SIMULATION OF RAINFALL AND TEMPERATURE USING REGIONAL CLIMATE MODEL IN BANGLADESH

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DECLARATION

This thesis work has been done by the candidate himself and does not contain any material extracted from elsewhere or from a work published by any body else. The work of this thesis has not been presented elsewhere by the author for any degree or diploma. No other persons work has been used or included without due acknowledgement.

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Abstract

The Regional Climate Model (RegCM) developed by ICTP, Italy is employed for the study of some meteorological parameters in and around Bangladesh. The validation of RegCM model in Bangladesh is performed with the surface observational data of rainfall and temperature (maximum and minimum) collected by the Bangladesh Meteorological Department (BMD) at 26 observational sites throughout the country from 1982-1989 are processed to calibrate model output. From the analysis it is found that regional analysis provides overestimation of RegCM values in Bangladesh whereas data extracted at some particular locations provide better performance of RegCM. The act of comparison has made between model and observational data at a wide spatial domain for a few scales (daily, monthly, seasonal and yearly). It is indispensable to do some conclusion of RegCM model outputs with the ground based data say rain-gauge rainfall and surface air temperature to choose the RegCM for this region. The RegCM model is run at 0.54°x0.54° horizontal grid resolution with the parameterization schemes of Grell and Fritsch-Chappell (GFC) assumptions where GFC system run is used in Lateral Boundary Conditions (LBCs) data for 1982-1989.

The Regional Climate Model (RegCM) data with well adapted with rain-gauge observational data for the Pre-monsoon (March – May). Monsoon (June- September) and Post-monsoon (October-November) seasons which has been conducted for the validation of rainfall over Bangladesh. For the case of temperature (maximum and minimum) daily data has been used for the validity check with model data in different seasons for the entire year.

It is observed that model overestimates in estimation of rainfall in Pre-monsoon and underestimates in Monsoon periods. For the entire rainy season (March – November), model estimates about 98% of the total surface rainfall for GFC assessment.

As Bangladesh is situated in the tropical belt and it has warm and humid climate in the summer and dry cool weather in the winter. Here three seasons are generally recognized: a hot, humid summer from March to June; a cool, rainy monsoon season from June to October; and a cool, dry winter from October to March. We see maximum summer temperatures range is 32°C to 38°C. April is the warmest month and January is the coldest month when the average temperature for most of the country is about 10°C.

Abbreviation

BATS: Biosphere-Atmosphere Transfer Scheme

CHRM: Climate High-Resolution Model

CRU: Climate Research Unit

CCRP: Climate Change Research Program

DTR: Diurnal Temperature Range

ECMWF: European Centre for Medium – Range Weather Forecasts

FIFE: First International Satellite Field Experiment

FCCC: Framework Convention on Climate Change

GrADS: Grid Analysis and Display System

GFC: Grill Fritsch and Chappell

GAS: Grill Arakawa and Schubert

GADS: The Global Aerosol Data Set

GBA: Grid Box Analysis

GCMs: Global Climate Models / General Circulation Models

GTS: The Global Telecommunication System

IPCC: The Intergovernmental Panel on Climate Change

LBC: Lateral Boundary Conditions

LTER: Long- Term Ecological Research

MM5: Mesoscale Model version 5

MODIS: Moderate Resolution Imaging Spectroradiometer

NCEP: National Centre for Environmental Prediction

NWP. Numerical Weather Prediction

NCDC: National Climate Data Center

OISST: Optimum Interpolation Sea Surface Temperature

OGCM: The Oceanic General Circulation Models

PIRCS: The Project to Inter-compare Regional Climate Simulation

PIER: Public Interest Energy Research Program

RFA: Regional Frequency Analysis

RCMs: Regional Climate/ Circulation Models

SST: Sea Surface Temperature

SOD: Summary -of- the Day

TRMM: Tropical Rainfall Measuring Mission

WWW: The World Weather Watch

CHAPTER 01

INTRODUCTION

The term weather is generally used to denote day to day variations in temperature, rainfall, snowfall, wind velocity, etc., experienced on the surface of the earth, whereas the term climate is used to describe the long-term observed, averaged data for any of the weather components for a particular time period which can also be several decades.

Weather may vary from day to day or week to week, whereas climate varies from season to season or year to year. Climate is dynamic by nature. It is highly influenced by a multitude of factors such as the change in earth's orbit, gaseous composition of the earth's atmosphere, changes in the surface of the earth, and human activities.

Natural and man-made activities are much influenced by weather and climate. The seasonal variation in the surface air temperature is important for understanding the impact of climate change on human activities.

Regional Climate Models (RCMs) share many of the same features as global climate models (GCMs) in terms of the parameterizations of their dynamics and physics though they are generally run at much higher spatial and temporal resolution. RCMs differ, however, in their need to assimilate lateral boundary and initial conditions from global models and / or reanalysis.

The precipitation or rainfall in tropic plays an important role in the global hydrological cycle, the tropical rainfall area and two-third of the global precipitation occurs in this tropics. Three-fourths of the energy that drifts atmospheric wind circulation comes from the latent heat released by tropical precipitation (Sellers, 1965; Hartman, 1994). Sometimes the presence of large amount of precipitation in space causes a unfortunate hazard to human beings. The risk can not be removed clearly because it is one of the most difficult atmospheric parameters present in space and time. It is especially different to measure precipitation over the oceans for the sake of surface based observations over most oceanic and underdeveloped land areas (Xie and Arkin, 1996). The actual amount of rainfall tender a partial solution from RegCM model output which is one of the limitations.

The tropical numerical weather prediction system is required to address these problems adequately. Much progress has been made in recent years in the development of numerical models for the low latitudes. The World Weather Watch (www), now supported by a variety of surface based and space based observing platforms, has considerably enhanced the observational data base for numerical modeling. The availability of faster computers has enabled as large volume of tests on analysis, initializations sensitivity to physical parameterization, and statistical evaluation of numerical weather prediction, resulting in an overall improvement in the skill of tropical dynamical models.

The numerical guidance products that are routinely available on the Global Telecommunication System (GTS) from the advanced global NWP (Numerical Weather Prediction) centers like ECMWF (European Center for Medium Weather Forecasts) and NCEP (National Center for Environment Prediction). Global models have the obvious advantage of dispensing with the need for lateral boundary conditions, which are invariably required for running a limited area model. While global models can provide good forecasts of large scale weather systems, the regional models have their own place in the field of NWP modeling.

A limited area numerical weather prediction model based on Florida States University (Krishnamurti et al., 1990) has been implemented in the SAARC Meteorological Research Center (SMRC), Dhaka for NWP research. Various versions of this model have been used in tropical prediction experiments by Krishnamurti et al. (1979, 1987) Krishnamurti and Ramanathan (1982).

The above model has been used in the present work for several case studies of heavy rainfall and movement of monsoon depressions during the summer monsoon season The cases chosen for experiments are in respect of some heavy rainfall episodes in 1987 and 1998, the two most prominent excess rainfall and flood years in Bangladesh, as also some cases of monsoon depressions originating in the Bay of Bengal in regard to their exceptional behavior. We describe in the basic frame work of the FSU model which provides some general information on the principal rain bearing systems the seasonal monsoon trough and the monsoon depressions of the southwest monsoon in the Indian subcontinent. A brief description of the data and methodology is given in table - 01. Results of case studies are presented in figure- 5. Table-01 gives concluding remarks.

The limited area models used for forecasting in limited space domains essentially need specification of lateral conditions. Numerical treatment of lateral boundary is a difficult but important aspect of limited area modeling as the flow in the interior of the domain gets influenced by changes outside the domain. The influence is important even in short range forecasting for a couple of days. In the present model we make use of the time dependent boundary conditions.

1.1 Climate Change

The earth's climate, by nature, is a complex system consisting of oceans, atmosphere, land surface and vegetation, which respond to influences of various time scales. Oceans are generally influenced on time scales of years to centuries, whereas atmosphere, which is defined as a blanket of air surrounding the earth, may change on a daily basis and vegetation changes on a seasonal time scale. Earth experiences changes in its climate continuously. Due to enormous increase in population and the advancement in the technology founded on carbon-based fuels there has been a significant change in global climate. Climate change is directly linked to the increase in the green house gas concentration, caused by human activities (IPCC, 2001a). Climate change does not necessarily mean that all regions experience a uniform change with respect to the direction and magnitude, but there may be regional variations. Also climate change may not imply that all successive years will necessarily have the same trend of increase or decrease.

1.2 Effects of Climate Change

Prediction of weather is important because it gives us a snap shot picture of climate which is helpful in many ways. It helps agriculture, industries, and long term planning of hydraulic structures and also in planning large domestic construction projects, such as roads, bridges, etc. Furthermore it is helpful in quantifying global warming and in mitigating it. Until recent years green house gases in the atmosphere were attributed primarily to the emission of carbon dioxide generated by fuel, but in recent years the role of trace gases has been recognized to be equally important. The knowledge about the change in temperature offers an insight into the impact of increasing CO_2 concentrations. Estimates of possible regional changes in the climate due to the increase of atmospheric CO_2 are required to evaluate the impact on various social and economic activities. Global warming has become one of the most alarming issues these days. The global change adversely impacts terrestrial and aquatic ecosystems. Some of the most important economic resources, such as agriculture, forestry, fisheries, and water resources may also be affected. Increased temperature, severe and frequent droughts and floods, and sea level rise would have huge impacts on human life and economic well being. Based on statistical evidence, the average global surface air temperature has increased by 0.6°C between 1860 and 2000 (IPCC, 2001). The increased global carbon dioxide emissions are mainly due to the energy burnt to run automobiles, power factories and heat homes and businesses.

Measurements of seasonal variations in the surface air temperature are important for better understanding of the impact of climate change on human activities. Although natural factors may have contributed to the temperature increase in the 20th century, studies indicates that warming in the last 50 years may be due to increases in the greenhouse gas concentration (Elaine and Rick, 2000). The major contributing factor for the climate change may be anthropogenic changes, which result in the decrease in the extent of snow cover and sea-ice thickness. Direct information can also be obtained from the instrumental records, such as average temperature. It is also noted that due to the thermal expansion of oceans, over the past century, global average sea level has been increasing by about 1 to 2 millimeter per year (Elaine and Rick, 2000). Even without the influence of anthropogenic factors climate may vary from year to year due to natural reasons, such as volcanic eruptions. In the past, the main reason for the change in the ecosystem was considered to be the human intervention, but now the influence of climate change on the ecosystem has been established (Beaubien and Freeland, 2000).

1.3 Evaluation of Climate Change

The most reliable tool for estimating change in the atmosphere is General Circulation Models (GCMs). General Circulation Models are numerical models that analyze the atmosphere on an hourly basis which is very small time slots in all three spatial dimensions based on the law of conservation of mass, momentum and conservation of energy. These models are complex computer simulations describing the circulation of air and ocean currents and how the energy is transported within a climate system. The best available GCMs for estimating the climate show that the annual global surface air temperature may increase at a rate of 2.5K to 4.5K due to the doubling of carbon dioxide concentration in the atmosphere (Grotch and MacCracken, 1990).

Some of them are listed below:

1. There is a possibility of having more hot days and higher temperatures in almost all land areas.

2. There is a possibility of having a few cold days and very low minimum temperatures in almost all land areas.

3. There is a greater risk to natural ecosystems and wetlands due to these changes.

4. Due to the increase in sea level, there will be greater potential loss of land erosion due to and flooding resulting in the damage of wetlands in coastal areas. With increasing global warming, people are concerned about these effects on local areas. Some of the basic observations are daily maximum and minimum temperature.

5. Temperatures and daily precipitation sometimes have localized features that may be difficult to produce with the current coarse spatial resolution of the GCMs. Many of these shortcomings can be overcome by considering local topography and regional geography. By observing the local climate and comparing it with the output of GCMs, we can improve the capabilities of current GCMs and have an understanding the local climate. Considerable attention is given to test the ability of GCMs to reproduce the observed data. The very important issue concerning this verification is the ability of GCMs to reproduce observed regional and local climates. Some of the difficulties in comparing the local climate with the climate generated from the GCMs control run are:

a. Since local surface based observations are highly influenced by the local Topography and geography, it is difficult to relate them.

b. There is always an uncertainty in the interpretation of the area represented by a GCM output at a grid point.

c. GCMs filter the important spatial discontinuities in the surface boundary due to coarse spatial resolutions.

For these reasons, it is important to understand the climate change on a local basis. In spite of the above difficulties, there are reasons why comparisons between the outputs of a control run from GCMs and the local observed data should be made. These reasons are:

1. Improved GCMs will give us a better understanding of their ability to reproduce local climate.

2. The impact of climate change occurs due to certain technological and socioeconomic issues, which are specific to local areas.

3. It is important to understand how well GCMs reproduce day-to-day weather transitions, which can be more accurately accomplished considering daily variations in the local weather.

4. As of now the validation has been confined to large-scale features and larger time scales. However, there is a growing need for this kind of information on smaller regional scales. Atmospheric events have a range of spatial and temporal scales. Meteorological variables, such as temperature, precipitation, and wind, at a particular location normally vary around the mean values from year to year, if they are not influenced by external agents, such as anthropogenic changes in the composition of the atmosphere.

Generally, global models have larger spatial resolutions of several hundred kilometers. The range of increase of temperature is estimated on a global scale but the range in increase of temperature varies drastically when applied to a smaller spatial feature. Hence there is a need for the regional estimation of various weather parameters.

As there is a need to simulate global climatic features, it is advantageous to have smaller regional scale changes to assess the potential impact of climate change.

The basic step for any study connected with the future climate should have a thorough analysis of current climate conditions and the possible variability. Many times current climate is referred to as the base line climate, which is taken as a 30-year reference climate defined by the World Meteorological Organization (WMO). This base line climate is important for many reasons, some of which are:

1. The ongoing trends in the climate can be easily identified.

2. Knowing the prevailing conditions helps us to adapt some of the most likely features for future design.

3. The base line climate is useful to describe the average conditions, spatial and temporal variability and extreme events that have occurred.

1.4 Objectives of the Study

The Regional Climate Model (RegCM) is employed for the study of some meteorological parameters. But model products have no consistence with the real observations. To make model product useful, the first and foremost thing is to do the validation. Once the model data is validated and calibrated it can be used to make climate scenario. There are lots of data collecting methods or observational facilities of climate parameters. Some of these are polar orbiting and geostationary satellites, radars, IRMM satellites etc. But these collection methods are not the real ones. In some cases they can estimate near to real ones. The actual scenario can be found by using thermometers, rain gauges located in a standard height from surface and standard condition defined by World

Meteorological Organization (WMO). But conventional instruments are not so sophisticated to calculate the parameters in a very small interval of time excepting RegCM Model. Therefore, to get the observation as much as small scale, model simulation is the best way subject to the validation or calibration. Bangladesh Meteorological Department (BMD) has the facility for collecting climate data in different parts of our country. But the density of stations is not uniform and high. In some areas data collection facilities are very rare. Therefore, climate change of those areas is not so well defined by the conventional observations. In this case RegCM model simulation is one of the best ways for making scenario. To make a good climate scenario (time and space domain) of Bangladesh, attempts has been made to run RegCM with different resolution and validate accordingly with the climate parameters collected by BMD.

1.5 The scope of the present work

The RegCM spatial resolution is fine enough to correctly represent climate processes of small dimensions such as the formation of clouds or thunderstorms, precipitations, evaporation and soil moisture.

The RegCM is a sub-model embedded within a worldwide or a GCM. Once the studied area is determined, it must be isolated on the GCM so that the conditions at the boundaries of the region can be determined. These conditions are then introduced in the RegCM, which will simulate the climate of the selected domain. Therefore, the regional simulation can take place over any region of the globe. The focus of present study is to adopt RegCM for the region in and around Bangladesh. Different meteorological variables such as rainfall, temperature obtained by RegCM are calibrated with available data from rain gauge and temperature.

The RegCM spatial resolution is adequate to evaluate the regional representations of climate changes. The outcome of RegCM research will contribute in operational sectors and government services which will benefit from the progress in climate modeling, e.g. meteorological and maritime previsions, as well as environmental status monitoring. Using the predicted range of precipitation and temperature it may be possible to formulate future panning for agriculture, water management etc.

To evaluate the RegCM model output like as rainfall and temperature with the ground based data of rainfall and temperature for the daily, monthly and seasonal (Pre-monsoon, Monsoon and Post-mosoon) for 8 years.

1.6 Temperature

Bangladesh is situated in the tropical belt and it has warm and humid climate in the summer and dry cool weather in the winter. Regional climate differences in this flat country are minor. Three seasons are generally recognized: a hot, humid summer from March to June; a cool, rainy monsoon season from June to October; and a cool, dry winter from October to March. In general, maximum summer temperatures range between 32°C and 38°C. April is the warmest month in most parts of the country. January is the coldest month, when the average temperature for most of the country is about 10°C.

The decrease of temperature during July and August is observed almost each year due to the high precipitation activities from the southwest monsoon. In these months of cloud coverage increases compared to the others months most of the years.

1.7 Rainfall

Bangladesh is situated in the most active zone of southwest monsoon Most of the precipitation 65% occurs in the monsoon season (June- September). Pre-monsoon receives about 20%, Post- monsoon receives 13% and winter receives 2% of the annual rainfall. The winter of Bangladesh is dry and cool.

Winds are mostly from the north and northeast 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 by local English speakers, 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.

Heavy rainfall is a characteristic of Bangladesh. With the exception of the relatively dry western region of Rajshahi, where the annual rainfall is about 1600 mm, most parts of the country receive at least 2000 mm of rainfall per year. Because of its location just north of the foothills of the Himalayas, where monsoon winds turn west and northwest, the region of Sylhet in northeastern Bangladesh receives the greastest average precipitation is about 4800 mm per years. Average daily humidity ranged from March lows of between 45 and 71 percent to July high of between 84 and 92 percent, based on readings taken at selected stations nationwide in 1986 (Source: http:// worldfact.us).

1.8 Verification of Climate Change

To validate and make climate scenario of Bangladesh simulation of RegCM model is very essential. To do this job RegCM model is run at Physics Department of BUET with the 0.54° x 0.54° horizontal grid resolution with the σ-levels of 23 vertically. After getting the output data, temperature data of 2m above ground (t2m) and precipitation data are extracted using GrADS. But before employed this model it is very essential to validate it.

But the validation of regional climate model in Bangladesh is performed with the surface observational data of rainfall and temperature (maximum and minimum) collected by the Bangladesh Meteorological Department (BMD) at 32 observational sites throughout the country from 1982-1989 are processed to calibrate model output. Here we found that regional analysis provides overestimation of RegCM values in Bangladesh whereas data extracted at some particular locations provide better performance of RegCM. The act of comparison has made between model and observational data at a wide spatial domain for a few scales (daily, monthly, seasonal and yearly).It is indispensable to do some conclusion of RegCM model outputs with the ground based data say rain-gauge and surface air temperature to choose the RegCM for this region. The Regional Climate Model (RegCM) is run at 0.54x0.54 horizontal grid resolution with Fritsch-Chappell (GFC) assumptions where GFC system run used in Lateral Boundary Conditions (LBCs) data for 1982-1989. Tropical storms strike the coast once in every four years on an average. As a result, many of the coastal wetlands are damaged and so also are the coastal aquatic systems. There is also an alarming rate of nearly 60 acres of loss for the wetlands per day due to increase in sea level, human interference with coastal processes and land sinking. Due to changes in global climate, impacts can be felt on human health and terrestrial aquatic ecosystems. This could result in serious social-economic consequences if this trend continues. There is therefore an urgent need to study the regional climate impacts, particularity for the coastal regions of Bangladesh. Various measures are being implemented in Bangladesh to protect coastal wetlands, reduce brown marsh problems and protect coastal aquatic life from the present and future danger. To make this study more effective one needs to have a clear idea about the future trends in climate.

1.9 Modern Climate Measurements

Here we compare the results of a modern day regional climate simulation to observation. The model simulation of present day conditions is similar in design to our 1xCO_2 and 2xCO_2 scenarios. CCM3 was run for 22 years forced with a single climatological year of SSTs (calculated from observation for the period 1950 to 1979).

The observational data used are historical weather station data collected by the western Regional Climate Center. The types of scope of data available vary depending on the climate characteristics of interest. For the analyses of seasonal temperature and precipitation we used climatological data calculated with a minimum of 22 years of data from the period 1971 to 2001. For the more specific analyses (DTR, growing season and extremes) the available data ranges from 27 to 100 years in length (on average 49.4 years) for the period 1901 to 2001. We began our analysis with ~ 26 stations and due to the shear volume of available data, narrowed it to stations where the actual and model derived elevations differed by no more than 100 meters. What remained were 16 stations representing a wide range of latitude, longitude and elevations across Bangladesh.

Overall the comparison between modern day regional model results and weather station data is very good. This is especially the case considering the data record is much longer than the model simulation and therefore provides a longer sample population. Furthermore the weather stations provide point data while the model results are derived from single grid cells with 40 km horizontal resolution. Still there are some issues the model results, especially for the DTR and the seasonality of precipitation.

The regional model adequately captures the seasonal changes in temperature as well as the annual mean temperature. On average the RCM is only 0.7°C cooler for the annual mean and no more than 2.4°C different seasonally than the observations (Table-1). The RCM more accurately captures the summer (JJAS) and fall (ON) temperature than the winter (DJF) and spring (MAM) temperatures. The DTR is too small by ~ 5 to 6°C annually and seasonally (Table-1) the growing season starts on average 16.5 days too soon and ends 13.8 days too late.

For extremes the model simulates ~ 28 too few hot (32.2°C) days /year and ~ 30° too few cold (0°C) days /year (Table-1). While the model simulates too few extreme events it does not overestimate the intensity of simulated extreme events. The historic 1- day events simulated by the model fall within the range of historic events in the longer observational record (Table-1)

The regional model outputs temperature twice a day at noon and midnight. These temperatures are used as proxies for the daily maximum and minimum and are not the actual maximum & minimum temperatures. As a result, the proxy maximum temperatures are too cool and the proxy minimum temperatures are too warm, producing a damped DTR.

Annually the regional model slightly overestimates total precipitation (3.8 cm/year) and poorly captures the seasonality of precipitation. The model overestimates winter & spring precipitation and underestimates summer and fall precipitation (Table-1). The model also simulates ~ 8 too many light rainfall days/year (< 1.27 cm / day). For moderate (1.27 to 2.54 cm /day) and heavier (> 2.54 cm /day) rainfall days the modal is much more accurate (Table -1). The model simulates one day too many per year of moderate precipitation and only 0.2 too many days/year of heavier rainfall.

Table-01: Comparison of observational (obs) parameters and simulated RegCM model output.

Components	Observed (obs)	RegCM (rcm)	Obs-rcm
TEMPERATURE			
Annual Mean (°C)	32.7	32.0	0.7
DJF (°C)	25.3	23.9	1.4
MAM (°C)	31.4	29.0	2.4
JJAS (°C)	34.4	34.8	-0.4
ON (°C)	33.6	34.1	-0.5
1-day max(°C)	39.1	35.1	4.0
1-day min (°C)	10	9.9	0.1
DTR			
Annual Mean (°C)	28.4	22.7	5.7
DJF (°C)	22.2	16.0	6.2
MAM (°C)	30.0	24.2	5.8
JJAS (°C)	33.3	28.4	4.9
ON (°C)	28.9	23.2	5.7
Precipitation			
Annual Mean (cm)	162.9	166.7	-3.8
DJF(cm)	26.6	22.0	4.6
MAM(cm)	82.1	84.8	-2.7
JJAS(cm)	210.8	209.1	1.7
ON(cm)	112.5	112.0	0.5
Light (days)	299.7	307.9	-8.2
Moderate (days)	246	247	-1.0
Heavy (days)	67.5	67.7	-0.2

Precipitation intensities are defined as: Light days < 1.27 cm, Moderate days < 2.54 cm and Heavy days> 2.54 cm.

Table -02: Changes in annual precipitation and frequency of 1-day extreme events.

