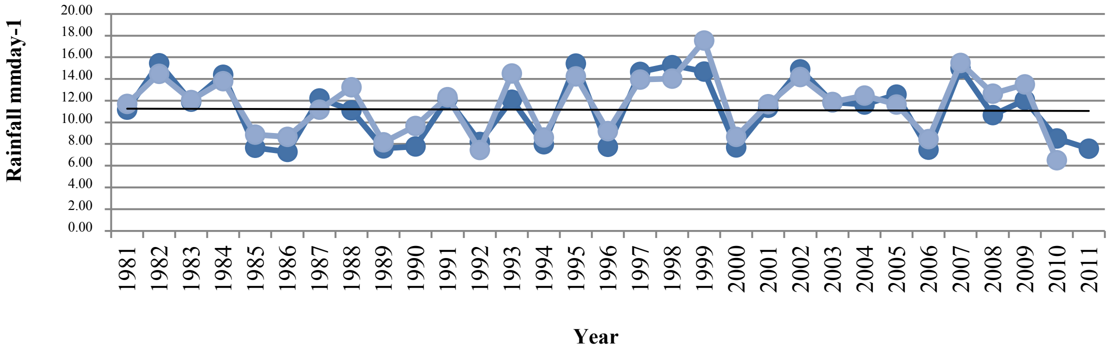


c) Madaripur

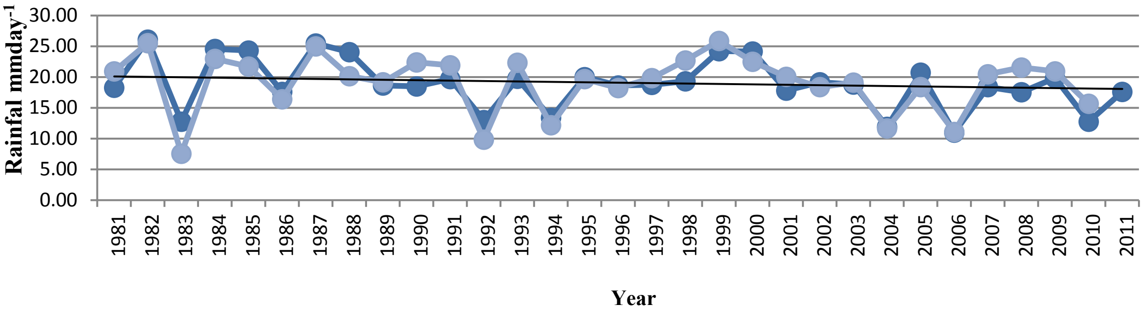


d) Patuakhali

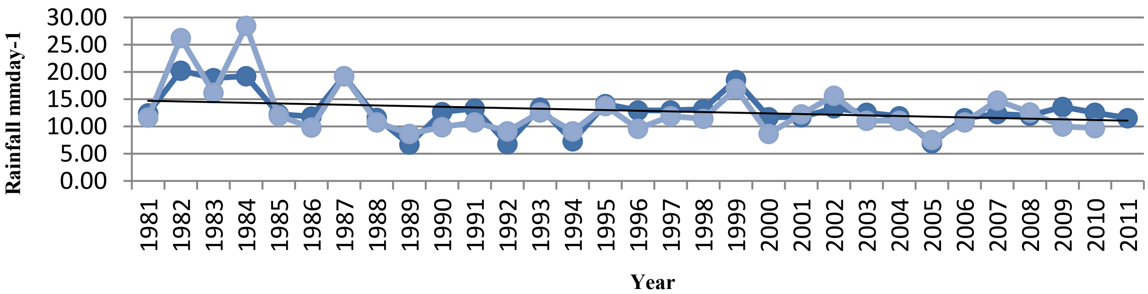
6) Observed **South-East** Hydrological Region BMD station based mean-rainfall of JJA during 1981-2009 with calibration during 1981-2009, validation for 2010 and projection for 2011