Basins	1	2	3	4	5	6	7	8	9	10
Annual rainfall										
Rain/rain day (cm)	-0.02	0.00	-0.02	-0.02	-0.02	-0.04	-0.01	0.02	0.02	0.05
Rain (days/yr)	-4.6	-3.2	0.9	-5.1	-7.6	-4.7	-2.1	-8.1	-9.1	-7.5
Total rain (cm/yr)	-3.0	-0.4	-1.4	-3.4	-5.4	-8.1	-1.9	1.1	-3.3	1.7
Extreme wet events (P_{95})										
P_{95} Index (cm/day)	0.68	0.07	0.29	0.49	1.18	1.25	0.44	0.44	0.72	1.10
P_{95} (days/yr)	-3.2	-3.2	-2.6	-2.4	-2.1	-1.7	-3.0	2.8	-1.1	2.3

All values are calculated as 2xCO_2 results minus 1xCO_2 results. Values in bold type Indicate statistically significant results at the 95% confidence level (5% significance level). Farkka barrage is Basin-1, Tista barrage is Basin-2, Kaptai Lake is Basin-3, Shangu Lake is Basin-4, and so on .

• Precipitation intensities are defined as: light days, 1.27 cm, moderate days, 2.54 cm, and heavy days $ 2.54 cm. atures (SSTs) were used to drive a second set of CCM3 Simulations. These simulations, using the prescribed SSTs for the corresponding CO_2 concentrations, were run for 08 years and results were saved at 12-h intervals.

The first 4 years of each simulation were removed as equilibration time and the remaining 18 yr of results were used to drive the RCM. This study employs a modified version of the second generation NCAR Regional Climate Model (RegCM3) (Giorgi and Shields 1999) (hereafter referred to as RegCM3) as described by Snyder et al. (2002). RegCM3 was run with a horizontal resolution of 40 km and a domain centered over Bangladesh. We performed two 18-yr simulations with the first three years removed for equilibration. These simulations varied only in the specified atmospheric CO_2 concentrations (280 and 560 ppm).

Table -03: Changes in annual temperature and frequency of 1-day extreme events.

Basins	1	2	3	4	5	6	7	8	9	10
T_{max}(°C)	.08	2.31	2.58	1.99	2.39	2.38	1.95	2.66	2.59	2.47
T_{min} (°C)	1.99	2.24	2.40	1.93	2.22	2.26	1.97	2.51	2.43	2.33
T_{range} (°C)	0.09	0.07	0.18	0.06	0.17	0.12	-0.02	0.15	0.16	0.14
Hot events										
T_{95} Index (°C)	32.5	40.2	34.7	30.9	30.8	29.7	31.6	25.8	30.0	28.3
T_{95}(days/yr)	10	22.1	30.6	15.0	25.5	11.2	12.7	34.5	32.1	27.1
T_{32}(days/yr)	11.3	20.1	26.9	12.1	20.3	16.1	9.8	0.8	21.2	9.5
Cold events										
T_{05} Index (°C)	5.1	7.5	0.8	6.7	0.9	-0.1	6.1	-7.6	-1.9	-1.0
T_{05}(days/yr)	-47.5	-43.6	-42.7	-57.3	-39.1	-34.9	-52.8	-29.6	-35.5	-36.9
T_0(days/yr)	-15.1	-9.6	-38.3	-7.6	-34.3	-36.0	-12.2	-39.9	-47.4	-44.6
Growing season										
First day	-35.1	-21.6	-22.3	-34.1	-21.1	-26.6	-37.5	-9.1	-20.5	-24.9
Length (days)	62.5	30.0	31.2	46.7	29.0	40.1	46.6	22.5	30.8	37.6

All values are calculated as $2xCO_2$ results minus $1xCO_2$ results. Values in bold type indicate statistically significant results at the 95% confidence level (5% significance level). The basins are located in different parts of the country in Bangladesh that illustrated as before.

Table – 04: Changes in prolonged (7-day) extreme temperature event.

Basins	1	2	3	4	5	6	7s	8	9	10
Prolonged hot events										
Frequency(#/yr)	0.8	1.0	1.1	1.0	1.2	1.6	0.4	1.5	1.5	1.6
Length (days)	0.1	6.3	10.0	0.7	5.1	3.7	0.5	7.2	5.4	3.2
T_{mean} (°C)	0.6	0.8	0.6	0.8	0.9	0.5	1.2	0.8	0.7	0.4
Prolonged cold events										
Frequency(#/yr)	-2.5	-1.3	-1.9	-2.8	-1.6	-1.2	-2.3	-1.2	-1.8	-1.3
Length (days)	-2.8	-4.3	-3.8	-2.7	-2.2	-3.2	-2.6	0.2	-0.5	0.1
T_{mean} (°C)	0.1	0.2	0.4	0.2	0.6	0.6	0.1	0.1	0.9	0.5

All values are calculated as $2xCO_2$ results minus $1xCO_2$ results. Values in bold type indicate statistically significant results at the 95% confidence level (5% significance level). For basin names and locations are given in Figure 5.1.0

1.10 CLIMATIC CONDITION OF BANGLADESH

Bangladesh is in the sub-tropical monsoon climate. Based on pressure, rainfall and temperature; the climate of this country can be described under the following four seasons:

1. Winter or North-East Monsoon: December, January and February.
2. Summer or Pre-Monsoon: March, April and May.
3. South-West Monsoon or Monsoon: June, July, August and September.
4. Autumn or Post-Monsoon: October and November.

1.10.1 WINTER SEASON

The season is characterized by mainly by an anti-cyclonic pressure system dominating the country except in February when a shallow trough of low makes its appearance over the northern districts. Very light northerly winds, mild temperature and dry weather with clear to occasionally cloudy skies over the country. Exceptionally some powerful western disturbance passes over the country.

The mean temperature is in the ranges of 18-21°C .In the south – western and the coastal districts the mean temperature range between 22-23°C with its lowest ranging between 6-10°C. The temperature occasionally goes down to less than 5°C in the north – eastern parts of the country.

The prevailing air mass is dry during 0900 to 1500 hrs local time. The dryness of air is not evident from morning and late afternoon humidity trends. This is due to the reason that continuous evaporation takes place from numerous rivers, lakes and natural water-sheds during clear sunny days and the evaporated moisture show up in the form of high humidity during the cool hours of late evening and morning. This ultimately helps formations of mists /fogs during the late nights and early mornings. The effect is more pronounced in the Genetic central districts and the coastal district. After passing the western disturbance morning fog occurred.

Rainfall over the country during winter is very scanty. But sometimes in winter Bangladesh receives rain or cloudy sky this particular system occurs when some powerful westerns disturbance approach from Mediterian Sea to east giving rain in Iran, Pakistan, Northern India and then to Bangladesh ,which is the only source of winter rain in Bangladesh exceptionally the depression over North Bay of Bengal which moves towards Bangladesh coast. The driest month of the season is December when the northern and the western districts get hardly 3-10 mm of rainfall; the districts of greater Barisal, Noakhali, Chittagong and Chittagong Hill Tracts get 15-30 mm of rain.

1.10.2 PRE-MONSOON SEASON

The winter anti cyclonic pressure regime starts changing of a summer heat low from March onwards. The low heat develops over Bihar and adjoining central India when the pressure system over Bangladesh forms a part of the resultant trough. In the northern and central districts the surface wind changes from northerly in the winter to south-westerly and it becomes southerly to south-easterly over rest of the country.

The mean temperature during the summer months remains within 23-30°C. April and May are the hottest months. The highest temperature ranging from 38-41°C is attained in the northern and north-western districts. Over rest of the country it ranges from 36-38°C. Practically the highest temperature attains in the month of May.

The southerly low level circulation brings in considerable amount of moisture from the Bay of Bengal over the country causing sultry weather towards late afternoon and evening. Such inflow of moisture causes local thunderstorms in the late afternoon and early night. These local pre-monsoon thunder storms are usually called Nor'westers as because they move across the country mainly from the north-westerly to northerly direction. The nor'westers is locally known as kalbaishakhis after the name of Bengali month "Baishakh" in which they occur frequently. These storms are often associated with strong squalls and occasionally with hail storms. The thunder storm activity is less in March moderate in April and severe in May. Tornadoes are frequent in this season. The tornado of Dhaka (1969), Manikgonj (1985) and Tangail (1992) are remarkable.

These local severe storms are responsible for the pre-monsoon rain over the country. In March the rainfall is 20-40 mm in the districts west of 90°E longitude and also over south- eastern tip, Cox's Bazar and Teknaf. Over rest of the country, the rainfall is between 40-80 mm. With the progress of the season the rainfall increases and in May it is 150-300 mm except in the district of Sylhet where the amount is about 600 mm. Sometime last week of May south –west monsoon onset over south – eastern part of the country. In the pre-monsoon season normal rainfall of the country 20 mm which is 70% of the total annual rainfall of the country.

The season is also characterized by cyclogenesis in the Bay of Bengal. Some of the depressions that form may develop into cyclonic storms which travel generally north – west wards initially and then turns to north- east moving towards Bangladesh and Myanmar coasts. Some of these storms may attain hurricane intensity and give rise to storm surges. The cyclone of 1970 and 1991 are still in the memories not only the people of Bangladesh but also the people of the world.

1.10.3 MONSOON SEASON

In this season. the surface wind changes to southerly direction over the southern and the central districts and to south-easterly to easterly over the northern districts of the country. Wind speed is light to moderate.

Monsoon normally reaches the coastal districts of the country by the last week of May to first week of June and progressively engulfs the whole country through June. Generally heavy to very heavy rain with overcast skies characterizes the season. On the average there are 20-25 rainy days per month during June to August, decreasing to 12-15 days in September. More than 75 percent of the total annual rainfalls occur in the season. The rainfall is the greater over the north –eastern, the southern and the south –eastern districts than over the central, western and north –western districts. During the first two months of the season the rainfall is between 450–600 mm per month over the northern and the southern districts and it is 700-850 mm per month over the districts of Sylhet and the south-eastern districts of Chittagong and Chittagong Hill Tracts. Over the central districts the rainfall is 250-380 mm per month in these two months. As the season advances, the rainfall over the country decreases generally. In September the rainfall is 200-250 mm over the country except in the district of Sylhet and the coastal districts of Barisal, Noakhali, Chittagong and Chittagong Hill Tracts, where the rainfall is 300-450 mm.

With the advance of the monsoon, the summer extreme temperatures fall appreciably throughout the country. Although the mean temperature falls hardly by one degree, the Maximum temperature falls by 2-5°C over most of the country except the coastal districts where the fall is by 5-6°C

Tropical depressions and storms from the Bay of Bengal during the season and generally move to the north-west or north towards India and Bangladesh coasts. Storms however seldom attain hurricane intensity in this season.

1.10.4 POST MONSOON SEASON

This is the transitional season from summer monsoon to the winter. South-west monsoon begins to withdraw in early October and its withdrawal from the country is complete through October. The surface wind is very light and variable.

Rainfall decreases considerably in October and in November the Dry period starts setting in over the country. The district of Sylhet gets 200-250 mm of rain in October and the rest of the country gets about 100-700 mm. In November the amount of rainfall over the southeastern coastal districts amounts to 25-65 mm whereas the rest of the country gets only 1-3 days in the month of November.

The mean temperature falls from 28-29° C in September to 25-26°C in October and to 23-25°C in November. The highest maximum temperature hardly exceeds 29°C and the lowest minimum does not fall below 10°C throughout the country.

Tropical cyclones form over the Bay of Bengal in this season and moves initially towards west and then towards north-west and at times towards north-east affecting Bangladesh coast. Some of these storms in the season may attain hurricane intensity.

The country is also subject to flooding almost every year starting from late April or early May to the end of September due to either high stream flows of three major tributaries i.e. Padma Jamuna and Meghna. Three recent worst floods occurred in 1987, 1988 and 1998.

1.11 HYDROLOGICAL ASPECTS:

The availability of water in the Ganges in Bangladesh is expected to increase due to the Ganges Water Sharing Treaty. If the agreed flow in the treaty is maintained at Farakka, the availability of water the Ganges River will certainly improve compared to non agreement period, particularly during the lean period of March and April.

Due to lack of control structure most of the dry season flow of the Ganges is drained to the sea. The Barrage will help contain that water for agricultural and environmental purpose. The project will be critical particularly for the period of March 21 to May 10. Because, for this period Bangladesh will receive a smaller quantum of water and the barrage would help maximizing the Utilization of Bangladesh's share of Ganges water.

1.11.1 FLOOD MODERATION:

The mean annual peak discharge of the Ganges river at the Hardinge Bridge has increased by 13% in the post Farakka period. While the Barrage project will not be able to reduce longitudinal propagation of flood waves, the embankments to be constructed in the lateral propagation of flood water. So, the risk of flooding in the vulnerable areas is likely to be reduced.

The Ganges Barrage will help by halting the penetration of saline water front. Besides, the barrage will also help in meeting the increased demand of water for irrigation. More irrigation, more evapotranspiration may result in more rainfalls. Thus changing or influencing the climate of the south-west region.

Chapter 02

Model Description

2.1 General Circulation Models

2.1.1 History of GCMs

The idea of mathematically simulating atmospheric motion, to aid the forecast of weather, was first started in the 1920s. But the numerical weather forecasting became very practical in the 1950s using electronic digital computers. Towards the end of the 1950s weather forecasters in United States and some parts of Europe incorporated computer-generated weather maps into their work on a routine basis. In the 1960s, with the increase in the computer power, it was possible to go beyond regional weather simulations to model the global general circulation. This helped scientists to simulate climate over very long periods.

By the 1970s, General Circulation Models (GCMs) had become a very important tool of climate science. During that time, scientists became concerned about the long term possible effects of carbon dioxide accumulation in the atmosphere, which resulted in the study of anthropogenic (human-induced) global climate change. GCMs simulations provided a crucial means of analyzing the effects of climate change.

Meanwhile, ocean modelers started to build similar computer simulations of the Oceanic General Circulation Models (OGCMs). Since oceans are a major component of the overall climate system, climate modelers began trying to "couple" OGCMs with atmospheric GCMs. Although there were some difficulties in coupling these models, by the middle of the 1980s, these coupled models had established a new standard for climate modeling.

In the 1980s, scientific concerns led to international political negotiations over how to respond to the possible climatic changes. A global body of climate scientists, the Intergovernmental Panel on Climate Change (IPCC), was formed to provide scientific advice to these negotiations. In 1992, most of the world's nations signed the United Nations Framework Convention on Climate Change (FCCC). After several meetings, FCCC focused on the ways to reduce the emissions and also in other ways of mitigating the effects of climate change. GCMs have thus played a major role not only in advancing the atmospheric Science but also in creating global awareness of a possibly serious threat to human civilization.

2.1.2 Definition of GCMs

A general circulation model is a numerical model that gives the analysis of atmosphere on an hourly basis in all three spatial dimensions based on conservation laws of momentum, energy and water vapor.

GCMs are the most reliable and powerful tool for estimating the changes in the climate. These are also known as global climate models, generally abbreviated as GCMs.

These are also the complex computer simulations that describe the circulation of air and ocean currents and also how the energy is transported within a climate system. These are mathematical representations of atmospheric and oceanic properties and processes that help describe the earth's climate system.

These are also computer models used to enhance our understanding of the factors that influence climate and improve our ability to predict future climate patterns. The main objective of a typical general circulation model is to predict climate having a spatial coverage with a temporal scale of years, having a very coarse spatial resolution, low relevance of initial conditions, having a high relevance of clouds, radiation, surface, ocean dynamics, and model stability.

2.1.3 Features of GCMs

The main features of General Circulation Models are

- The main goal is to predict the future climate.
- They have a global spatial coverage.
- They have a temporal range of years to centuries.
- They have a very coarse resolution of several hundreds of kilometers.
- They are based on the conservation laws for mass, momentum, energy and water vapor.
- They are controlled by spatial resolution.
- The method used to run GCMs is finite difference expression of continuous time and space equations, or a spectral representation.

Global climate models are the only powerful tools currently available for simulating the response of the global climate system to the increasing greenhouse gas concentrations. These three-dimensional models of the atmosphere and ocean have been used to investigate the effects of changes in the atmospheric composition on the global climate. The more recent GCMs are able to differentiate between the warming effect of greenhouse gases and the regional cooling effect of sulphate aerosols.

Sulphate aerosols affect climate directly through the scattering and absorption of solar radiation and also by altering the properties and lifetime of clouds, which ultimately cool the earth's surface. Currently, the available GCMs only have the direct effects of sulphate aerosols. Unlike greenhouse gases, sulphate aerosols have a relatively short atmospheric lifetime.

Sulphate aerosols are produced mainly in industrial regions and depending upon atmospheric conditions they may be rained out in a matter of days. To model the atmospheric effects of sulphate aerosols adequately, GCMs must be able to reproduce the geographical variation in their atmospheric concentration. Patterns of aerosol emission can vary immensely from season to season and decade to decade, depending on the sources and volumes of sulphate emissions. Many GCM experiments are now available for use in climate change studies.

There is a large library of equilibrium GCMs experiments available for use (http://ipccddc.cru.uea.ac.uk). For the impacts and those who are unfamiliar with GCM studies, the choice of experiments is large and most likely confusing. Even for the familiar it will be confusing to decide the right experiment to choose. For this reason Smith and Hulme (1998) put forward a number of criteria to guide the selection of GCM experiments:

2.1.3.1 Vintage:

Simulations taken from a more recent model are likely to be more reliable than those from the earlier ones, since they will be based on the current Knowledge involving more processes and feedbacks and will usually have a higher spatial resolution than the earlier models.

2.1.3.2 Resolution:

GCM resolutions have been becoming finer with time due to the advances in computing technology and also with more recent models having spatial resolutions of the order of 250 km and about 20 vertical levels, compared to a resolution of about 1000 km and between 2 and 10 vertical levels in earlier GCMs. Sometimes, though the recent models contain more spatial details, better boundary conditions and more complex topography, they may not necessarily have high performance compared to the previous ones.

2.1.3.3 Validity:

The very important factor to be considered in the selection of GCMs is the model performance that is the selection of GCMs that simulate the present day climate more accurately. It is generally assumed that these GCMs are the most reliable representation of the future climate. Though statistical methods can be employed to compare the mean values, variability and climatic patterns of the observed data and model results for the current baseline period, still the choice of GCM, will much depend on the region of interest. The relative performance of GCMs depends critically on the size of the region, on its location and on the variables to be analyzed. It must also be noted that comparisons between observed data and model results should take place at the resolution of the model, rather than at the resolution of the observed data set. GCMs operate at a particular spatial resolution and they cannot be expected to capture the features of climate, which occur at the sub-grid scale. Hence, some 'upscaling' of the observed data is necessary, that is, the construction of observed regional climates from station data. Rather than trying to identify the model, which simulates current climate most accurately, a better approach may be to identify those models whose performance is unacceptably poor, particularly in the estimation of climatic features which are of critical importance to the impact application. A number of international model intercomparison projects currently exist, in which specific components of different GCMs are compared in order to determine why model performance may not be particularly good in some cases.

2.1.3.4 Representativeness of Results:

It is strongly recommended that more than one GCM is used in any impact assessment and the selected GCM should show a range of changes in a key climate variable (e.g., temperature, precipitation) in the study region. At the regional level GCMs can display large differences in their estimates of climate change, particularly for variables, such as precipitation where one model will indicate wetter conditions while another will show significant drying in the study region. It is important to try and capture this range of future climate conditions in any assessment of climate change impacts.

2.1.3.5 Validation

It is important when discussing the need for more regional and local scale studies of climate change and impacts to be able to demonstrate the capability for such studies. Here we demonstrate (1) the ability of the regional model to adequately capture both the general (seasonal temperature & precipitation) and specific (diurnal temperature range (DTR), growing season length , frequency and intensity of extreme events) characteristics of regional climate observed for the modern day. and (2) that regional models are currently better suited for the type of analysis than global models. Mearns et al. (1999) have performed a similar validation for RegCM2 with a domain centered on Dhaka while Synder et al. (2002) performed a more general validation over Bangladesh.

Model validation is performed using National Climate Data Center (NCDC), Summary–of–the Day (SOD) meteorological – station precipitation and maximum & minimum air temperature data. These SOD observations are available throughout the year and have a daily temporal coverage that includes approximately 33 stations distributed across the country Fig-2. Also shown in Fig-2 is the outer – boundary of the 50 km grid from Fig-1 . The SOD station data are grided to the 50 km ClimRAMS grid using an objective analysis scheme Cressman, 1959 and then compared with the model outputs. Before this comparison is made , the model – produced maximum and minimum temperature fields are adjusted to account for the difference between the model and station elevations. This is done by gridding the station elevations to the model grid , and then applying a spatially and temporally – constant lapse rate of -6.5°C per km to the difference between the station and model topography. The resulting temperature correction Fig-3 is then added to the model temperatures. We have chosen to adjust the model temperatures to the station elevations to avoid any modification of the observed data. We also recognize that the observations are biased towards lower elevations , and that, in some sense, the modeled temperatures may be more representative of the true grid – cell averages. The observational data sets are known to include other errors , such as urban heat island effects on temperature (Karl et al., 1988) and wind , mesoscale and regional, cloud & land – surface atmospheric phenomena and interactions (Pielke et al., 1974).

2.1.4 GCM vs. RCM

An RCM offers higher spatial resolution than a GCM, allowing for greater topographic complexity and smaller scale atmospheric dynamics to be simulated and investigated .Theoretically, higher resolution should lead to more realistic simulations of regional scale climate. The biggest weakness with RCMs is the dependence on lateral boundary input either via GCM, reanalysis or observational data. If an RCM receives poor quality input it is not likely to output much higher quality results. So if quality GCM input is needed then is the use of an RCM necessary? The answer to that question depends on the inquiry to be addressed. Obviously an RCM would be inadequate to address issues of global or even hemispheric, changes in atmospheric circulation. Likewise a GCM may not be appropriately suited for questions that are sub- .continental in scale, especially for complex regions. California is a climatically and topographically complex region and therefore a study of the regional climate there warrants the use of an RCM.

2.1.5 ASSOCIATED RAINFALL PATTERN

The distribution of rainfall associated with a monsoon depression is rather unique in each case, depending on its intensity, direction and speed of movement and the prevailing large scale environmental conditions with which it interacts. Nevertheless there are some common features. In the case of a normal westward moving depression in the mid monsoon months of July and August, maximum rainfall is concentrated in a belt ahead of its current position to a distance of about 500 km and to the left of the truck, viz, in the southwest sector of the depression field , in about 400 to 500 km wide belt (Rao. 1976). However, this relationship does not always hold good, particularly in the late monsoon season, i.e. September and October. A typically of the late monsoon depressions is that the rainfall associated with them is often concentrated in a small area and is much more intense than their mid monsoon counterparts. The late monsoon depressions have a special significance in view of their high flood producing potential due to a combination of concentrated heavy rainfall associated with them and a high antecedent precipitation index.

2.1.6 WATER POTENTIAL OF MONSOON DEPRESSION

The monsoon depression produce heavy to very heavy rainfall in the areas through which they pass. The intensity of rainfall being heavy or very heavy is conventionally measured in terms of the cumulative rainfall in 24 hours at an observing station. As per the convention in Indian meteorology the magnitude range of 7 to 12 cm in a 24 hour period is classified as heavy rainfall. 13 cm and above is known as very heavy rainfall. Rainfall amounts of 20 to 30 cm in 24 hour are not uncommon with monsoon depressions. Exceptionally heavy rainfall of as much as 60 to 80 cm per day may also occur in some intense stations. The highest 24 hour point rainfall on record at a plains station in India is 99 cm on second July. 1941 at Dharampur in South Gujrat. This event was associated with a monsoon depression.

2.1.7 SUMMARY

The Regional Atmospheric Modeling System (RAMS) has been widely used to simulate relatively short-term atmospheric process. To perform full- year to multi- year model integrations, a climate version of RAMS (ClimRAMS) has been developed, and is used to simulate diurnal, seasonal and annual cycles of atmospheric and hydrologic variables and integrations within the central United States during 1989. The model simulation uses a 200 km grid covering the conterminous United States, and a nested, 50 km grid covering the Great Plains and Rocky Mountain States of Kansas and Colorado. The model's lateral boundary conditions are forced by three hourly NCEP reanalysis products Clim RAMS includes simplified precipitation and radiation sub- models and representations that describe the seasonal evolution of vegetation – related parameters. Regional climate modeling studies have demonstrated their ability to simulate the seasonal cycles through comparison with observed monthly mean temperature and precipitation data sets. this study demonstrates that a regional climate model can also capture observed diurnal and synoptic variability. Observed values of daily precipitation and maximum and minimum screen – height air temperature are used to demonstrate this ability.

Chapter 03

Review

3.1 Statistical Methods

In this section we summarize the statistics we used to analyze our one month simulation. The statistics are similar to Denis et al. (2002).

3.1.1 Root Mean Square Errors: Root Mean Square Error is defined by:

RMSE = ***n*** *i* =1(*UBB* − *ULB*)2*n* ………………..(1)

Where *UBB* and *ULB* are respectively Big and Little Brother fields and *n* is the total number of grid points (in space). Since we wanted a unitless reference, we have actually calculated the following ratio:

Ratio = ***n*** *i* =1(*UBB* − *ULB*)2 ***n*** *i* =1 *UBB*2 ……………(2)

3.1.2 Spatial Correlation Coefficient : Spatial Correlation Coefficient is defined as follows:

R = *CORRCOEF* = ***n*** *i* =1 (*UBB* − *U_BB*) · (*ULB* − *U _LB*) ***n*** *i* =1 (*UBB* −*U_BB*)2 · ***n*** *i* =1 (*ULB* −*U_LB*)2 ……………………………………………………(3)

Where *U_* is a spatial averaging operator over *n* grid points:

*U_* = _*n* *i*=1 *Un* ……………………………………………(4)

3.1.3 Stationary and Transient Variance Ratios: To complete the assessment of the Little Brother

Ability to reproduce stationary and transient small-scale behavior we define two variance ratios. Temporal decomposition for each variable U is given as a sum of its time mean (denoted by an overbar), and its time deviation (denoted by prime):

U(*x*, *t*) = *U*(*x*) + *U*_(*x*, *t*) ………………………(5)

Our filtering technique allows us to distinguish between large- and small-scale components of all fields. We define the ratio of domain-averaged stationary small-scale variances as:

Γ*stat ss* = *U* 2 *ss*_*LB* _*U*2*ss*_*BB*……………… …….(6)

Where "*ss*" denotes small-scale.

And, then we define the domain-averaged transient small-scales (denoted by subscript "ss") variances

as:

Γ*trans ss* = *U_2 ss_LB _U_2 ss_BB*...... .... (7)

The variance ratios Γ*stat ss* and Γ*trans ss* provide us with the ability of the Little Brother to regenerate

the spatial variance of the stationary and transient Big Brother small-scales.

3.2 Betts' scheme (thermodynamic equations)

Betts formulated his model in terms of the thermodynamic quantities' moist and dry static energies.

$$s = c_pT + gz$$

and moist static energy h is defined as

$$h = c_pT + gz + Lq$$

In a water – saturated environment they may be defined as

$$S_L = c_pT + gz - Lq_l$$

and

$$H_s = c_pT + gz + Lq_s$$

The behavior of the quantities s and h may be considered to be analogous to the behavior of θ and θl, respectively.

The fundamental premise in Betts' model is that the eddy fluxes of heat and moisture can be represented as the product of a single convective mass flux (ω^*) and a perturbation Quantity derived from a single entraining cloud parcel (subscript c) rising through a known mean environment. Thus.

$$F_x = -\omega'x' \equiv \omega^*(X_c - X_e)$$

Where X represents h, q, or SL. The convective mass flux represents the cloud area – averaged flux due to clouds having active updrafts with velocity w_c and having a fractional coverage σ. Thus

$$\omega^* = \sigma\rho w_c$$

In a manner similar to that used to parameterize the effect of cumulus clouds , we write the budget equations for a saturated cloud layer in pressure coordinates,

$$Q1 = \partial\hat{S}/\partial t + V.\hat{S} + \omega\partial\hat{S}/\partial p = Q_R . \partial/\partial p\,(\omega' S'_L)$$

Betts' saturation – point analysis scheme:

**Using the transformation

$$d/dp = (dp_{SL}/dp)(d/dp_{SL}) = \beta(d/dp_{SL})$$

the gradient following a parcel of pressure p can be written

$$d\theta_{SL}/dp = \beta(d\theta_{SL}/dp_{SL})_M,$$

$$d\theta_{ESL} = \beta(d\theta_{ESL}/dp_{SL})_M,$$

$$dr_{SL}/dp = \beta(dr_{SL}/dp_{SL})_M,$$

Where the subscript M refers to gradient along a mixing line. If $\beta = 0$, no mixing occurs in the cloud and the SP (saturation point) at C (cloud base); $\beta = 1$ corresponds to mixing at a rate that corresponds to totally evaporating the water condensed as the parcel rises. The cloud parcel SP reaches D'' (mixing line) as the parcel p. For $0<\beta<1$, partial evaporation of cloud water by mixing occurs. Thus, for example, for $\beta = 0.5$, the parcel path of θ_{ES} (moist adiabat) lies halfway between the mixing line and the moist adiabat [$\theta_{ES}(0)$], where the parcel path for θ_L lies halfway between the mixing line and the dry adiabat.

Betts also estimated the ratio r_l/r_{la} as

$$r/r_{la} = (p_{SL} - p)/(p_B - p) = 1 - \beta$$

Since

$\beta = (pB - pSL)/(pB - p)$ and pB is the cloud base pressure. For an ascending parcel to remain cloudy, $rl > 0$ and $\beta < 1$.

For a parcel to remain buoyant, however, its θES and θ paths must lie to the right of the environment stratification illustrated

$$\beta < (d\theta_{ES}/dp) / (d\theta_{ESL}/dp_{SL})_M = 0.7 \quad \text{where} \quad r/r_{la} = 0.3$$

The annual validation of Rainfall for Observed and Model (GFC)

3.3 Realistic Simulation of Regional Climate

Accurate regional climate predictions are important but difficult. Shown here are the station observed daily rainfall (panel a) and rainfall spatial variability (panel b) from May to August during the 1998 East Asian monsoon and the results from a simulation with the newly developed IPRC-Regional Climate Model. Also shown are the observed and modeled daily minimum and maximum temperatures (panel c). The simulated region is the Yangtze-HuaiRiver Basin together with southern China (23-34°N, 105-122°E). Overall, the model captures the unique features of Meiyufronts, the associated rainfall events, including a severe flood during the period, and the land-surface processes. It can thus be used to study the regional climate over East Asia, and to make climate predictions by nesting it into a GCM.

Based originally on a mesoscale tropical cyclone model, the model incorporates advanced radiation and land surface schemes with high-resolution vegetation and soil classification data. The model uses NCEP-NCAR reanalysis data for initial and lateral boundary conditions, and weekly Reynold's SST as lower boundary conditions over the ocean. Where Rnet is the net incident radiation at the surface, H is the sensible heat flux, Lv is the latent heat of vaporization, and E is the rate of evapotranspiration. Evidence has shown that over the course of a year the net surface heating (or ground heat flux) hs is negligibly small compared to the other terms in equation (1). When taking a long-term view in a stable climate the net surface heating should be essentially zero. On the other hand, in a changing climate we would expect a long-term drift of the net surface heating. Hence the net surface heating is an important indicator of long-term climate change. Unfortunately, it is difficult to measure and can be a source of considerable variation between climate models themselves.

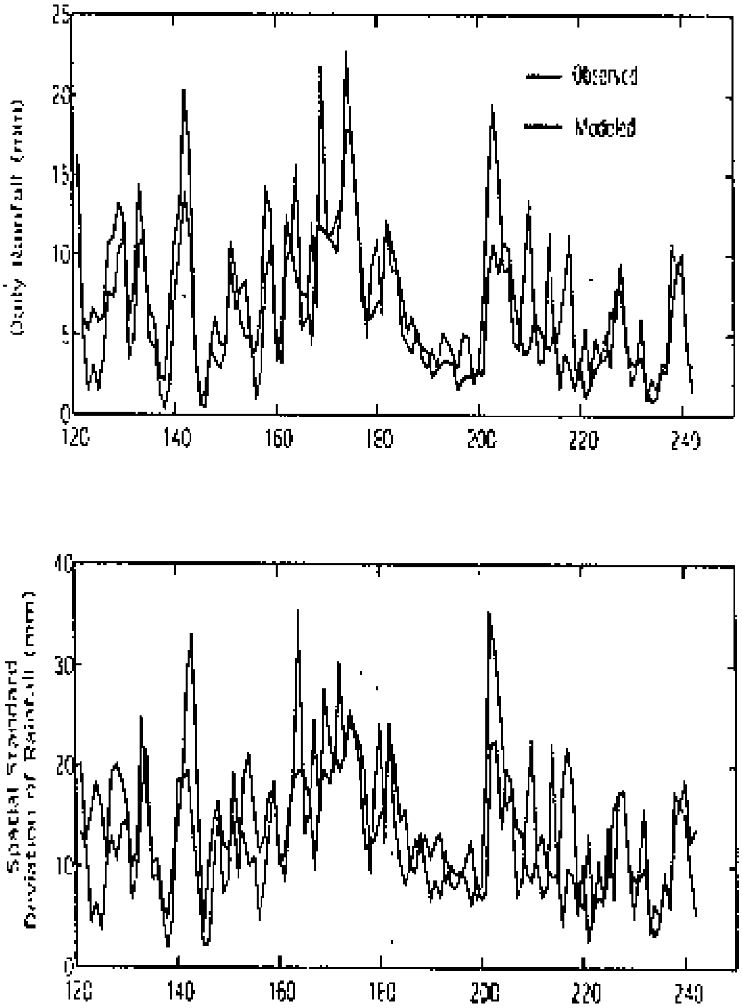

Fig. 3.3: Spatial Standard Deviation of Rainfall over South Asia (mm).

The water budget equation, which expresses the conservation of mass in a lumped or averaged hydrological system, can be written as

ðP _ EÞA _ Q ¼ dS=dt : ð2Þ

Here P is the mean rate of precipitation on the system. E is the rate of evapotranspiration. A is the surface area. Q is the net outflow of water (runoff). S is the water volume stored in the system. and t is time. Similarly to the ground heat flux, the change in soil moisture in a stable climate should be negligible over the long term. Unlike the ground heat flux, though, soil moisture can change considerably over the short to medium term. Even on an interannual basis the soil moisture can vary greatly from flood years to drought years.

A number of previous regional climate model intercomparison studies have been conducted. The Project to Intercompare Regional Climate Simulations (PIRCS) experiment 1a involved eight RCMs (including MM5/BATS and RegCM2) run on a domain covering the continental United States for a period of 2 months covering 15 May to 15 July 1988. Some results from this experiment are reported by Takle et al. [1999]. They found that the RCMs were able to reproduce bulk temporal and spatial characteristics of meteorological fields; in particular, the 500-hPa-height field was well simulated by participating models. They found that large-scale precipitation was simulated well in terms of time and location though amounts often varied from observations, while convective precipitation is represented only in a stochastic sense with less agreement in temporal and spatial patterns. Simulated surface energy budget was also compared to FIFE observations. While the simulated results show broad agreement with the FIFE observations, significant scatter among results meant that no strong conclusions could be drawn. PIRCS experiment 1b was performed over a similar domain but covered the period June–July 1993 with 13 RCMs involved. This period included a flood in the central United States. The results are reported by Anderson et al. [2003]. They found that the models were able to reproduce recycling ratios within the range estimated from observations even though many of the RCMs demonstrated a low precipitation bias. The majority of the RCMs were able to reproduce the observed nocturnal maxima in precipitation though none of the models accurately reproduced the characteristics of the mesoscale convective system.

The Project for Intercomparison of Land Surface Parameterization Schemes (PILPS) has conducted several experiments focused on assessing the performance of land surface schemes. Most of these studies have driven the various land surface models with observational data [Henderson-Sellers et al., 1996; Liang et al., 1998; Lohmann et al., 1998; Wood et al., 1998]. While studying the performance of land surface schemes in an "offline" mode may provide useful information for the development of those models, it has been shown that these results may not be directly relatable to the performance of the same models when fully coupled to an atmospheric model [Hu and Islam, 1996; Kim and Entekhabi, 1998]. Margulis and Entekhabi [2001] state that "offline" land surface model intercomparison sensitivity studies can lead to incomplete and misleading sensitivities of land-atmosphere interactions. Some later PILPS experiments coupled several land surface models to the same RCM [Timbal and Henderson-Sellers, 1998]. They found that the scatter among the schemes, while different than that observed in the offline experiments, was of the same order of magnitude. In this study the land surface models are coupled to their native atmospheric components; thus the model sensitivities are those applicable to these coupled model systems. As well as the above formal projects, there have been several other studies which have performed intercomparisons of various climate model parameterizations. Chen et al. [1996] compared the simulation of land surface evaporation for four land surface parameterizations over FIFE. The simplest of these models was the simple bucket model with two parameters [Manabe et al., 1965], and the most complex model is the simplified Simple Biosphere (SSiB) model of Xue et al. [1991] with 22 parameters. They conclude that some complexity in the canopy resistance scheme is important in reducing both the overestimation of evaporation during wet periods and underestimation during dry periods with the two most complex models performing the best. They also demonstrated that simply increasing complexity of the model does not necessarily improve performance, with the most complex model (22 parameters) performing similarly to the second most complex model (15 parameters). Leung et al. [1999] intercompared three RCMs which were used to simulate an extreme flood event over eastern Asia. They found that each model simulated the gross flood conditions reasonably well, though significant differences were found in the simulated energy and hydrological cycles, especially over cloudy areas. The reasons for this include the simulation of the amount and vertical distribution of clouds, the treatment of cloud radiative feedbacks, and the representation of land surface processes. They also note that "One special important criterion is the radiation balance which has serious implications for long term climate simulations." This study differs from previous intercomparison studies due to a combination of factors. Of the four RCMs used, two share the same land-surface scheme (RegCM2 and MM5/BATS), allowing their differences to be attributed largely to the atmospheric components, while three share the same atmospheric components (MM5/BATS, MM5/ SHEELS and MM5/OSU), allowing their difference to be attributed largely to the land-surface schemes. All of the models use their native parameter values and initialization with no site-specific initialization performed: that is, they are applied in their default configuration just as they would be for climate change impact studies, etc.

Chapter 04

Review of the work

4.0 Case Studies

Based on an analysis of the discharge data by Mirza et al. (2003) reported that the discharge levels in the Ganga, Brahmaputra & Meghna river systems attained their highest ever peaks in these years at some locations. An analysis of the seasonal rainfall departure from the long period average over Bangladesh during the monsoon period revealed that the floods in 1987 & 1998 occurred due to excess rainfall within Bangladesh as also in the upstream portion of the river basins that shows the year to year time series of the percentage departures of the country average monsoon rainfall of Bangladesh during the two main monsoon months of July & August with reference to the long period average (1971-2000), where the years 1987 & 1998 stand out clearly.

We identified the dates of heavy rainstorms by computing the daily country average rainfall of Bangladesh. The daily country average rainfall of Bangladesh during the period 1 June to 30 September for the years 1987, 1988 and 1998. The monsoons of highly excess rainfall over Bangladesh, as may be seen in the year 1988 and1998 respectively. The day to day rainfall distribution in both the years is marked by occurrence of several peaks in the bar diagram. A high peak in the country average is a reflection of widespread heavy rainfall with many stations reporting high values of 24 hour precipitation, at times exceeding 20 to 30 in a continuous spell of several days. The most significant peaks in 1987 occurred in the last week of July, continuing into the beginning of August, and in the last week of August, the latter recording a country average rainfall exceeding 90 mm. The one in the last week of July exceeded 80 mm. The highest peaks in 1998 were comparatively moderate as compared to 1987. The most significant peaks in 1998 occurred in the 2nd week of July and the 2nd week of August. During 1988 on the other hand, the month of June appeared to be quite active but the rainfall in July and August was considerably subdued. The forecast model was run based on the initial conditions of 24 July with lateral conditions calculated from analysis at 6 hourly intervals. The 24 hour and 48 hour predicted rainfall valid for 25 July and cumulative for 25 and 26 July 1987 are presented in the south and south-west respectively. The model produced heavy rainfall in the areas covering Assam and adjacent states and Bangladesh, consistent with the synoptic patterns and the areas of heavy moisture convergence. The observed rainfall on 25 July and

26 July as verification. Widespread heavy rainfall along the coastal areas of Bangladesh, influenced by orography, as well as northern and central parts was the prominent feature.

The monsoon trough stayed north for a considerably long period of about 10 days through the beginning of August. As a corroboration of this statement, the mean sea level pressure analysis on 31 July is presented in south zone, which shows the monsoon trough persisting in the same location across north Bangladesh. The observed rainfall distribution on 1 August (the day of peak in the country average rainfall in 1987) is shown in the east of Sylhet, which lies at the foothills of Khasi-Jaintia hills near Cherrapunji, recorded 30 cm of rainfall on this day. Many stations in northern and central parts of Bangladesh reported heavy rainfall exceeding 10 cm. The 24 hour predicted rainfall valid for 1 August 1987, based on the initial conditions of 31 July 1987. The model simulated the observed precipitation reasonably well.

4.1 Calibration /Validation/ Sensitivity Analysis

The regional climate models (RCM) used to generate the climate projections adequately reproduces historical climate conditions. These models are driven by outputs from global circulation climate models that due to their coarse geographical resolution can not be used directly for regional impacts and adoption analyses. The global models, however, adequately reproduce large scale atmospheric features. RCMs are used to downscale the outputs of global circulation models to a specific region.

4.1.1 Conceptual Basis

Global Coupled Atmosphere – Ocean General Circulation Models (GCMs) currently used for projecting future climate have a grid box size of 100-200 km. Many of these models are able to simulate present-day climate well on spatial scales of 1000 km upwards, and the best models provide reasonable representations of the climate on some what smaller scales. Their grid-box resolution, however, can not capture regional orographic details nor resolve important cyclonic disturbances or similar–sized circulation features. This produces an accurate representation of the climate on scales of individual grid boxes. For many impact models, however, information is required on sub grid scales of 10 to 100 km (referred to here as the local to regional scale). The method for producing local-to regional scale information from larger-scale GCM data is called downscaling.

Two downscaling methods are commonly used dynamical and statistical downscaling. Dynamical downscaling methods include: the use of a limited area, high-resolution Regional Climate Model (RCM) nested within and driven by time-dependent lateral and lower boundary conditions from a GCM; the use of a global model with variable spatial resolution (a stretched - grid atmospheric GCM); or the use of a high-resolution atmospheric GCM in time-slice experiments driven by Atmospheric-Ocean GCM forcing factors and surface boundary conditions. There are two types of RCM based downscaling depending on whether the RCM results feedback to the driver GCM (two-way nesting) or not (one-way nesting). Statistical downscaling involves the derivation, validation and application of a statistical model (usually based on regression analysis) that relates local / regional-scale climate variables to global-scale predictors. PIER is using both numerical and statistical downscaling techniques but only one-way nesting of numerical regional climate models will be pursued.

4.1.2 Theoretical Basis

GCMs simulate the law of motion, based on conservation of mass and energy, in a quest to estimate potential changes in climate given external forcing factors such as the increased atmospheric concentration of green – house gases. However, these models require the use of several simplifying assumptions due to lack of scientific knowledge or lack of computer resources to solve all physical process at all the spatial and temporal scales. Numerical RAMs or limited area models also numerically solve the equations of motion (conservation of mass and energy) and are in some respect very similar to the global models. Several numerical experiments have confirmed that the use of RCM models driven by the output of global models can adequately reproduce the main features of regional climate.

4.1.3 Numerical Basis

The global and regional dynamic models solve the basic equations of motion; conservation of mass and energy, using numerical integration schemes. This is done for a three dimensional mesh of grid points at different horizontal and vertical resolutions. Some features (e.g. cloud formation) are parameterized (simple semi empirical mathematical representation of certain processes) to be able to obtain numerical solutions with existing computer resources.

Statistical downscaling consists of the development of mathematical relationships or correlations between large scale features of climate (e.g. geo potential heights) estimated by numerical GCMs and climate conditions at given grid points in the region of study. An example of this technique is the canonical correlation method being enhanced by PIER researchers at Scripps.

4.1.4 Input and Output

The inputs needed for the global circulation models are the boundary conditions for the atmosphere and the oceans. Initial conditions to start the simulations and a description of how important features would change with time (e. g. atmospheric carbon dioxide concentrations). The regional climate models require the same type of information but only for the specific region being modeled. In addition, the regional models require the use of outputs from the global models at the boundaries of the modeling domain.

The outputs from the global and regional models are the estimated changes of temperature, precipitation and other meteorological variables.

The model does a good job simulating historic 1- day events considering the differences in sample sizes. The average 1– day high is 1.3 cm in the model than in the observations.

4.2 Data and Methodology

The basic data sets required for preparing the synoptic maps and the initial and lateral boundary conditions for running the limited area model in the present study are drawn from the European Centre for Medium-Range Weather Forecasts(ECMWF) Reanalysis (era-40) data downloaded from their ftp site. The ERA data sets in GRIB coded form are available on a coarse resolution of 2.5° x 2.5° lat / long . grid on constant pressure surfaces.The data downloaded are those of the five basic flow variables; geopotential (gz), temperature (T), u & v components of wind and relative humidity (RH) on 15 isobaric levels. The lateral boundary conditions in this study are calculated from the 6 hourly analyzed fields, the so called perfect boundary conditions. The input fields for the model are the five basic flow variables Z, T, u, v, RH & the fixed fields of orography (terrain), the sea surface temperature (SST) and the albedo. The highest point in the orography field carries a value of about 5400 meters in the Himalayan region. The SST are the monthly climatology and albedo are available for June and December, which are appropriately selected in the model run.

The observed daily rainfall data of about 33 rainfall stations of Bangladesh were obtained from the Bangladesh Meteorological Department (BMD). The data were subjected to a visual inspection and message, before being used in the computations, to deal with the erroneous and missing entries. and each station's file was reconstructed. For the purpose of this study we have constructed the country average rainfall on day to day basis. The daily country average rainfall was used as the basic element for constructing the long period averages of the monthly and seasonal rainfall. The above method of computing the cumulative monthly and seasonal country average rainfall using the daily country average rainfall as the basic element was considered superior as it obviates the need for artificial interpolations to fill the missing rainfall entries when individual station data are taken as the working elements. Such missing entries were substantially large in number in some cases and the interpolation procedures using graphical methods and / or substitution by long period averages, which are normally resorted to have their own limitations.

The intensity and amount of rainfalls in Bangladesh depends on period and. About 2%, 20%, 62% & 16% of the annual rainfall (2200mm) in Bangladesh occurs during winter (DJF). Pre-monsoon (MAM), monsoon (JJAS) and Post-monsoon (ON) periods respectively (Islam and Uyeda, 2005). North-eastern and south-eastern parts of the country are heavy rainfall regions compared to western parts of the country (Islam et al., 2005). This technique consists of using output from GCM simulations to provide initial and driving lateral meteorological boundary conditions for high-resolution Regional Climate Model (RegCM) simulations. with no feedback from the RegCM to the driving GCM.

General circulation models (GCMs) used to simulate weather and climate do not operate at fine enough grid resolutions to resolve many observed regional weather and climate features. To simulate these meteorological features. regional or limited–area atmospheric models have been used. These models are run at higher resolution than the GCMs and are thus able to better represent mesoscale dynamics and thermodynamics. including processes resulting from finer-scale topographic and land–surface features. Typically the regional atmospheric model is run while receiving lateral boundary–condition inputs from a relatively–coarse resolution atmospheric analysis model or from the output of a GCM. The model simulations performed as part of the Project to Intercompare Regional Climate Simulations (PIRCS) (Takle et al., 1999) are an example of these kinds of simulations. , Typically, full-year regional climate model integrations have been validated against monthly mean temperature and precipitation observations (e.g. Giorgi et al., 1993, Marinucci et al., 1995). Such studies have been able to demonstrate the model's ability to simulate the seasonal cycles associated with the particular domain of interest. Because of the non–linear interactions between the land surface and atmosphere, a realistic climate model must also be able to simulate the diurnal and synoptic cycles that average to make up the observed monthly climatologies. Mearns et al. (1995), for example, has compared regional climate model outputs with daily observations. As a specific illustrative example of why comparison with daily observations is important, consider an observed monthly precipitation total of 30 mm of water; the behavior of the land–atmosphere system is expected to be quite sensitive to whether this precipitation falls as a one day, 30 mm precipitation event, or if it falls for 30 days at 1 mm per day. Consequently, efforts to validate the performance of regional climate models should include an assessment of the model's ability to simulate general atmospheric variables at a range of temporal scales. Specifically, a regional climate model should be able to reasonably simulate diurnal, synoptic, and seasonal cycles. An additional measure of a regional climate model's performance is its competence in simulating interannual variability; something that is not addressed in this paper. The analysis presented here in assesses a regional climate model's performance on diurnal, synoptic and seasonal time scales.