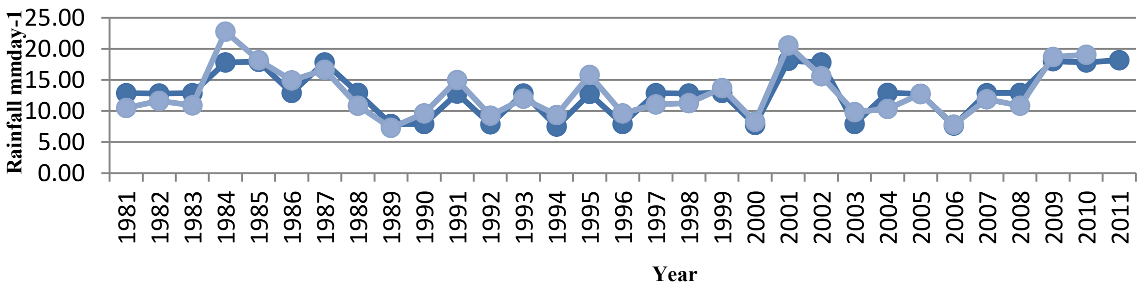
a) Comilla



b) Feni



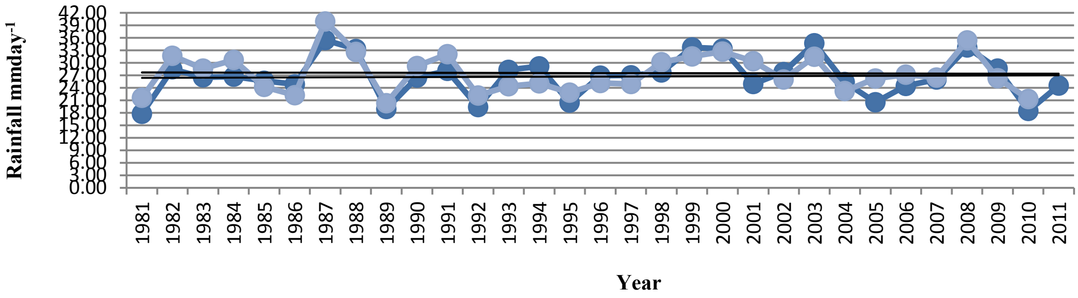
c) Chandpur



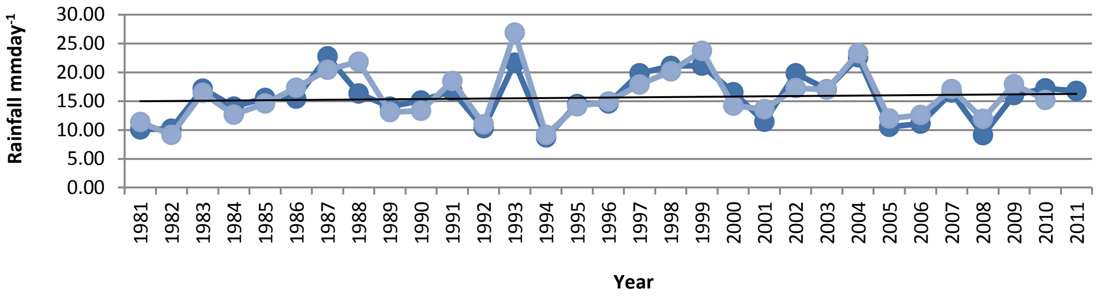
d) Maijdeecourt

Forecast Oberserved

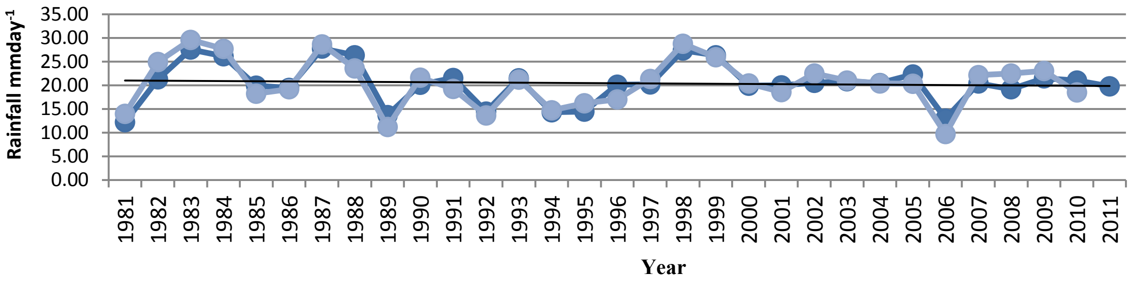
7) Observed **East Hill** Hydrological Region BMD station based mean-rainfall of JJA during 1981-2009 with calibration during 1981-2009, validation for 2010 and projection for 2011