To perform full–year to multi–year regional atmospheric model integrations, a climate version of RAMS (ClimRAMS) has been developed. It contains additional features required to satisfy both computational constraints and time–evolving boundary conditions and land–surface features like vegetation parameters and seasonal snow cover. The model is used to perform historical simulations where atmospheric analysis data are available to define the lateral boundary–condition forcing. The model could also be configured to use GCM outputs for the lateral boundary conditions. A necessary (although not sufficient) condition for using GCM outputs as lateral boundary conditions, is that realistic regional climate model simulations should result when the analysis lateral boundary conditions are used.

A current deficiency in most regional and global climate model land-surface parameterizations is that they use only simple climatological approaches, based on time of year, to define the model vegetation parameters. The climatological approach is incapable of realistically responding to deviations from climatology, such as wetter and drier than average seasons, or to changes in climate. In addition, climRAMS has been used to develop sub-grid scale snow–

distribution representations for application in regional and global climate models (Liston et al., 1999) . Both of these research efforts require an atmospheric model capable of performing realistic diurnal, synoptic and seasonal cycles.

4.2.1 Convective Precipitation Schemes

Mean Square Error (MSE) is a common measure used to assess the accuracy of a forecast system. In our application MSE is defined as

$$MSE=1/mn \sum_{j=1}^{m} \sum_{i=1}^{n} \{ g(i,j) - y(i,j) \}^2 \quad ....(1)$$

Where g(i , j) is the forecast value and y(i , j) is the observed value at a grid point (i , j) within the domain , with n & m the total number of grid points within the domain in each direction g & y are forecast and observed cumulative precipitation respectively. The above equation can be decomposed as (Murphy 1988):

$$MSE= (\hat{g} - \hat{y})^2 + Sg^2 +Sy^2 - 2r_{gy} \, Sg \, Sy \quad ....(2)$$

Where the bar refers to the average value over the area ;
Sg Sy denote the spatial standard deviation of the forecast and observed variables respectively; and r_{gy} is the spatial correlation between forecast & observation .
We rewrite eqn (2) by adding & subtracting 2 Sg Sy to obtain

$$MSE= (\hat{g} - \hat{y})^2 + (Sg- Sy)^2 + 2(1 - r_{gy}) \, Sg \, Sy \quad .... 3)$$

The comparison between the model outputs and observations are performed in terms of two statistical measures, bias and root-mean square error (rmse). Denoting $m_{i,j}$ & $r_{i,j}$ model outputs and observation (reality) at the point at space and time characterized by two indices, i & j and defining the model error as their difference,

$d_{i,j} = m_{i,j} - r_{i,j}$. We can define the bias as

$$\text{Bias}_j = \bar{d}_j = n^{-1} \sum_i d_{i,j}$$

and root- mean square error as $\text{rsme}_j = \sqrt{(n^{-1} \sum d^2_{i,j} - \tilde{d}^2_j)}$

If i indexes time & j indexes space, we obtain a spatial distribution of errors, which can be mapped : if the indexes are interchanged, i.e., i indexes spaces & j indexes time, a temporal evolution of errors is described.

4.2.2 Analysis Methods

Bangladesh and SAARC'a wide latitudinal range and contains a variety of microclimates. Due to this diversity of microclimates, we perform our analysis on the hydrologic basin scale, as defined by the Bangladesh Department of Water Resources (1998). The methods for analysis of changes in extreme events are similar to those of Salinger and Griffiths (2001). Annual extreme events are defined based on the 5th and 95th percentiles of the $1xCO_2$ results.

4.2.3 Results

The fields discussed are surface temperature, precipitation, and specific humidity, and meridional and zonal winds at 850 hPa. We provide statistics for the total fields, as well as for the corresponding large/small-scale components, defined by removing wave numbers larger/smaller than the cut off wave number. The annual average Precipitation and annual average minimum mean and maximum temperature diagrams over South Asia are shown bellow:

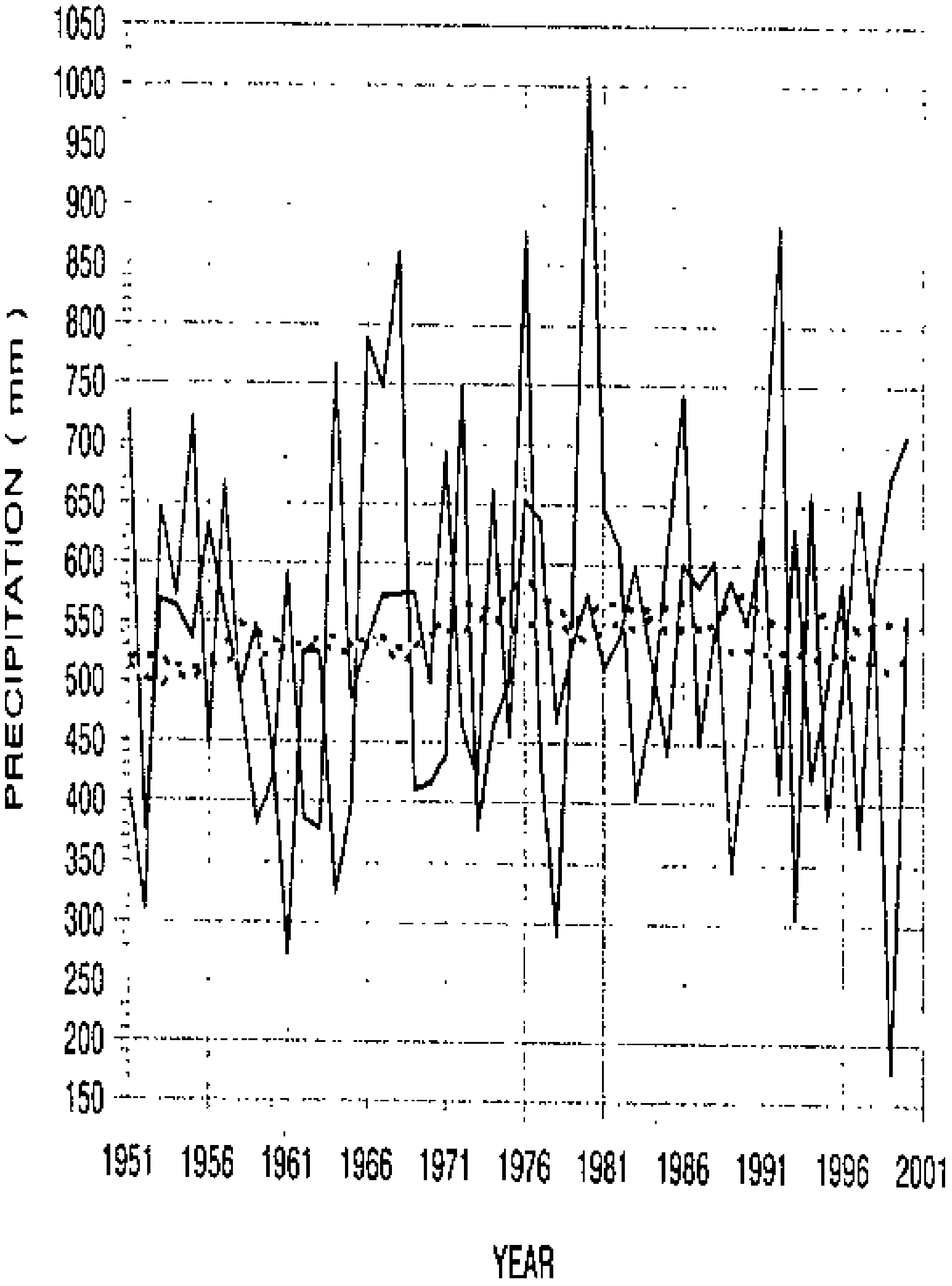

Fig. 4.2.5(i): Annual Average precipitation over South Asia (mm).

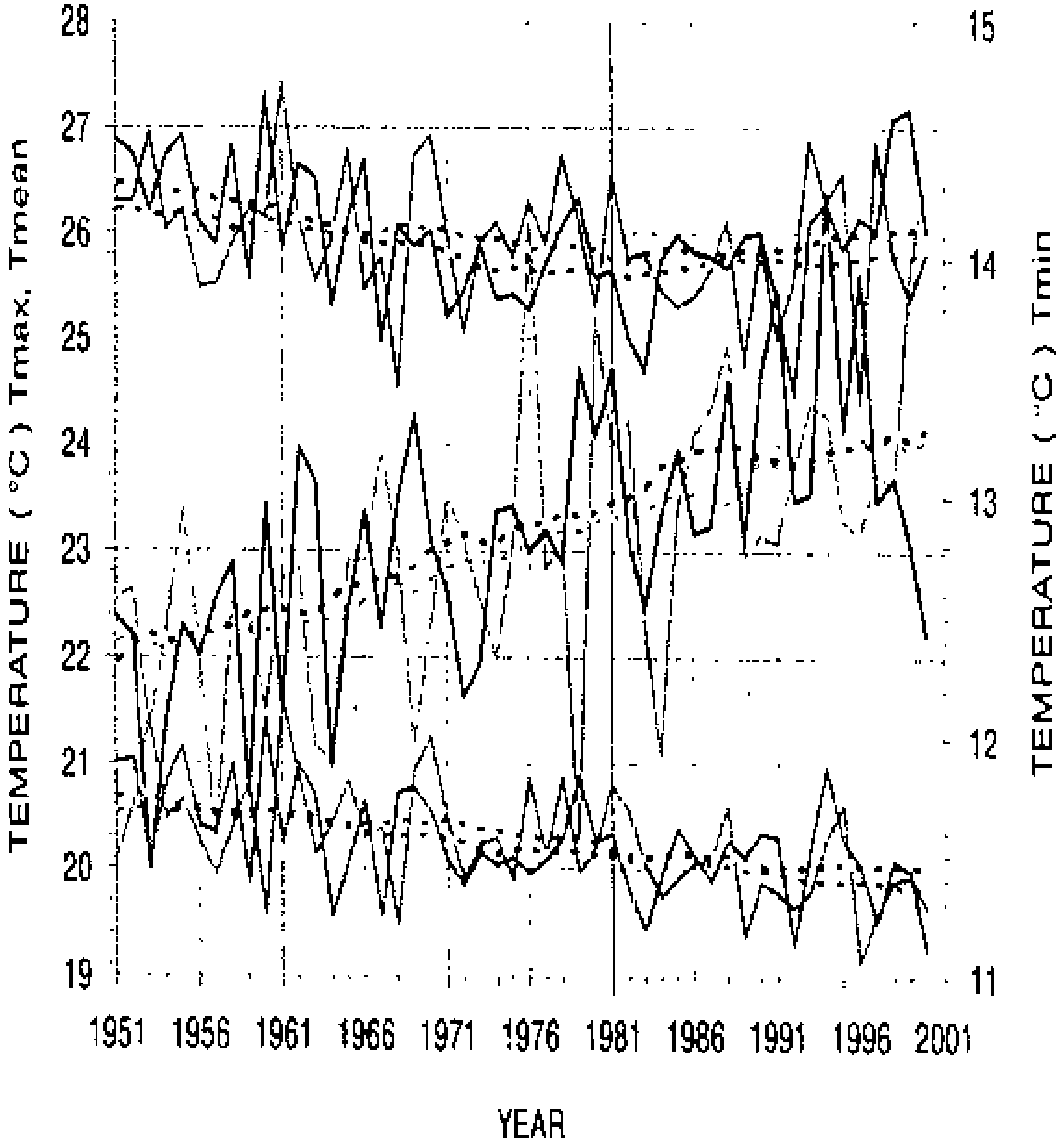

Fig. 4.2.5(ii): Annual average min., max. and mean temperature over South Asia

a. Temperature

We define three types of extreme temperature events and examine changes between the 1*CO2 and 2*CO2 scenarios. 1) The first type of extreme event is based on the 95th and 5th percentiles of daily maximum and minimum temperatures, respectively.

These percentiles correspond to the 18th hottest maximum and coldest minimum temperatures in a year (based on the number of events per year multiplied by the percentile). For all 15 years of the 1xCO2 simulation the annual 5th percentile events were averaged together to create a long-term extreme cold index value, likewise for the annual 95th percentile events. These long-term indices are used for the evaluation of changes in extreme events. 2) The second type of extreme event examined is based on specific temperature thresholds. We examine the frequency of events below 0°C and above 32.2°C. 3) The third type of extreme event is a prolonged extreme event. These are events where the maximum (or minimum) temperature exceeds the long-term 95th (or 5th) percentile for seven or more consecutive days. Indices of temperature examined are:

Changes in mean daily temperature maximum, minimum, and range: T_{max}, T_{min}, T_{range}, respectively. The frequency of days with maximum (minimum) temperatures above (below) the 95th (5th) percentile: T_{95} (T_{05}). (Extreme event of type 1 described above). The frequency of days with temperatures above (below) 32.2°C (0°C): T_{32} (T_0) (Extreme event of type 2 described above).Changes in prolonged extreme events, including frequency, mean length and mean temperature of prolonged hot and cold extreme events. (Extreme event of Type 3 described above). Changes in the beginning and length of the annual growing season (based on the Frost-free period).

b. Temperature

In general the $2xCO_2$ scenario is hotter than the $1xCO_2$ scenario. For every basin the mean daily maximum and minimum temperatures are greater in the $2xCO_2$ scenario than in the $1xCO_2$ scenario, with differences statistically significant at the 95% confidence level (5% significance level). While the increases in both maximum and minimum are similar, the increase in daily maximum is greater, for 9 of 10 basins, than the increase in daily minimum. This leads to an increased mean DTR in these regions. Although the change in DTR is relatively small, it is still significant in 7 of 10 basins. Our results indicate an increase in extremely hot days (T95), days exceeding 32.2°C, and in prolonged hot spells. Not only are there more prolonged hot events in the $2xCO_2$ scenario, but these events are longer and hotter on average than the prolonged events in the

$1xCO_2$ scenario. While the maximum temperatures are rising in the $2xCO_2$ scenario, so are the minimum temperatures, resulting in a decrease in days below the 5th percentile (T05) and in days below 0°C. Due to the decrease in days with temperatures less than 0°C the frost-free period begins, on average, 25 days earlier in the $2xCO_2$ scenario and is on average 38 days longer. In our $2xCO_2$ scenario we also find that prolonged cold events occur less often and are shorter and warmer on average than in the $1xCO_2$ scenario.

Chapter -05

Results and Discussions

5.1.0 Geographical Situation of Bangladesh

Bangladesh lies between 87.5°E to 92.5°E longitudes and between 20.5°N to 26.9°N latitude. It is surrounded on the west, north and east by Indian territories. To the south lies the Bay of Bengal. The area of Bangladesh is 1,44,000 square kilometers or 55,600 square miles. It is divided into six divisions and 64 districts. It has a population of about 144 million. In point of the size of population, it is the tenth largest state in the world. The physical features of Bangladesh are mainly a plain land criss-crossed by a network of rivers and canals. In the eastern and south-eastern regions there are only a few hilly tracts. Places like Paharpur, Mahasthangarh and Mainamati and numerous historical monuments and relics give evidence to our glorious past, rich culture and high civilization.

Bangladesh is often called a land of natural calamities. Flood, cyclone, storm, and heavy downpour and drought often visit the country. People here work and live fighting against recurring natural calamities. Bangladesh lies in the tropical region and its land is low. Almost every year cyclone or storm hits the land in summer or in the late autumn. Torrential rains and rush of water from the upper north bring about flood almost every year. On no other country of the world has Natural bestowed so much beauty as on Bangladesh. Its beauties consist in bounty and variety. The tropical climate brings for its abundance of sunshine, on the one hand, and copiousness of cloud and rain, on the other hand.

The country is bounded in the west by west Bengal (India): west Bengal, Assam and Meghalaya (hilly area of Khashi and Joyonti hills) in the North: to the east by Tripura and Assam (hilly states of India) together with Myanmar, and South by the Bay of Bengal. The Himalayas demarcated the northern border of the Bengal basin while Shilong plateau and Tripura hills define the northeastern and eastern boundaries, respectively and Chhotanagar plateau delineate western boundary. Bangladesh is a revering country within mighty drainage systems (Ganges, Brahmaputra and Meghna) along with its innumerable tributaries which originates in the Himalayas Mountains is largely responsible for the hydro-meteorological cycles of the whole Indian subcontinent including Bangladesh. It has a small border with Myanmar in the southeastern side.

The country is frequently hit by the tropical cyclones, which affect the coastal zone by storm surges and wind actions. Salinity intrusion is a major problem in the coastal zone during the dry season. Floods frequency occurs in Bangladesh due to heavy monsoon rainfall in the country and also in the upper catchments of GBM outside the country. Nearly 22% of the area of Bangladesh gets flooded in a normal monsoon year. The floods like those of 1988, 1998 and 2004 occur once in 10-years, which are highly destructive to live and properties. In Bangladesh, 33 stations are set up by BMD to observe the weather and climatic conditions of our country. Among these stations, 26 are used in this research work.

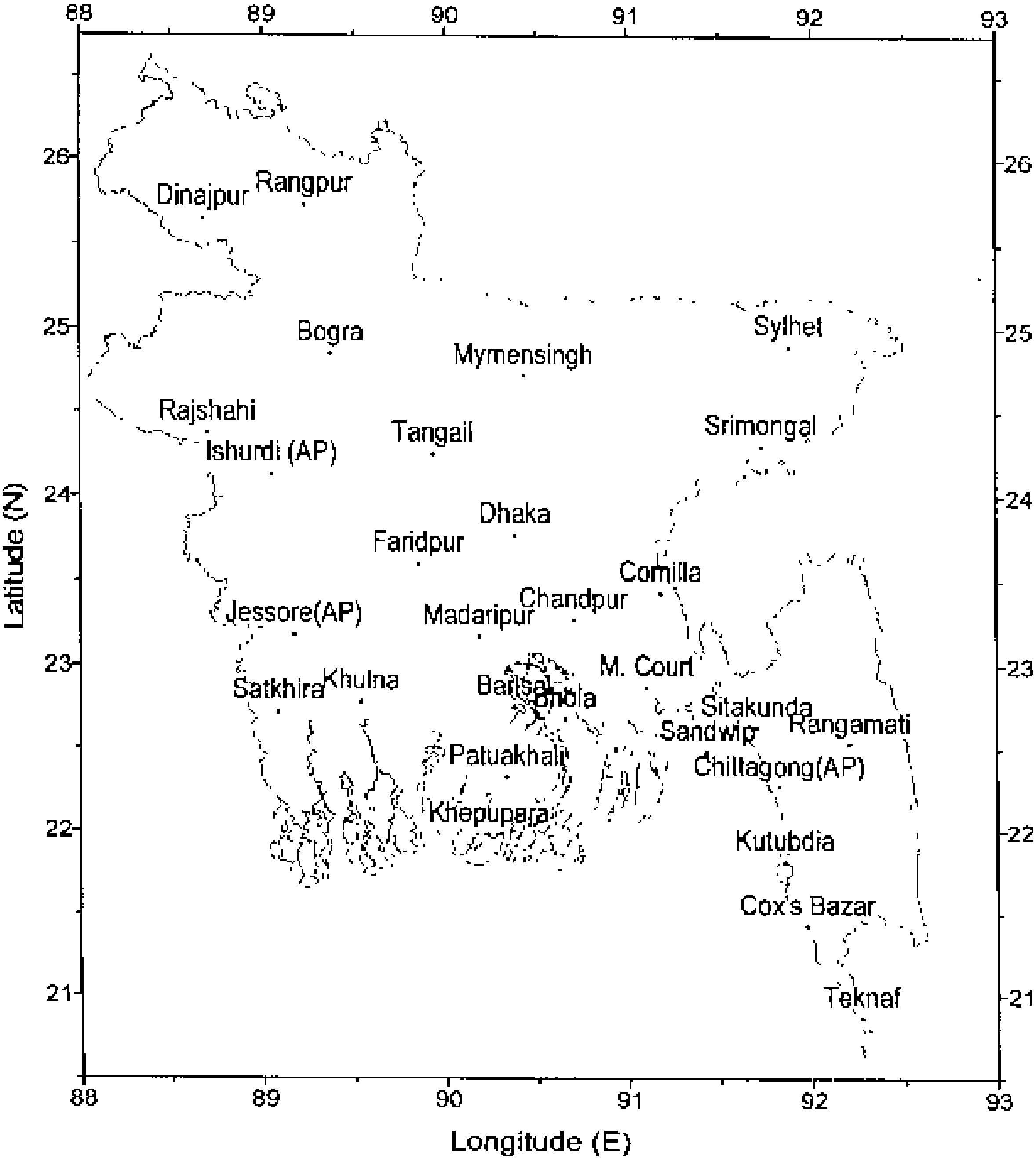

Fig. 5.1.0: Location of BMD stations in Bangladesh.

5.1.1 Rainfall Validation

Analyses of the differences between model results and observations suggest that the temperature and precipitation fields are acceptable representations of the region's spatial and temporal climatology. These research efforts require an atmospheric model of the year 1982-89 that capable the representations of diurnal, synoptic and seasonal cycles.

It is turned out from the analysis of synoptic situations in respect of the selected heavy rainfall events in the two outstanding excess monsoon rainfall years 1987 and 1998 that the typical synoptic setting for heavy rainfall in Bangladesh is the positioning of the axis of seasonal monsoon trough in a northerly latitude passing across the country's territory. The shifting of the monsoon trough northward usually takes place in the wake of a monsoon depression or a low pressure area from the Bay of Bengal moving across central and northern parts of India. It another case, in August 1998, the surface monsoon trough located in the same position as in 1987 over north Bangladesh, the upper air flow pattern was typical of a strong monsoon situation viz, the monsoon trough extending upto the middle troposphere levels sloping southward with height, and the subtropical ridge in the upper troposphere located in its normal position in a northerly latitude. 1998 was a good monsoon year in India as well as Bangladesh. It developed into a land depression after reaching Bangladesh possibly aided by increased moisture supply from the Bay of Bengal. The depression produced heavy rainfall in south Bangladesh, particularly in the coastal hill areas. Thus it appears that a prolonged residence of the axis of the monsoon trough in northerly latitude across north Bangladesh is the primary factor leading to persistent heavy rainfall in the country.

Bangladesh is situated in the most active zone of southwest monsoon. Most of the precipitation (65%) occurs in the monsoon season (June-September). Pre-monsoon receives about 20%. Post-monsoon receives 13% and winter receives 2% of the annual rainfall. The winter of Bangladesh is almost dry and cool. Heavy rainfall is a characteristic of Bangladesh. With the exception of the relatively dry western region of Rajshahi, where the annual rainfall is about 1600 mm. most parts of the country receive at least 2000 mm of rainfall per year. Because of its location just north 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 is about 4800 mm per year.

5.1.2 Monthly (Mar-Nov) rainfall variation over Bangladesh for observed and RegCM model

From Fig. 5.1.2(a), it is seen that the spatial distribution of rainfall for the month of August in 1982, the highest rainfall in Bangladesh and the second highest rainfall in July1982 and the lowest rainfall at November to March in Bangladesh for the observed data The model data for the same month shows the highest rainfall bar in August and second highest rainfall bar in July and poor rainfall shows from November to March in Bangladesh. Similarly, it can be seen that the spatial distribution of rainfall for the month of June in 1982. The highest rainfall shows RegCM model gradually decreasing for the observed data is shown in Fig. 5.1.2(a). The model data shows the second highest rainfall in July 1982 and less rainfall shows in March & November for the whole year of Bangladesh. In 1982 the observed rainfall in the month of May, October and November is measured less amount by BMD compared to RegCM model, whereas almost similar in the month of August and April.