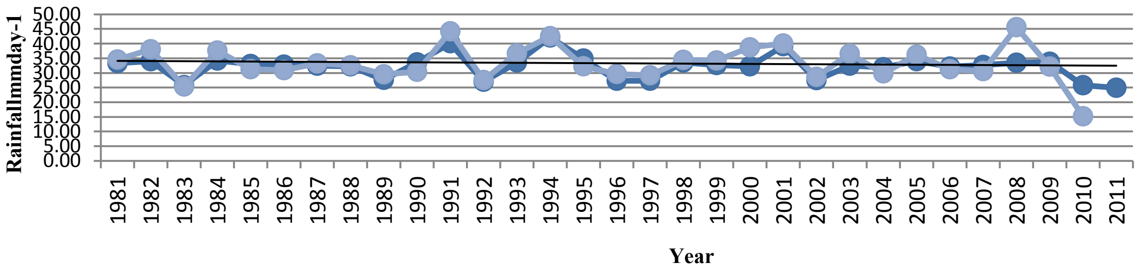
a) Cox's Bazar



b) Rangamati



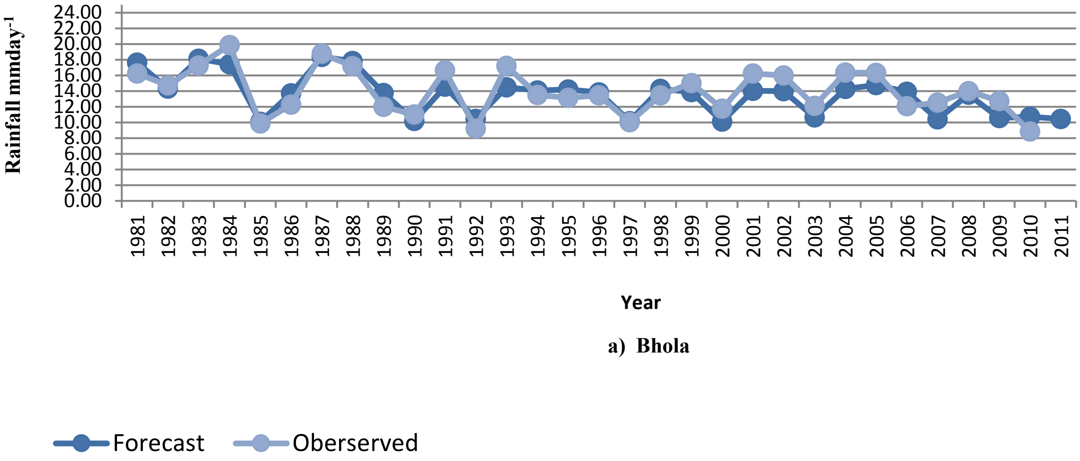
c) Sitakunda



d) Teknaf

Forecast Oberserved

8) Observed **River & Estuary** Hydrological Region BMD station based mean-rainfall of JJA during 1981-2009 with calibration during 1981-2009, validation for 2010 and projection for 2011



a) Bhola