From Fig. 5.1.2(b), it is seen that the highest amount of rainfall about 600 mm in the month of August is recorded by BMD which is overestimated about 30% compared to RegCM model. The net does not capable to detect precipitation in the month of November and December'1983. Almost same amount of model precipitation is shown in May, June and August which is almost equal compared to observed data. The huge amount of rainfall is collected by BMD in August for the entire year. But RegCM model data overestimates in May, June and November compared to observed data. The spatial distribution of rainfall is almost similar in March, May, and July in 1983. The precipitation gradually increase from May to August and decrease towards November. As the precipitation can not be capable to detect in December to February by model and even observed representations.

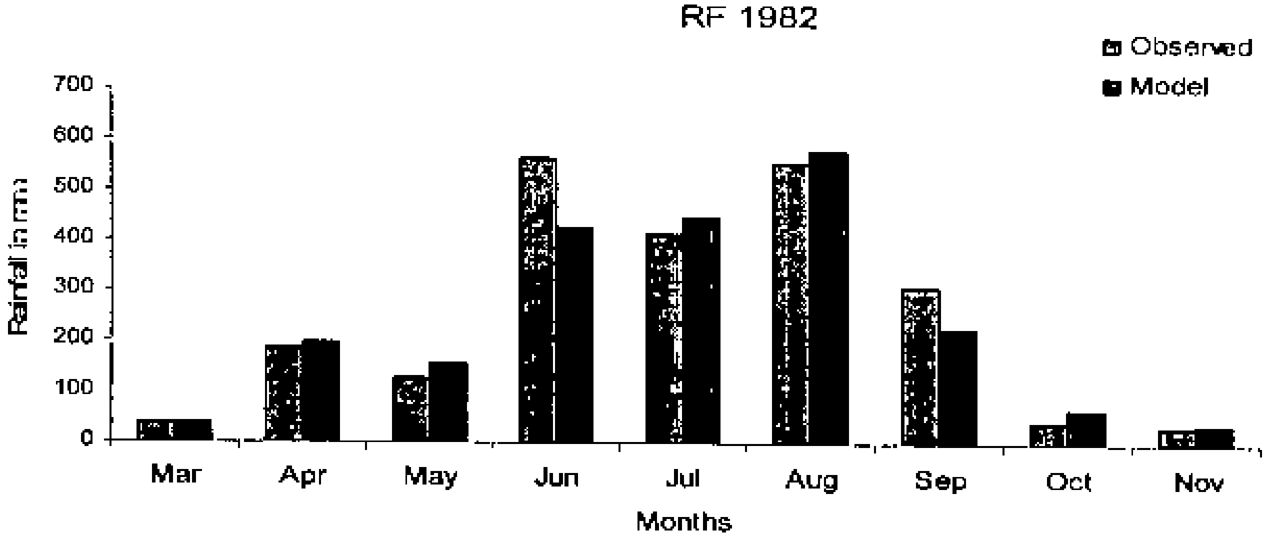

Fig. 5.1.2 (a): Monthly average rainfall for observed and RegCM model.

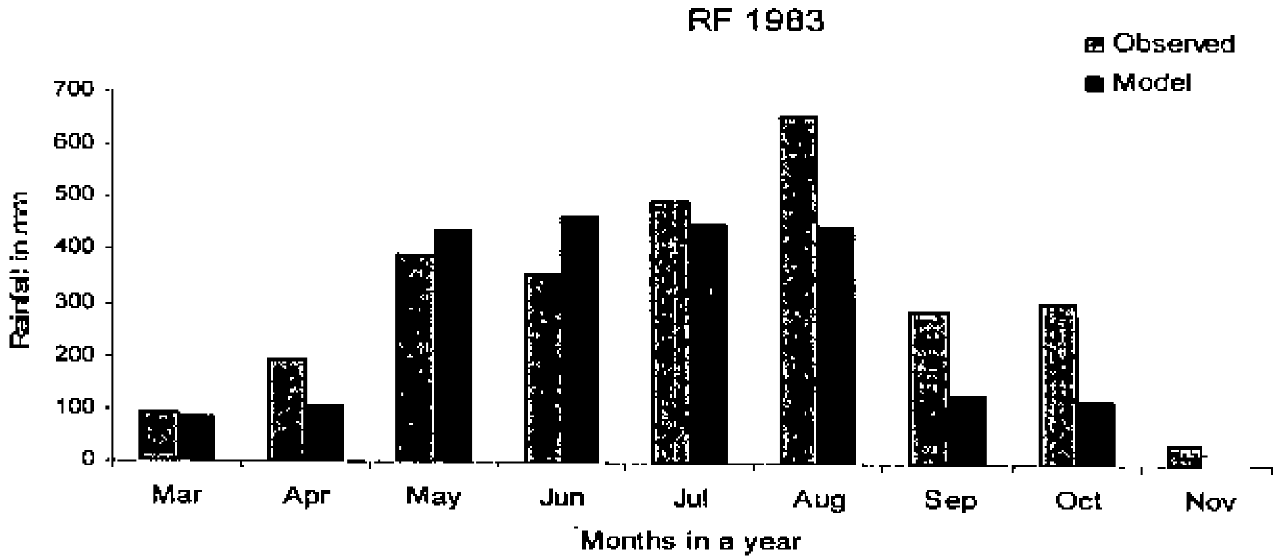

Fig.5.1.2 (b): Monthly average rainfall for observed and RegCM model.

From Fig. 5.1.2 (c), it is clearly measured the amount of model precipitation in the month of May is about (800-900) mm that is overestimated compared to BMD collection and monthly counted amount explicitly unexpected. The model overestimates approximately 50% than that of observed rainfall. In November to March BMD can not be capable to detect rainfall whereas net data remain visible something. The observed precipitation gradually decrease from June to November in 1984 where model is underestimated compared to observed precipitation. The observed rainfall abruptly changed from March to June whereas the modal breaks its sequence in May to August so average annual rainfall can be considered as 400-450 mm that approximately coincide with RegCM model.

From Fig. 5.1.2(d) it can be analyzed the heavy rainfall period and approximately dry period. In this case, BMD collection gradually increase from March-July and decrease July to November in 1985. The highest rainfall is measured in June & July about 400mm that are approximately 70% rainfall of the total annual where model over estimates compared to observed rainfall. The model is always capable to detect precipitation throughout the entire year whereas the observed remain absent in some months as November. In the month of April, BMD record is 30% lesser compared to RegCM model and even in November 1985. The natural balance depends on the climatic condition and air flow pattern of a country. When torrential rains perform from June to September, the annual average rainfall stored that can be counted (1200-1500) mm abont 70% of the total annual rainfall.

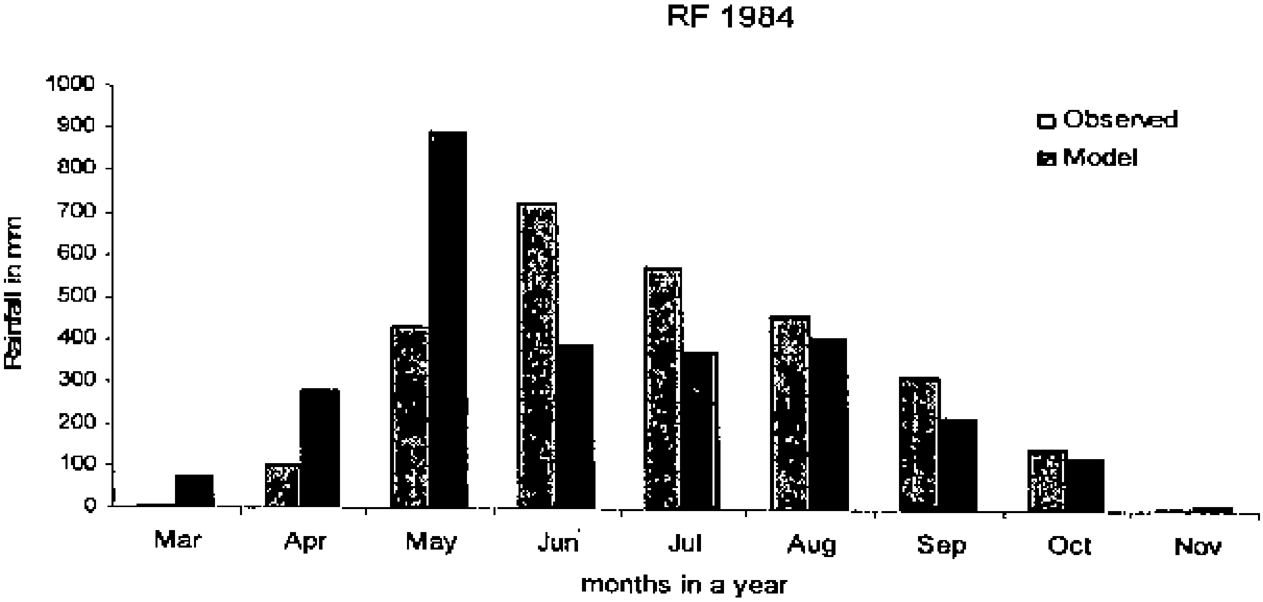

Fig. 5.1.2 (c): Monthly average rainfall for observed and RegCM model.

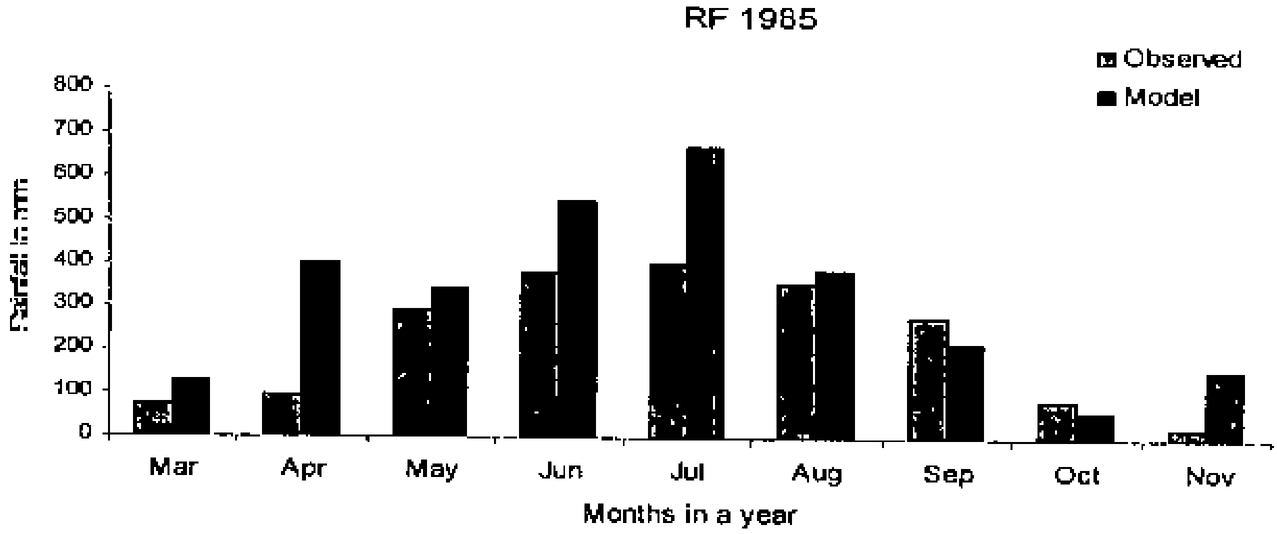

Fig. 5.1.2 (d): Monthly average rainfall for observed and RegCM model.

From Fig 5.1.2(e) it is easy to compare the model and observed rainfall variation in bar chat. In July and September of 1986, the huge amount of rainfall can be capable to measure by BMD whereas at the same period RegCM model can not be capable to detect such amount. So RegCM model remain underestimated position of about 45% of BMD collection. The period of June model overestimate about 30% compared to observed precipitation. As the variation happened between the two observations. So analysis must be difference between model and observed results. In March 1986, a few amount of rainfall is measured whereas at the same period model shows about 30% more precipitation from April to July rainfall gradually increase and then abruptly decrease till November 1986.

In Fig. 5.12(f) monthly observed precipitation is almost negligible from March to June 1987, whereas the model can be capable to show the expected results of net data. Only in July and August 1987, the huge amount of rainfall measured by BMD which is about 25% heavier than model. So model underestimates compared to observed data. In October and November 1987, the net data and observed data are very few. So maximum amount of rainfall can be able to record (600-700) mm by BMD observation and less amount (0-100) mm is measured during March, October and November. Month of July experience the highest rainfall and second highest rainfall is observed in August in Bangladesh for the year 1987 for observed rainfall. For model data, month of July experience the highest rainfall and the second highest rainfall at June is observed in Bangladesh for the same year.

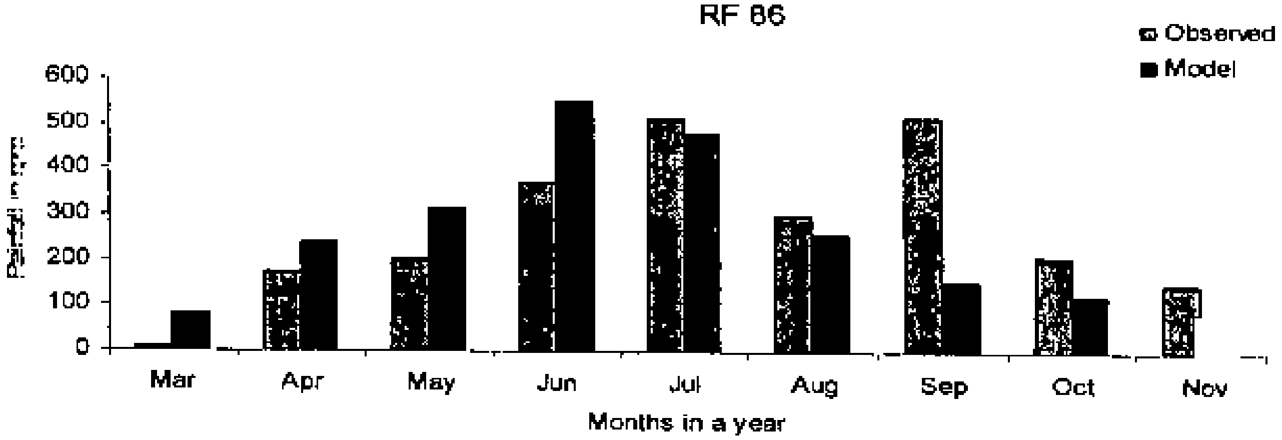

Fig. 5.1.2 (e): Monthly average rainfall for observed and RegCM model.

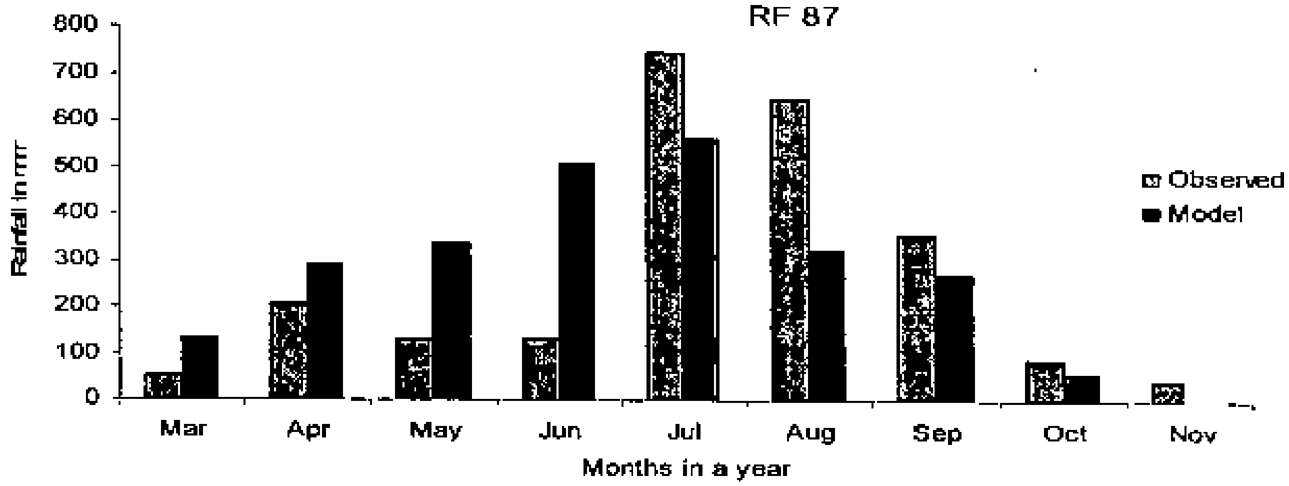

Fig. 5.1.2 (f): Monthly average rainfall for observed and RegCM model.

In Fig. 5.12(g), June is the highest rainfall month and the second highest rainfall month is May for model whereas June, July and August in Bangladesh for the year of 1988 for observed rainfall. For model data, month of June is the highest rainfall month and the second highest rainfall month is May that over estimates compared to BMD for the same year. The maximum amount of rainfall (700-800) mm is measured by BMD in the month of June 1988 which is about 30% of the total annual precipitation, Whereas RegCM model overestimates compared to BMD output. In the month of September, model can detect a few amounts of precipitation which underestimates compared to observed rainfall. In the year 1988, the total annual average rainfall for the both systems remains approximately equal. The average height of precipitation for the both cases is about (300-350) mm.

In Fig. 5.1.2(h) month of July is the highest rainfall and the second highest rainfall is observed in June and September in Bangladesh for the year 1989 for observed rainfall. For the model data, June is the highest rainfall month and the second highest rainfall month is July in Bangladesh for the same year. The maximum amount of rainfall about 450 mm is measured by BMD in the month of July where RegCM model underestimates compared to observed output whereas BMD can not be capable to detect the expected amount of rainfall in the month of March and November1989, at the same period, RegCM model shows sufficient amount of precipitation. The total average rainfall for the whole year is about 350-400 mm. In the month of July about 70% of the total annual rainfall is counted and about 1% of the total annual rainfall is measured in the months of March and November for the same period.

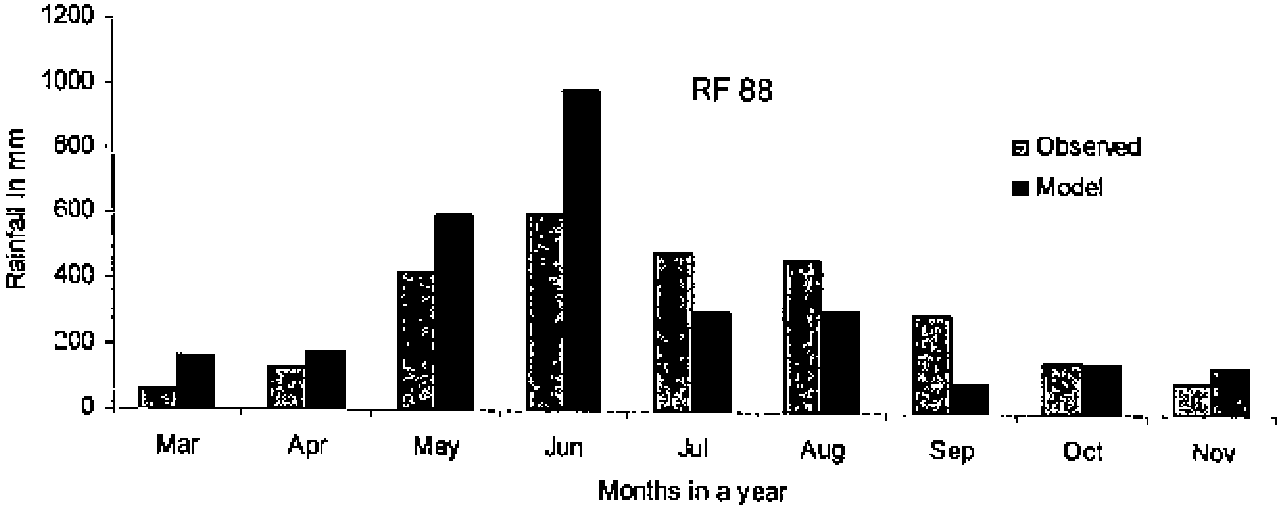

Fig.5.1.2 (g): Monthly average rainfall for observed and RegCM model.

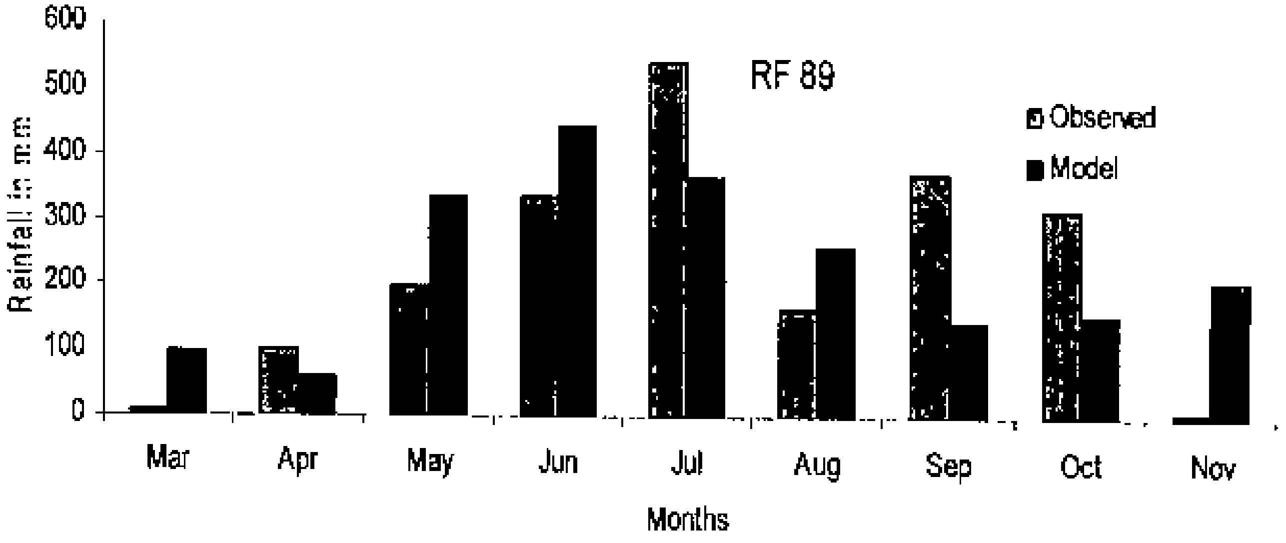

Fig. 5.1.2 (h): Monthly average rainfall for observed and RegCM model.

5.1.3 Seasonal rainfall variation over Bangladesh for observed and RegCM model

The yearly data of monsoon season have been used in this study for eight years. The spatial distribution of rainfall for the month of June to September shows the highest rainfall period in bar diagram in Bangladesh and second highest rainfall period in the pre-monsoon of Bangladesh is estimated.

In Fig. 5.1.3(a), the amount of monsoon rainfall in bar diagram about 1700 mm for observed data which under estimates compared to observed data in the year 1982 whereas in the period of Post-monsoon that is very few about 100 mm for observed collection which is overestimated by the RegCM model. The Post-monsoon was observed about dry in that year whereas the model would be able to detect something at the same period. But the rainfall in the pre-monsoon season shows the marginal level of precipitation for both cases. Therefore, the total annual average estimation showed poor performance for the year 1982.

The schematic diagram for the year 1983 is shown in Fig. 5.1.3(b), the monsoon rainfall about (1700-1800) mm for observed data is higher than the RegCM model data which is approximately 70% of the total annual rainfall of the country. The overall performance in three seasons for observed data is better than RegCM model data in the same year. This time is very useful for understanding the major periodicity associated with the Pre-monsoon, Monsoon and Post-monsoon seasons. In three seasons model underestimates compared to BMD collections. So this year gave the better performance of the model to the peoples' Republic of Bangladesh.

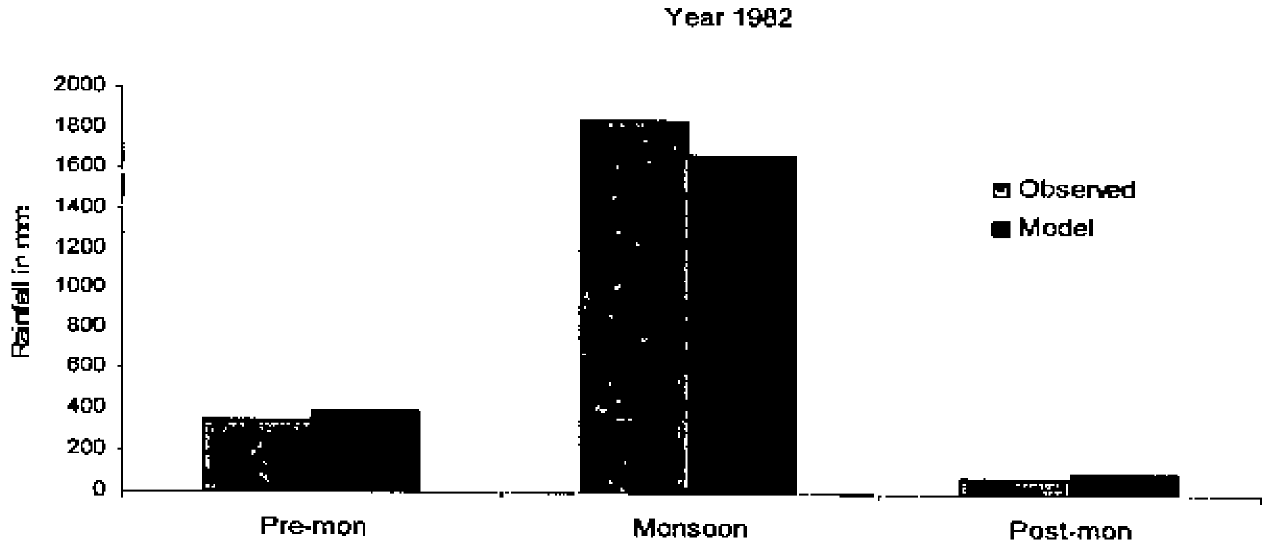

Fig. 5.1.3 (a): Seasonal Variation of Rainfall (mm) for observed and RegCM model.

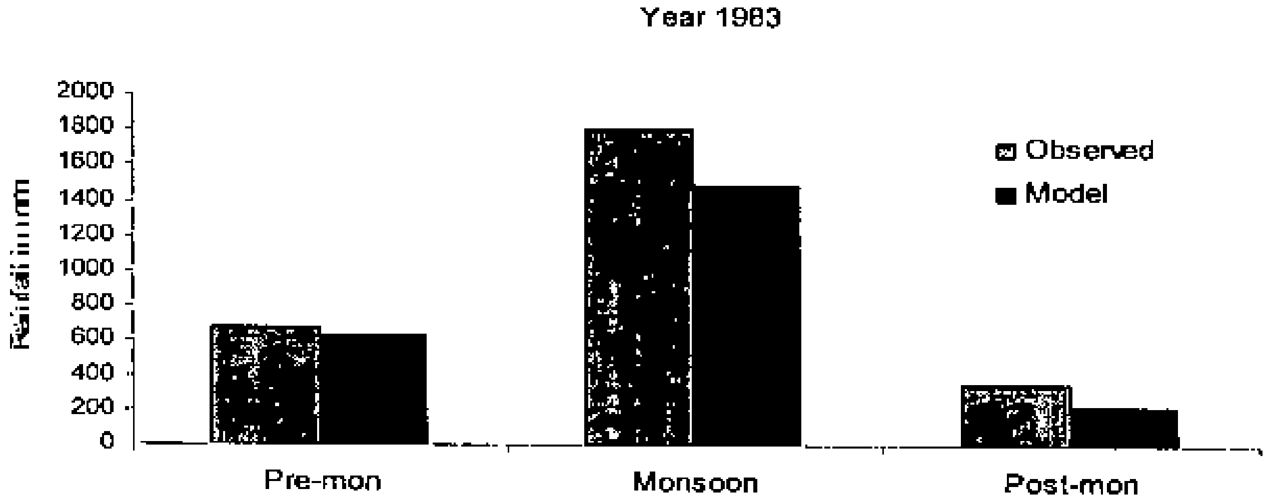

Fig. 5.1.3 (b): Seasonal Variation of Rainfall (mm) for observed and RegCM model.

In Fig. 5.1.3(c) it can be seen that Post-monsoon of observed collection in Bangladesh is somewhat better where model data under estimates compared to BMD collection for the year 1984. The monsoon rainfall for observed data about 2000 mm is higher than RegCM model data which is approximately 75% of the total annual rainfall of the country for the same year whereas in the Pre-monsoon season, the model overestimates the observed data by approximately 60%. The annual average rainfall for the year 1984 is about (400-450) mm which is less good than the previous year.

The seasonal variation of rainfall over Bangladesh is determined by observed data and RegCM model data for the year 1985 is shown in Fig. 5.1.3(d), the highest amount of rainfall about (1800-1830) mm for model data is measured which overestimates compared to the observed data. In this year, RegCM model also shows the better performance compared to BMD collection in Pre-monsoon and Post-monsoon seasons. In Post-monsoon, BMD collection is very negligible which is about (70-100) mm of rainfall that can be considered almost dry season.

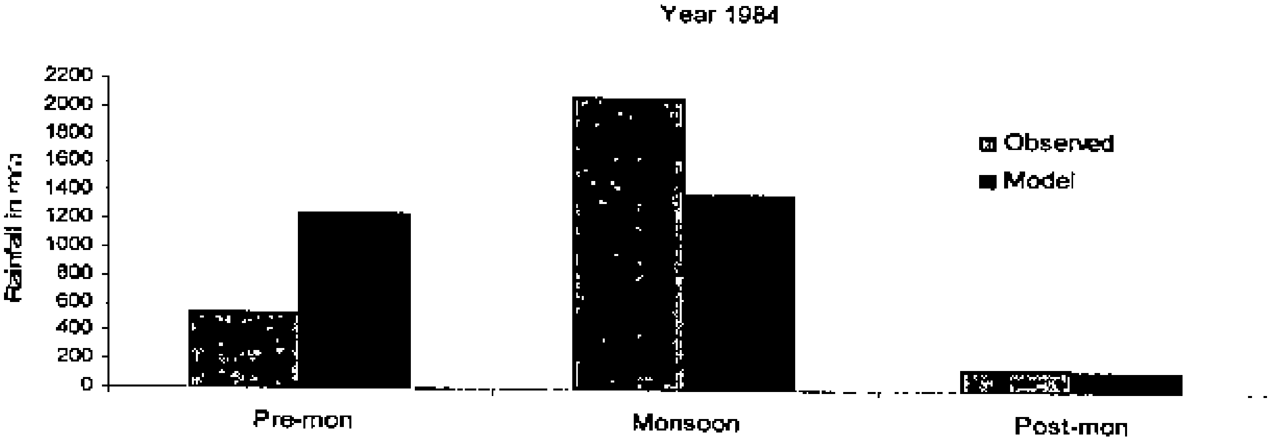

Fig. 5.1.3 (c): Seasonal Variation of Rainfall (mm) for observed and RegCM model.

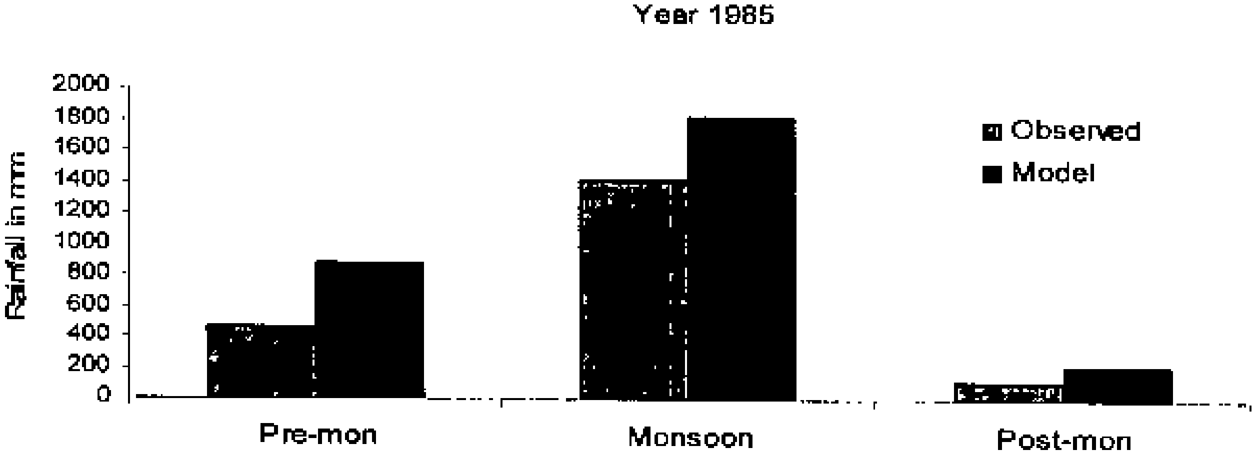

Fig. 5.1.3 (d): Seasonal Variation of Rainfall (mm) for observed and RegCM model.

In Fig: 5.1.3(e), the highest rainfall about 1700 mm rainfall which is almost 60% of the total annual rainfall of the country is observed by BMD in the year 1986 where RegCM model underestimates compared to observed data. The same manner is also seen in Post-monsoon by BMD which is about 400 mm of precipitation. Only in Pre-monsoon, the model overestimates compared to observed data. This year, 1986 is better for agricultural activities than previous year. The observed collection shows 30% better performance compared to RegCM model in case of Monsoon and Post-monsoon.

The schematic diagram is shown in Fig. 5.1.3(f) for the year 1987, the highest rainfall about 1820 mm is recorded by BMD where RegCM model underestimates compared to observed data in Monsoon season. The model detection is very poor in Post-monsoon that underestimates compared to observed data, this season can be considered almost dry. In Pre-monsoon, model performance is 30% better than BMD collection. The observed record is about (400-420) mm rainfall in Pre-monsoon where RegCM model overestimates compared to BMD collection.

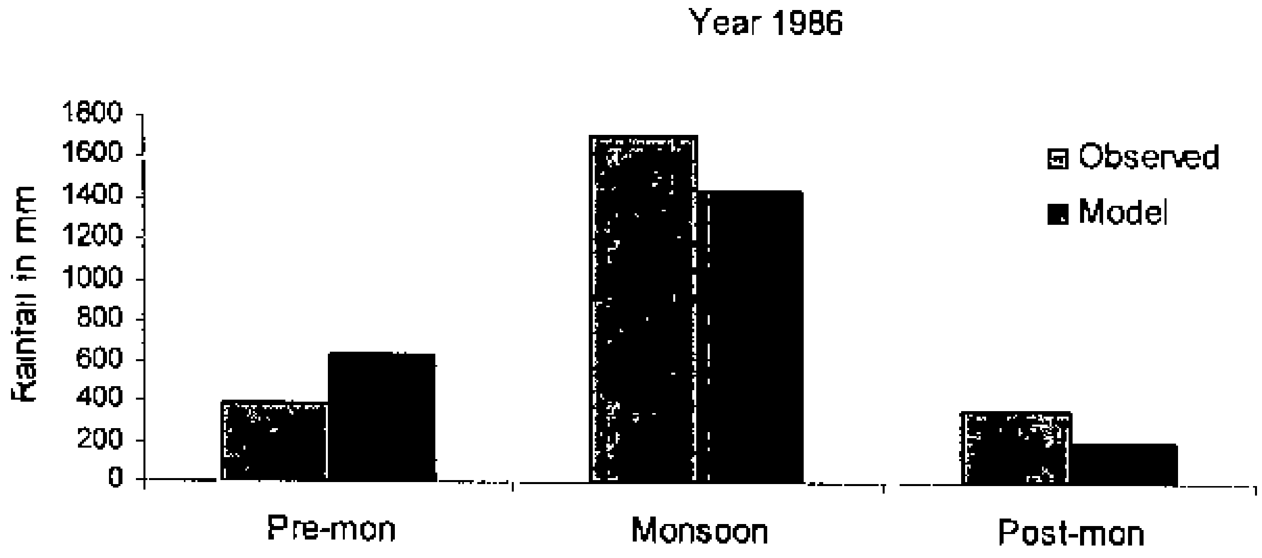

Fig. 5.1.3(e): Seasonal Variation of Rainfall (mm) for observed and RegCM model.

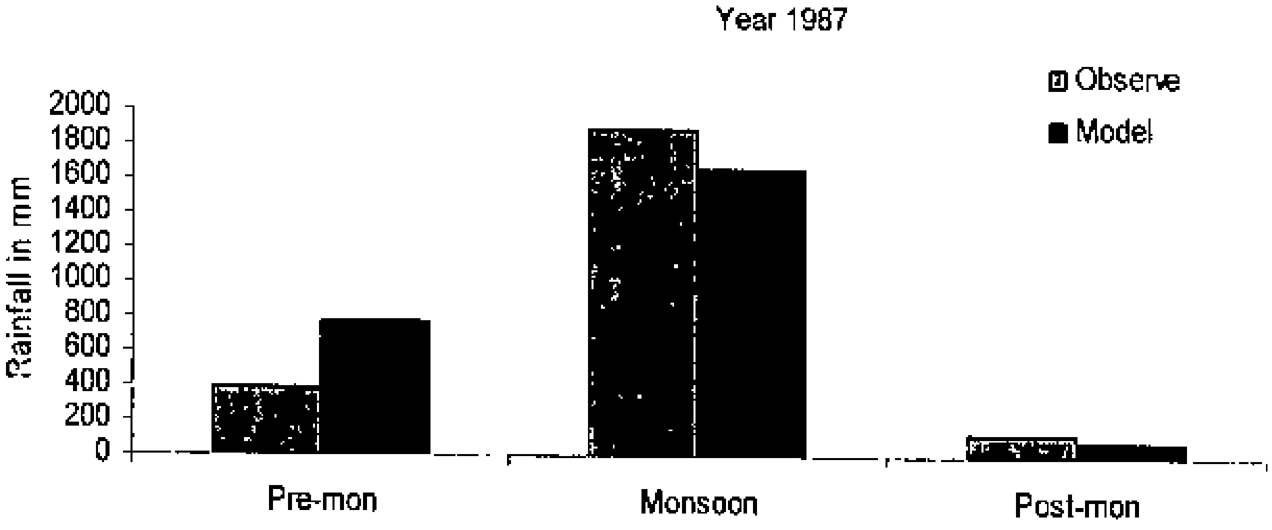

Fig. 5.1.3(f): Seasonal Variation of Rainfall (mm) for observed and RegCM model.

In Fig.5.1.3(g), the observed data collection is about (1800-1850) mm of rainfall which is almost 70% of the total annual rainfall in the year 1988 that is approximately 25% better than RegCM model. In case of Pre-monsoon and Post-monsoon, the model shows better performance compared to BMD. The overall results for the year 1988 gives better performance in agricultural sectors compared to previous year. As the economic and socio-economic conditions depend on the monsoon season, so this year can be considered better welfare to the people.

In Fig. 5.1.3(h), the highest amonnt of rainfall about (1400-1500) mm is observed by BMD where RegCM model underestimates compared to observed data for the year 1989. In this season, almost 65% of the total annual rainfall is measured by BMD whereas in Pre-monsoon and Post-monsoon seasons, BMD collection is poor compared to RegCM model. The performance of this year is better compared to the previous year. The socio-economic condition of the Peoples' Republic of Bangladesh was remaining well in that year. Some natural calamities snch as flood occurred during monsoon season which devastate our crops and other products in the fields and forests. As aus crop mainly in this season, the yield loss occurs by heavy monsoon rainfall in this season.

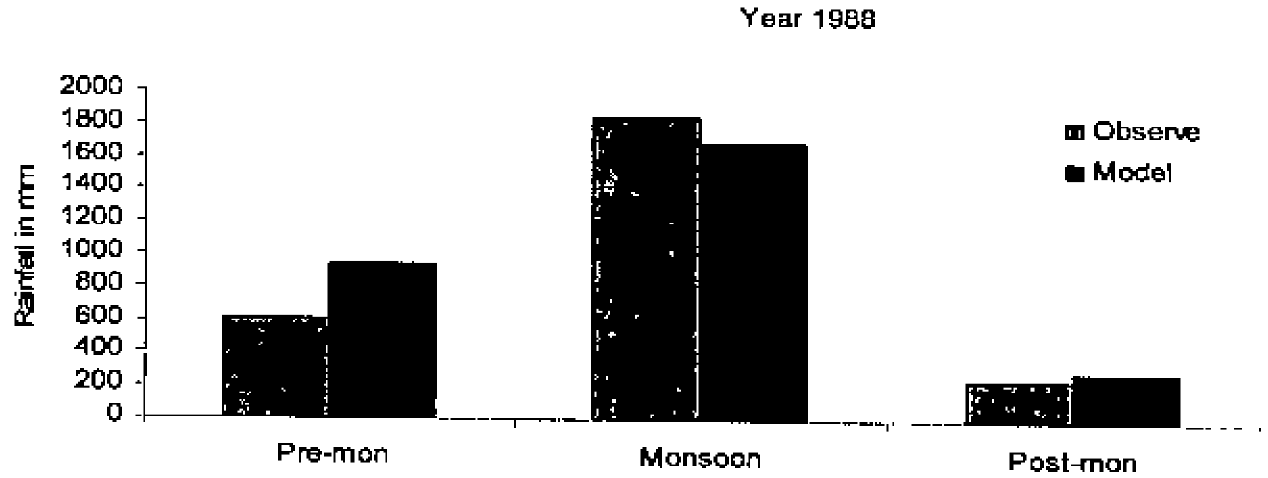

Fig. 5.1.3(g): Seasonal Variation of Rainfall (mm) for observed and RegCM model.

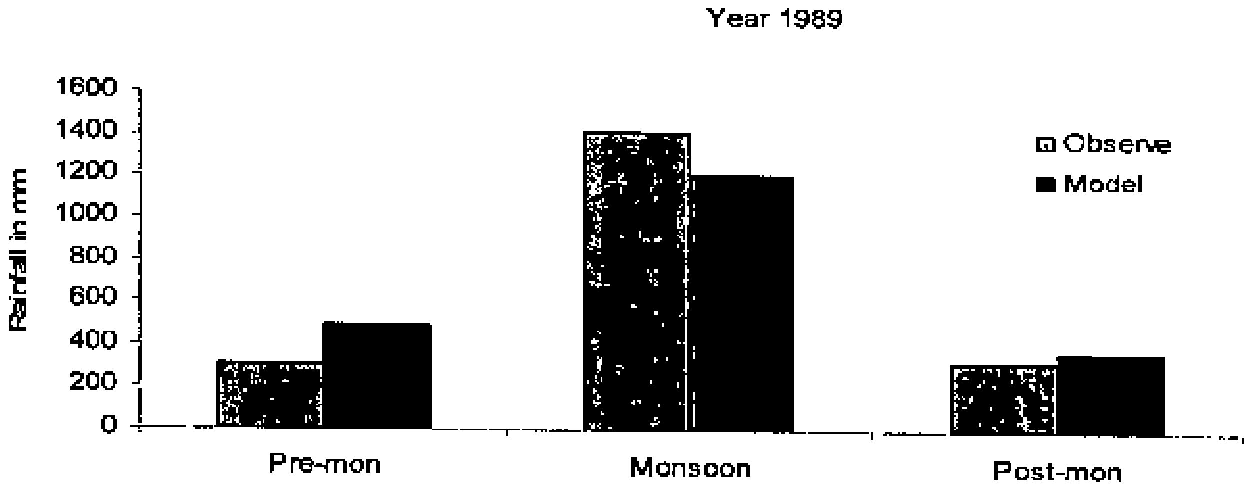

Fig. 5.1.3(h): Seasonal Variation of Rainfall (mm) for observed and RegCM model..

5.1.4 Yearly Station-wise rainfall variation over Bangladesh for observed and RegCM model

The highest rainfall is observed in Sylhet which is about 45% overestimated than RegCM model. The similarities are seen at Cox'sbazar, Madaripur, Patuakhali and Sandwip for the whole year 1982 where model data underestimates in differently. In Rajshahi net data is approximately 50% lesser than BMD annual collection. The overestimated annual model precipitation is detected in Bogra, Ishurdi, Jessore and Satkhira that are approximately similar to Rajshahi. In 1982, the annual average rainfall of (400-430) mm in Sylhet about 70% of the total annual rainfall of Sylhet Division.

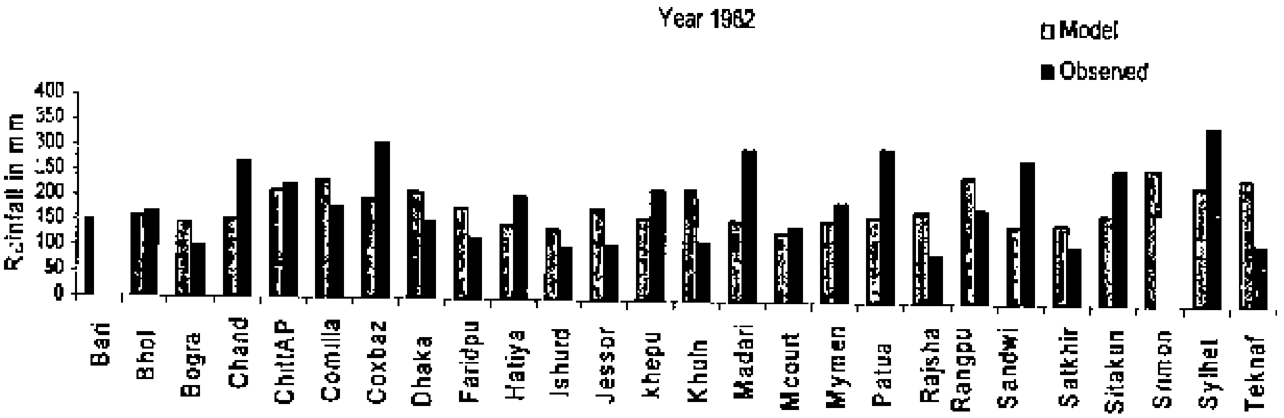

Fig. 5.1.4(a): Station-wise rainfall variation for observed and RegCM model.

The schematic diagram is shown in Fig. 5.1.4(b) for the year 1983, the highest rainfall is observed in Sylhet is about 430 mm of rainfall which is approximately 60% of the total annual rainfall of Sylhet and Chittagong Divisions. The second highest rainfall are observed at Chittagong, Cox's Bazar, Madaripur, Pataskala and Sitakunda at the same year that are all overestimated by RegCM model separately. The model and observed data are found sufficiently for the whole year 1983 at each station in Bangladesh. The annual average collection by BMD is about (200-220) mm of rainfall whereas the RegCM model capable to show nearly the same amount as observed accumulation. This year was the favorable period for cultivation crops to the cultivators.

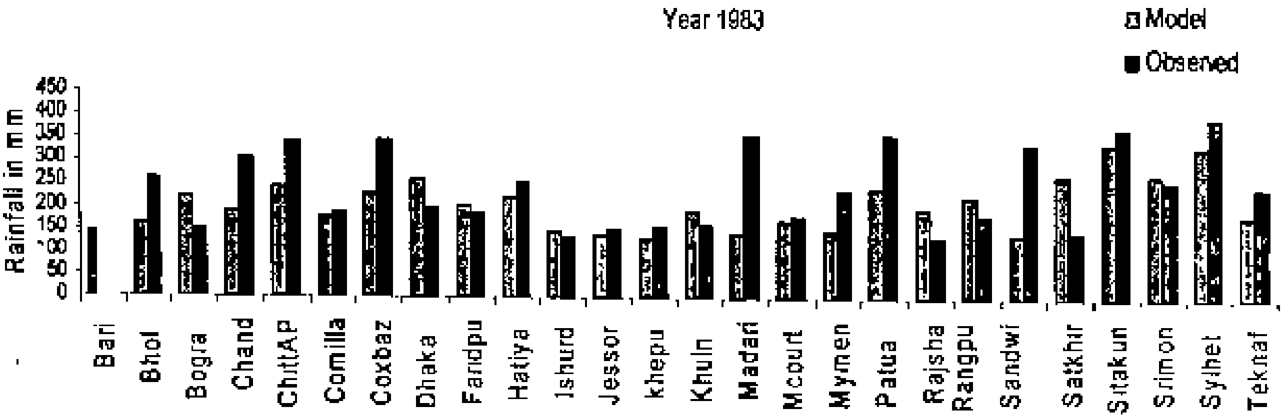

Fig. 5.1.4(b): Station-wise rainfall variation for observed and RegCM model.

The following features are obtained for observed and model rainfall in 1984 at different stations Fig. 5.1.1(c). The highest amount of RegCM model is seen at Sitakunda which is about 30% more overestimated than BMD collection, whereas the lowest amount of BDM collection is observed at Irshurdi. In the same year the annual average rainfall of (400-450) mm is about 60% of the total annual rainfall of Sylhet Division. In most of the stations, the model overestimated the observed rainfall, whereas in Chittangong, Cox's Bazar, Faridpur, and Sylhet are almost same amount of model and observed rainfall are compared. A few amount of rainfall is detected by BMD in some stations as Ishurdi, Rajshahi and Khepupara during the whole year.

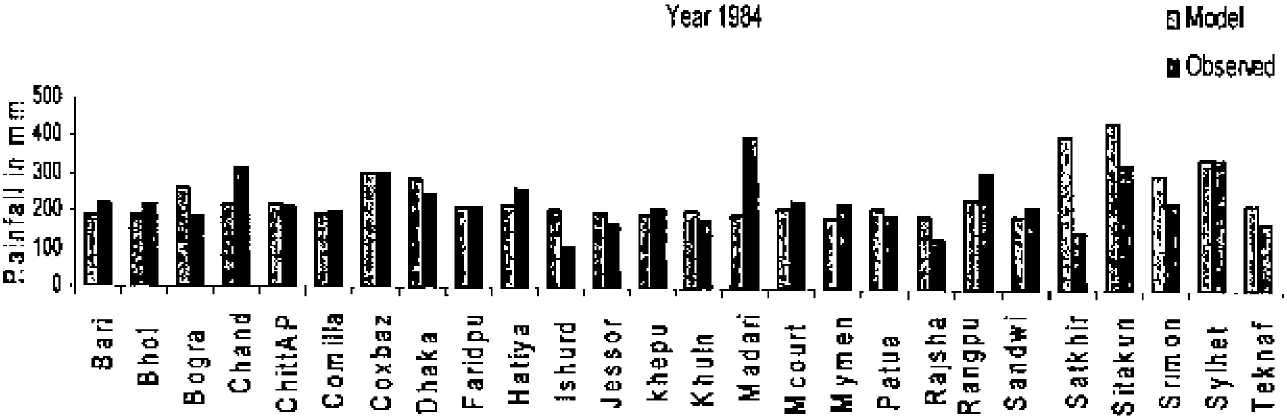

Fig. 5.1.4(c): Station-wise rainfall variation for observed and RegCM model.

The schematic diagram is shown in Fig. 5.1.4(d) for the year 1985, the highest rainfall about 480 mm is measured by BMD at Sylhet for observed data which is about 20% of the total annual rainfall of Sylhet Division. In this year the model can be able to detect good performance in almost each station that overestimates the observed rainfall. Analyses of the differences between model results and observed suggestions we get the precipitation fields are more acceptable the RegCM model compared to observed data. The lowest rainfalls at Cox's Bazar, Ishurdi, Khulna and Rajshahi which are about (100-150) mm for BMD collection where RegCM model data overestimates compared to BMD collection.

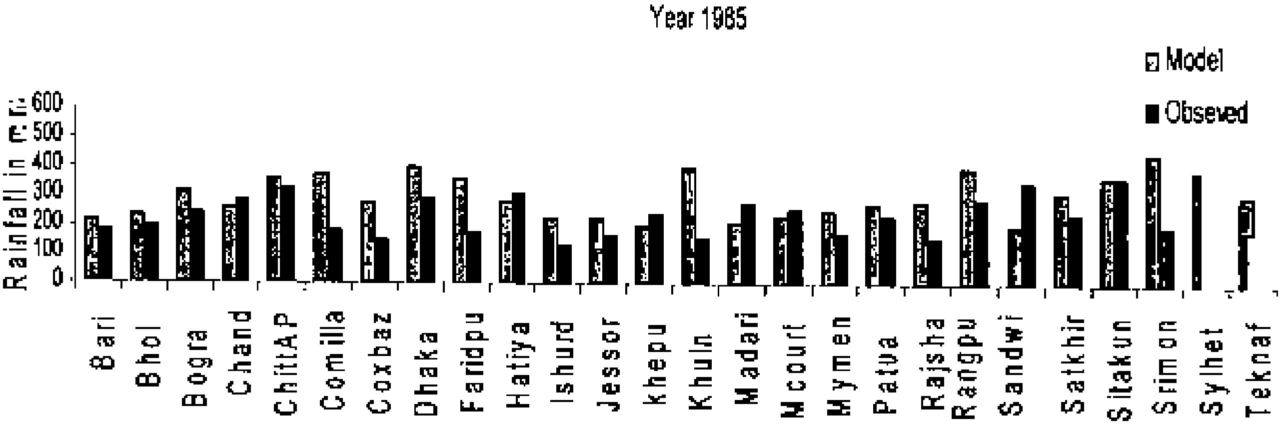

Fig. 5.1.4(d): Station-wise rainfall variation for observed and RegCM model.

The station-wise rainfall in the year 1986 is observed by BMD is fewer amounts at the stations as Ishurdi and Rajshahi compared to RegCM model. In fig: 5.1.1(e) Srimongal and Dhaka the highest amount of precipitation is detected by net data which is almost 35% overestimated more than BDM collection. The total annual precipitation recorded by net is about (300-350) mm that are approximately 40% of the total annual rainfall of the country. The station wise response gives an idea that the minimum rainfall is the north-west region of Bangladesh and maximum rainfall is the north-east region of the country. The average annual rainfall is considered for the whole year 150 mm. The stability condition does not attain between model and observed precipitation for long period in 1986. In coastal region net data is less detected and it is about 30% less than BDM collection. Only the hilly areas are substantially heavy rainfall region detected by model.

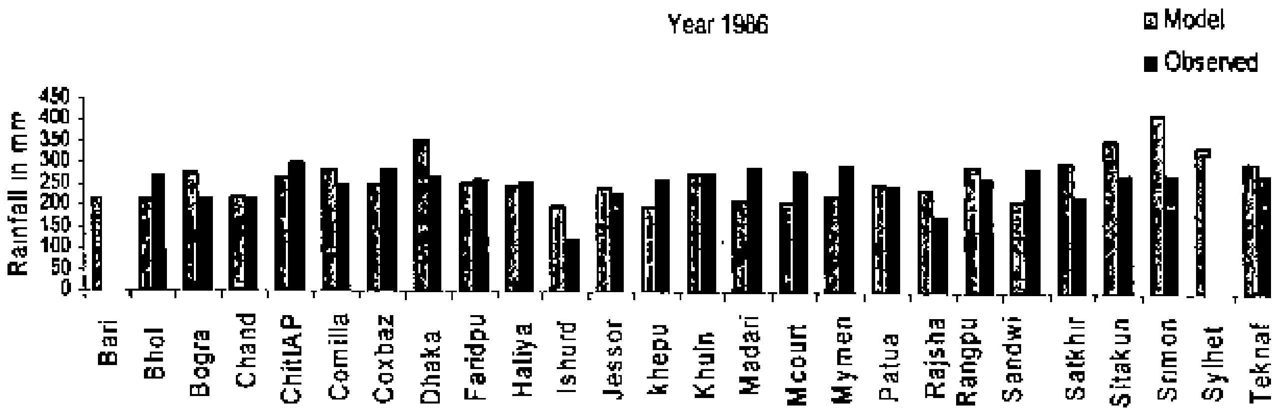

Fig. 5.1.4(e): Station-wise rainfall variation for observed and RegCM model.

The variation of yearly station-wise rainfall over Bangladesh for the year 1987 is shown in Fig. 5.1.4(f), the highest rainfall about 350 mm is at Cox's bazar and Sylhet by BMD collection which is about 40% of the total annual rainfall of Sylhet Division whereas the highest rainfall about 380 mm is found at Srimongal by RegCM model. The lowest rainfall about 100 mm at Rajshahi and Ishurdi are found by BMD where net data overestimates compared to observed data.The performance of net data collection is always proceeding ahead compared observed data. The annual average rainfall collection by BMD is about (100-150) mm for the whole year.

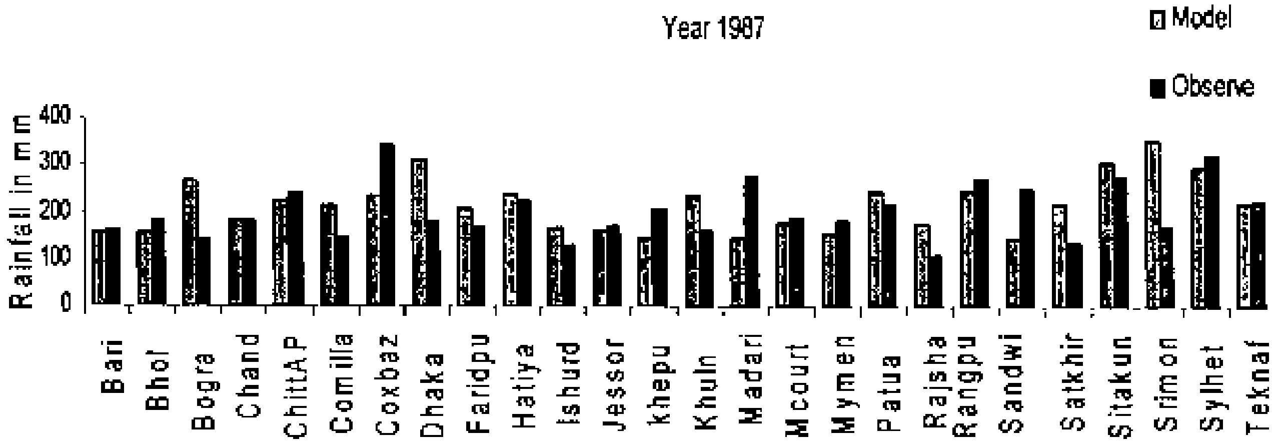

Fig.5.1.4 (f): Station-wise rainfall variation for observed and RegCM model.

The station-wise annual average rainfall variation over Bangladesh for the year 1988 is shown in Fig. 5.1.4(g), the highest rainfall about 420 mm is observed at Sylhet which is approximately 60% of the total annual rainfall of Sylhet Division where the net data underestimates compare to BMD collection. The lowest rainfall collection by BMD is about (70-100) mm at Rajshahi where RegCM model overestimates compared to BMD collection. The annual average rainfall for the whole year is about (200-230) mm for observed data whereas the average performance of RegCM model data is sufficiently better for the year 1988. The results show that the variability patterns are not uniform at station –to-station which is due to the cause of heterogeneous orographic characteristics of Bangladesh; as north-east region is the hilly, west region is the plain land and south region is the coastal alluvial in Bangladesh.

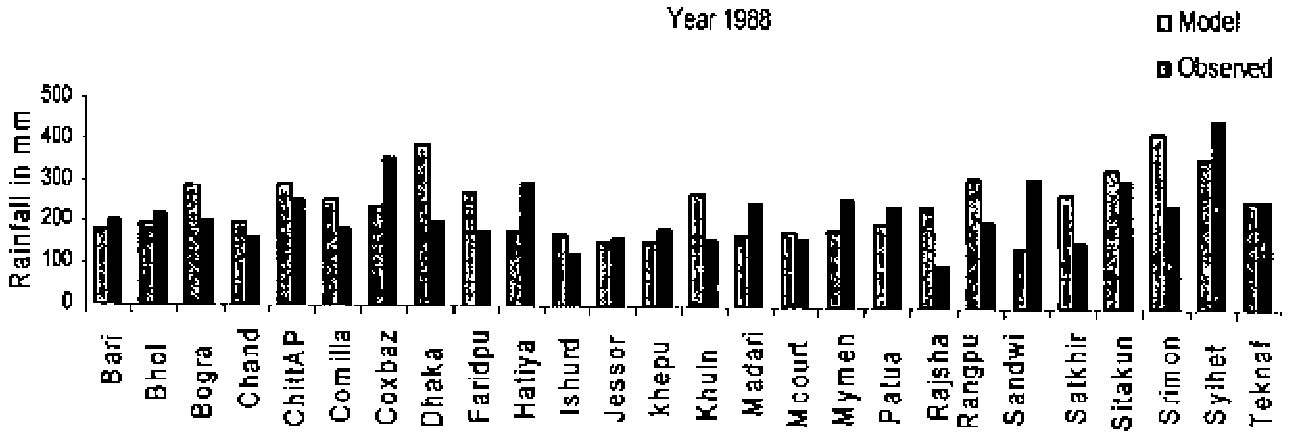

Fig. 5.1.4(g): Station-wise rainfall variation for observed and RegCM model.

It can be analyzed the difference between model result and observation in the year 1989 that suggests the precipitation is more detected by BMD at Sylhet about (450-500)mm rainfall annually recorded that are about 60% of the total rainfall of Sylhet Division. In fig. 5.1.1(h) the less amount rainfall are detected by BMD at Rajshahi, Sathkhira, Maijdi-court, Jessore and Bogra compared to RegCM model. The exactly same amount of precipitation has been found by BMD at Sandwip, Madaripur, Hatiya and Chittagong that are more than RegCM model output. The annual record amount by BMD is about 30% more compared to RegCM model precipitation. Generally simple precipitation has been observed in plain region and heavy precipitation region in hilly area detected by BMD, whereas model can not detected more precipitation in hilly area. The total precipitations gradually decrease towards the coastal region compared to plain area in case of BMD. The model appreciably shows the similar precipitation for the whole year and is about 10% more than BMD collection in case of annual total rainfall. The model has been able to simulate these spatial distributions in both cases at landmass and coastal regions.

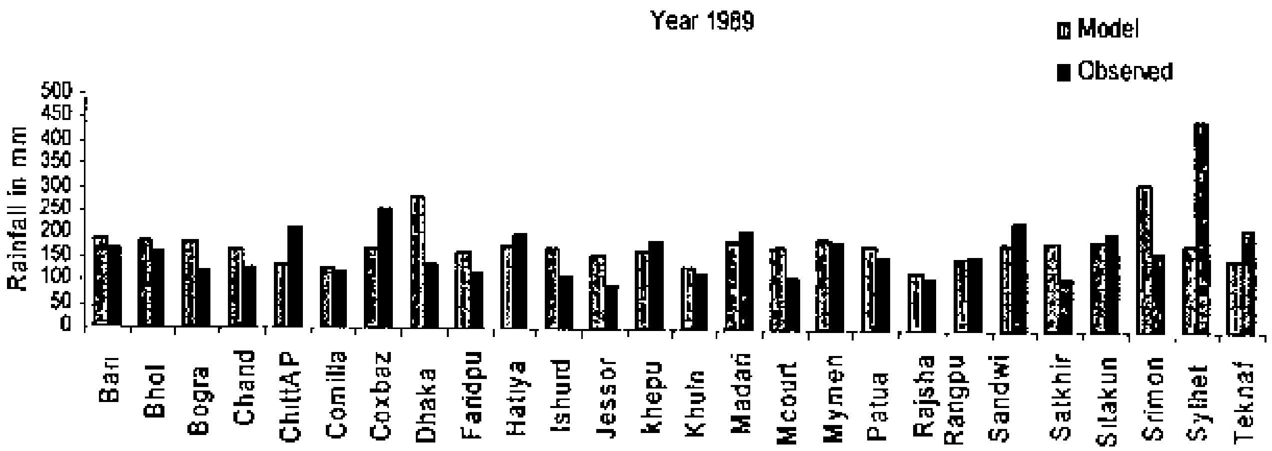

Fig. 5.1.4(h): Station-wise rainfall variation for observed and RegCM model.

5.1.5 Year-to-year rainfall variation iso-line at contour map in Bangladesh for observed and RegCM model

There are six seasons mainly follows in Bangladesh depending on the climatic conditions. Among these six seasons monsoon is the vital season that governs mainly on the country, as the period which brings forth torrential rains (1700-1800) mm average rainfall of the country in this seasons. This monsoon season mainly governs the life-style and socio-economic conditions of the people of Bangladesh. Variations of season give the evidence of climate variability over the whole country. Seasonal variation of rainfall is the most distinguishing feature of densely populated region of Bangladesh. Year-to-year variation of season occasionally leads to extreme hydrological events (i.e. large scale droughts and floods) over major parts of the country; these results are serious reduction in agricultural sector that affects greatly to the national economic conditions.

As the monsoon season starts from the first week of June every year, the onset of the monsoon takes place with the northward movement of the Inter Tropical Convergence Zone (ITCZ) due to the development of the large scale north-south thermal gradient between landmass of south Asia and the Indian Ocean. During monsoon seasons, the torrential heavy rainfall conditions for about three or more days (Quardir et al., 2005) that onset gradually takes place over the areas north of the Bay of Bengal i.e. over Bangladesh.

In Fig. 5.1.5(a) the spatial distribution of rainfall for the year 1982 shows the highest rainfall areas in the north-east of Bangladesh and the second highest rainfall areas lie in the south-east of Bangladesh in case of model contour map, the same conditions observed in BMD collections. In this case the RegCM model data overestimate the observed data especially in the north-west region of Bangladesh. We can see the lowest rainfall in the south-west region where RegCM model overestimates compared to BMD data. For both cases, the hilly areas are observed in the heavy rainfall region in Bangladesh where approximately 60% rainfall occurred during the whole year. About 30% regions remain dry for BMD performance, although RegCM model can be able to show something precipitation, especially north-west region of Bangladesh for the collection of observed data. The rainfall intensity is seen substantially reduce more or less in rest of the region of Bangladesh. These estimations are very useful for understanding the major periodicity associated with the pre-monsoon, Monsoon and Post-monsoon.

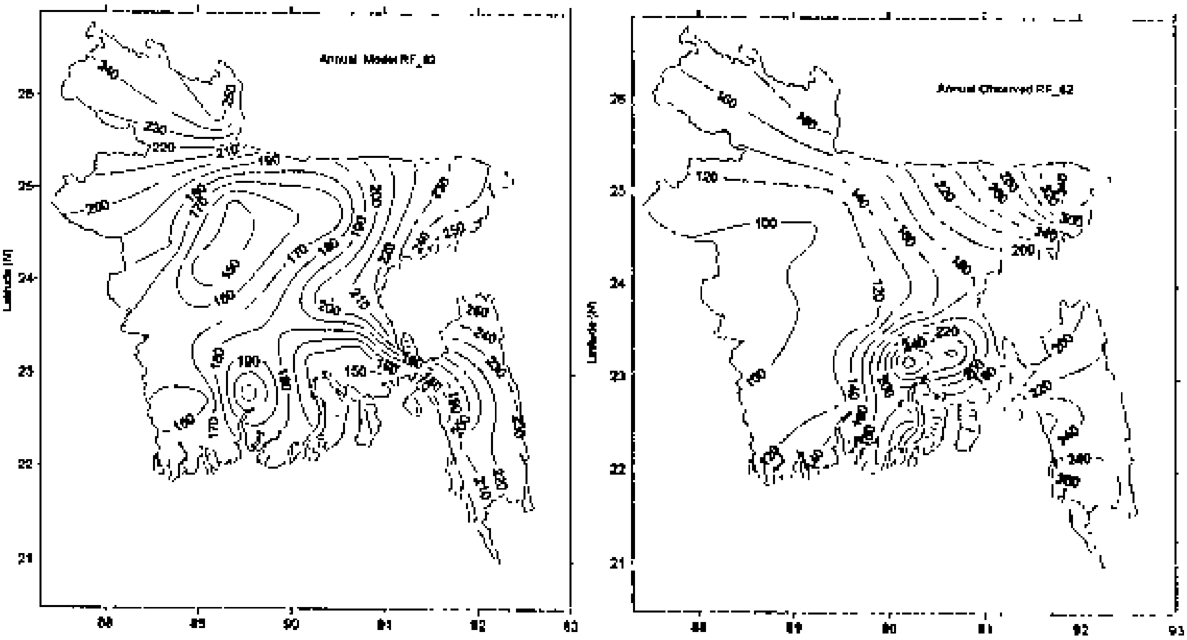

Fig. 5.1.5(a): Rainfall variation at contour map for observed and RegCM model.

The variation of rainfall is shown Fig. 5.1.5(b) for the year 1983 over Bangladesh map, the highest rainfall region is in the north-east and the 2nd highest is in the south for RegCM model data and for observed data it is somehow varies. The highest rainfall region is same as model and 2nd highest region is in the south-east part of the country for observed collection. The poor rainfall region is to the western part of Bangladesh in case of BMD observation whereas the model shows something for the central and north-west part of Bangladesh. The iso-line decreasing gradually to west for observed data and for the model it is shown to the south and coastal area. For most of the areas, model overestimates the observed data.

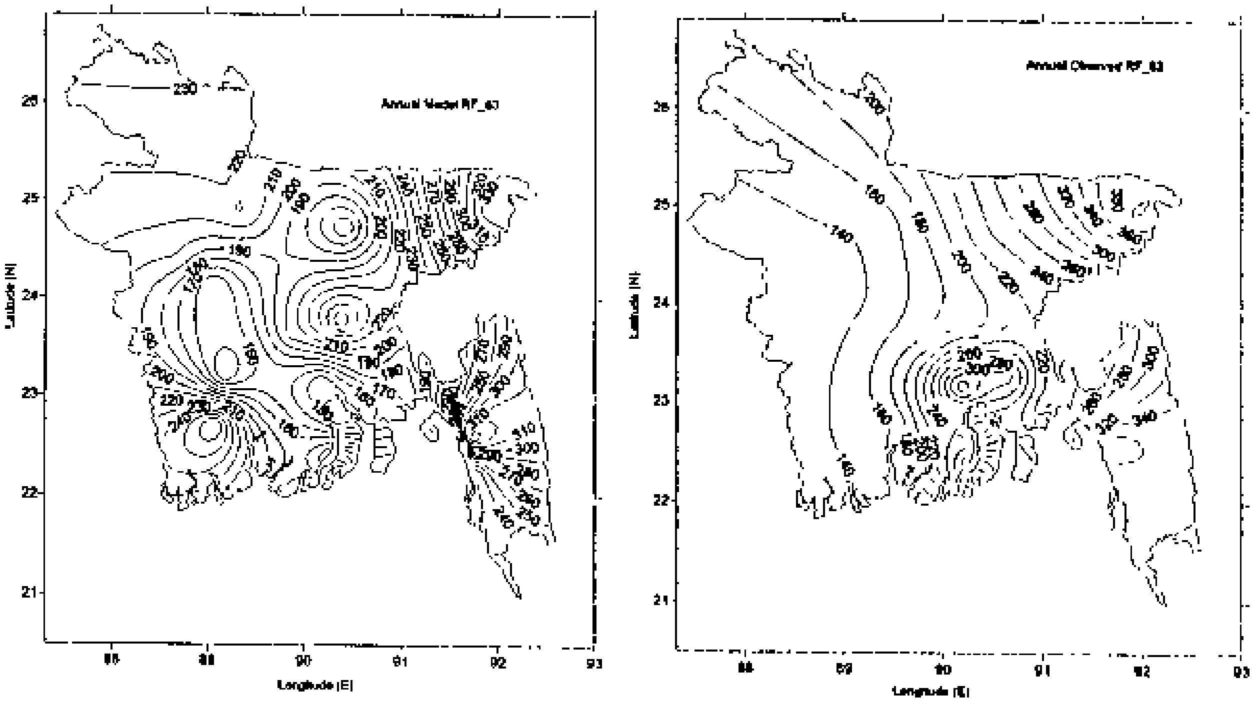

Fig.5.1.5 (b): Rainfall variation at contour map for observed and RegCM model.

From Fig. 5.1.5(c) it can be seen that the spatial distribution of rainfall for the year 1984, the highest rainfall region is in the eastern part and the 2nd highest rainfall area is in the south-west part of Bangladesh for RegCM model, whereas it is seen for observed data, the highest region is the north-east and the 2nd highest rainfall region is the central part of Bangladesh for the same year. For observed data, the dry and poor rainfall region is seen to the north-west and western part of Bangladesh, whereas the model can be capable to show something everywhere for the same year. The iso-line gradually increasing to the east for RegCM model data and it is found same to the eastern part of Bangladesh for observed data. About the overall of Bangladesh, the model overestimates the observed data.

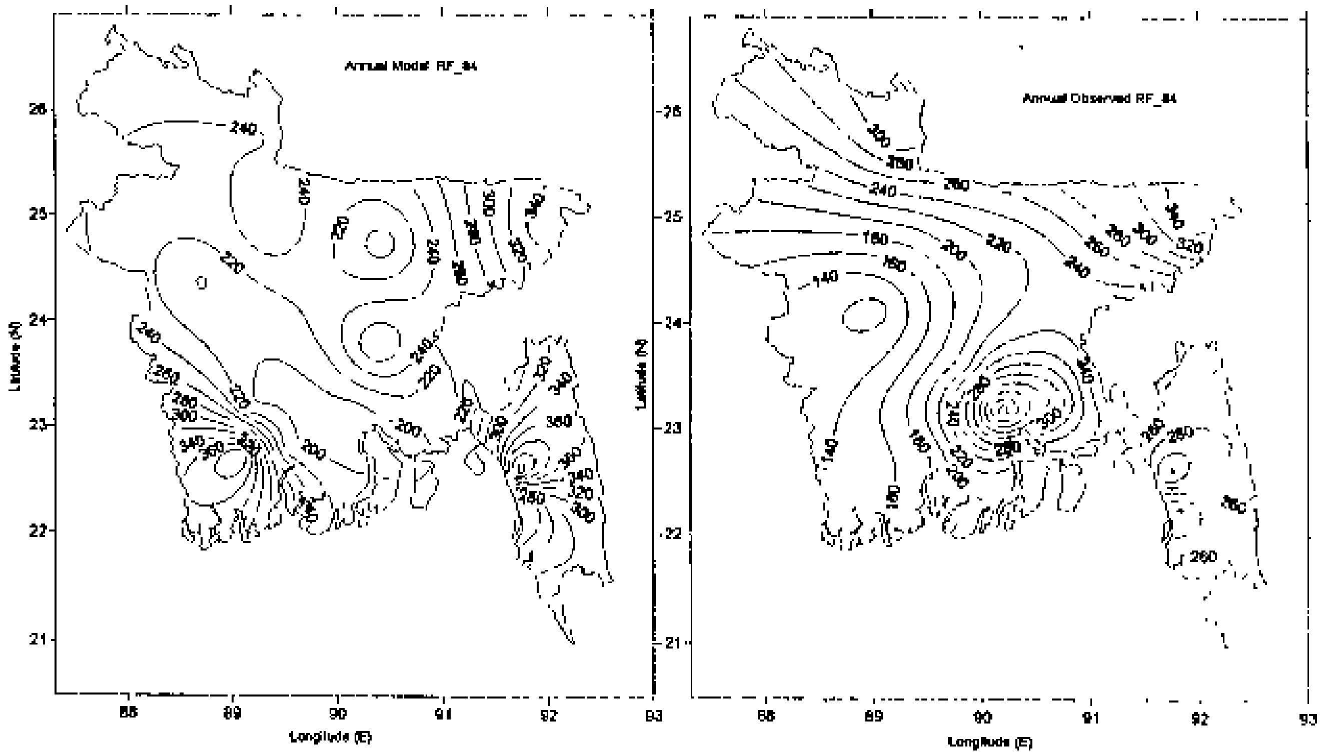

Fig. 5.1.5(c): Rainfall variation at contour map for observed and RegCM model.

It can be seen from Fig. 5.1.5(d) the spatial distribution of rainfall for the year 1985, the highest rainfall area is in the north-west part and less rainfall region is to the south and coastal area for model observation whereas the highest rainfall region is in the north-east part and lowest region is in the south-west part of the country is shown for observed data. The rainfall intensity of model data is seen substantially much more to the eastern part of Bangladesh whereas for observed data it is similar to the north-east of Bangladesh. The western part of the country remains almost dry and the annual average rainfall is very poor for observed data, whereas RegCM model can be able to detect something for the same year.

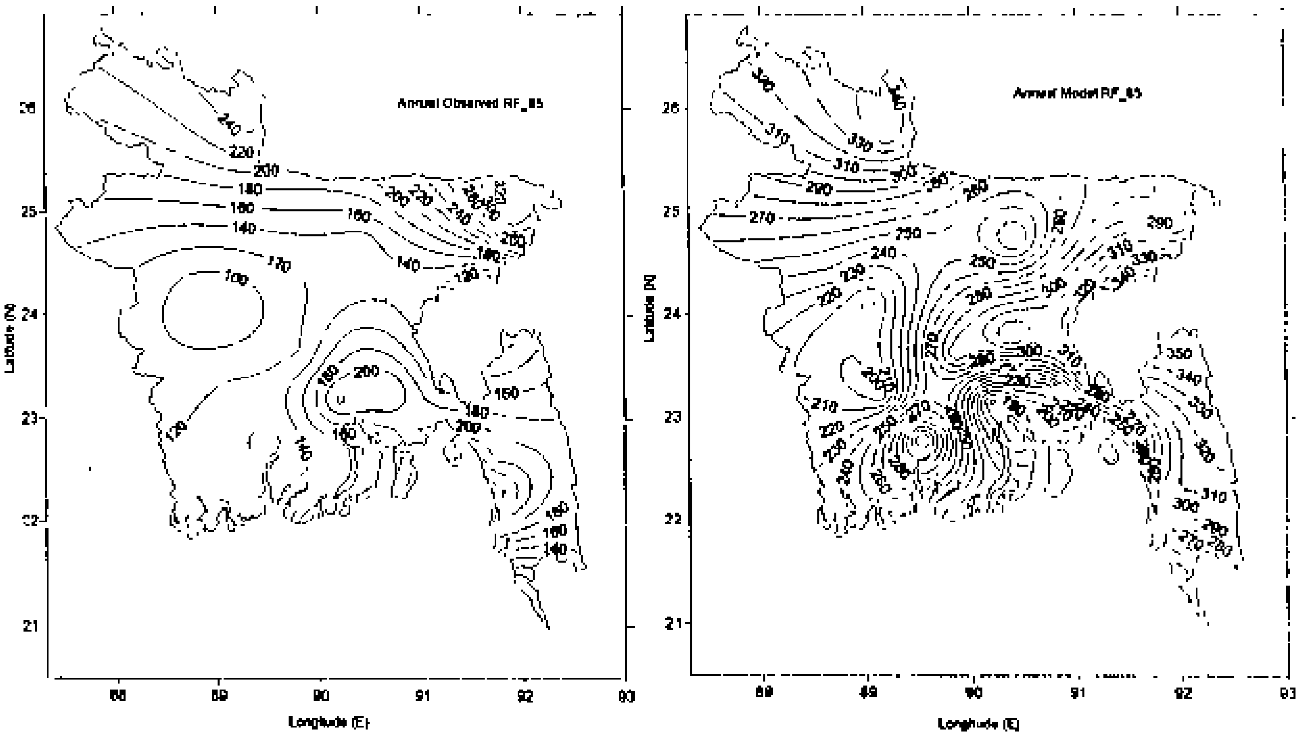

Fig. 5.1.5 (d): Rainfall variation at contour map for observed and RegCM model.

In Fig. 5.1.5(e) the heavy rainfall region of Bangladesh is seen for RegCM model observation is in the central and north-west part and less rainfall region is to the south and coastal area for the year 1986. At the same time, the observed data shows the highest rainfall region in the north-east of Bangladesh and less rainfall or about dry region in the western part north-west of the country. The iso-line gradually decreasing to the western side for observed data and for RegCM model data is also similar to the iso-line of observed data line. The annual average rainfall observation is overestimated by model compared to observed precipitation. The central part of Bangladesh remains poor rainfall region for observed precipitation in the year 1986.

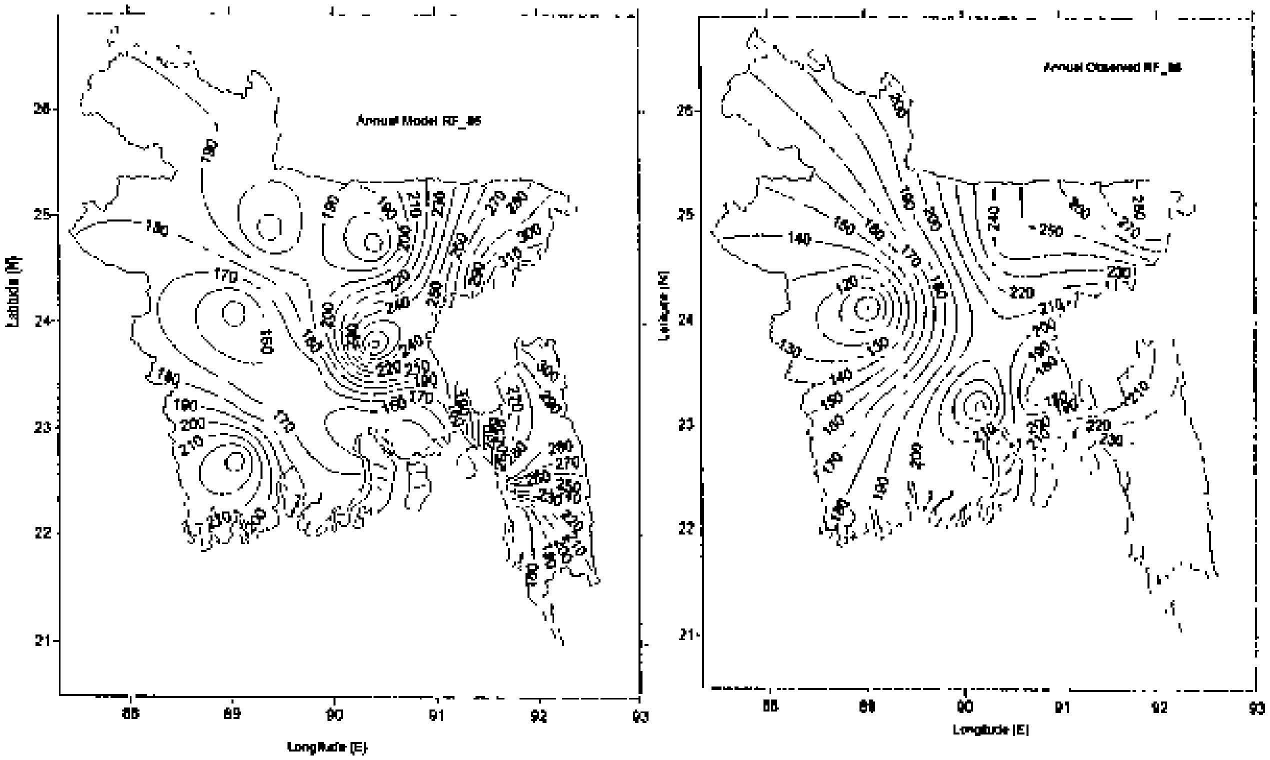

Fig.5.1.5 (e): Rainfall variation at contour map for observed and RegCM model.

From Fig. 5.1.5(f) it can be seen that the spatial distribution of rainfall for the year 1987, the highest rainfall shows in the north-east region and the 2nd highest rainfall shows in the south-east i.e. hilly area and less rainfall is from central part to western part of Bangladesh for observed data. The model data for the same year shows the highest rainfall in the same part as observed data and the 2nd highest rainfall is in the hilly area of Bangladesh. The similar iso-line gradually decreasing from central part towards western part and also to coastal region. The annual average rainfall is very poor to the western part for observed data as well as RegCM model precipitation. So total annual rainfall is overestimated by RegCM model compared to observed precipitation.

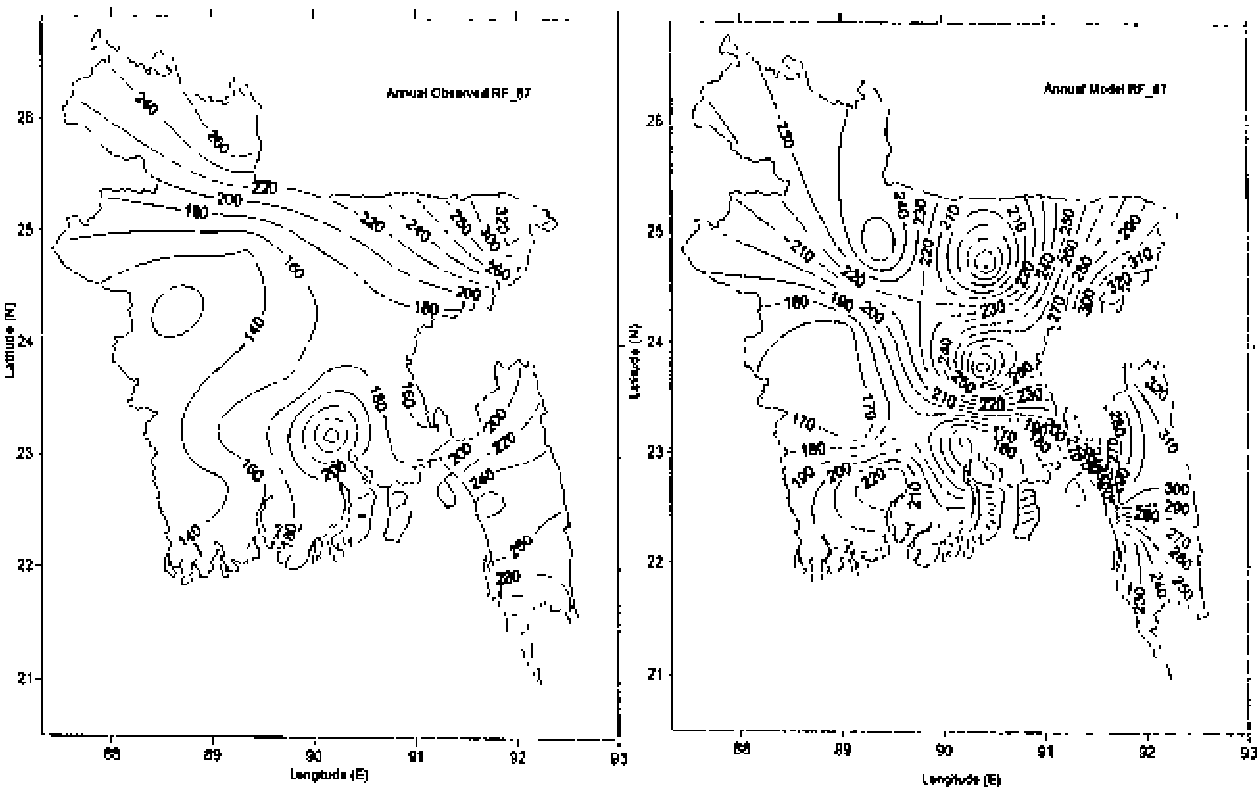

Fig.5.1.5 (f): Rainfall variation at contour map for observed and RegCM model.

The schematic diagram is to be seen in Fig. 5.1.5(g) that the spatial distribution of rainfall for the year 1988, the highest rainfall shows in the north-east region and the 2nd highest rainfall in the south-east i.e. hilly area and poor rainfall area is in the western part of Bangladesh for the observed data. The model data for the same year also shows the same pattern as observed data. The iso-line gradually decreasing towards western part of Bangladesh for observed data whereas the model data shows the well performance to same site. The observed data give the same performance as RegCM model data to the coastal area of Bangladesh.

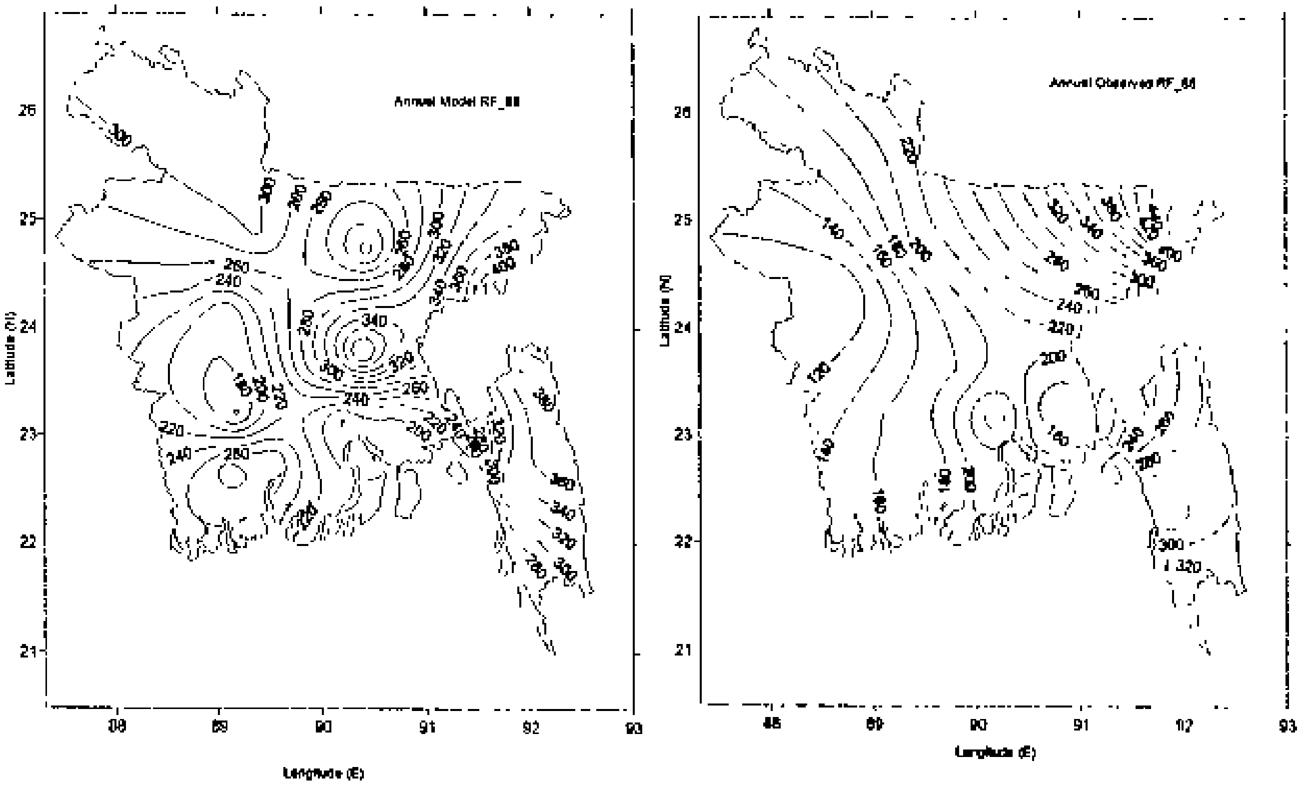

Fig.5.1.5 (g): Rainfall variation at contour map for observed and RegCM model.

The spatial distribution of rainfall for the year 1989 is shown in Fig. 5.1.5(h) the highest rainfall area is in the north-east and the 2nd highest rainfall region is in the south-east of Bangladesh for observed data. The model data shows for the same year as similar pattern as observed data. The poor rainfall area is from central part to south and south-west of Bangladesh for observed data. The same condition of iso-line for model data is from central part to the north-west of Bangladesh. The amount of annual average rainfall for observed data where RegCM model overestimates slightly compared to observed data. The observed data intensity is seen substantially reduce to west side of Bangladesh whereas the model reduce towards the north-west of Bangladesh.

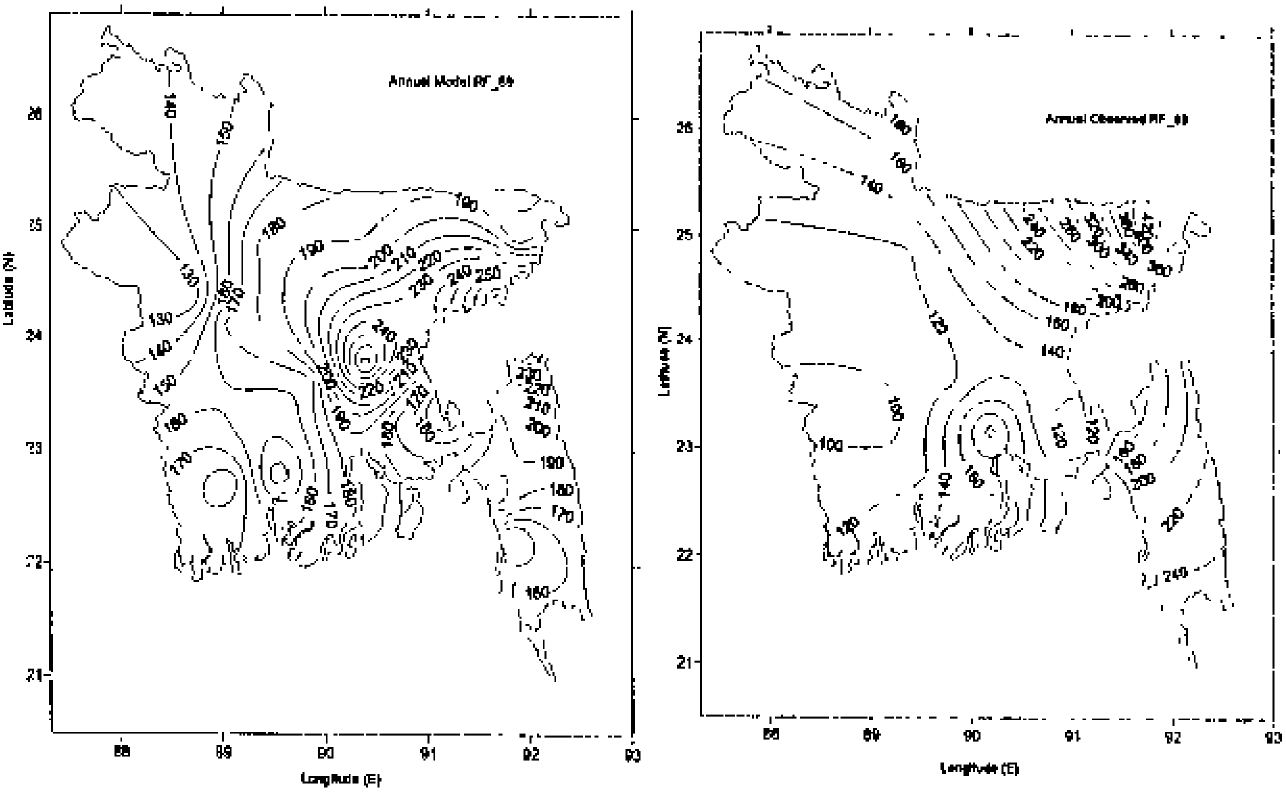

Fig: 5.1.5 (h): Rainfall variation at contour map for observed and RegCM model.

5.1.6 Annual Variation of Rainfall for Observed and RegCM model

From Fig.5.1.6 (ii), it can be seen that the annual highest rainfall shows in 1985 and the second highest rainfall is observed in 1988 for RegCM model in Bangladesh during the period 1982-89. Relatively lower amount of annual rainfall occurs in 1985 for the observed data. Another way it can also be seen that the highest rainfall is obtained in 1988 and the second highest rainfall is observed by BMD in 1983 for the same period. Very low amount of rainfall occurs in 1982 for model data and in 1989 for observed data. The annual rainfall indicates that both observed and model rainfall follows unimodal variation of rainfall for the period of 1982-89. This result shows the discrepancy between observed and model rainfall. Hence the change of the model option is necessary to check this discrepancy. The Grell and Fritch-Chappell scheme in RegCM is described in details at Table 06 and in appendix.

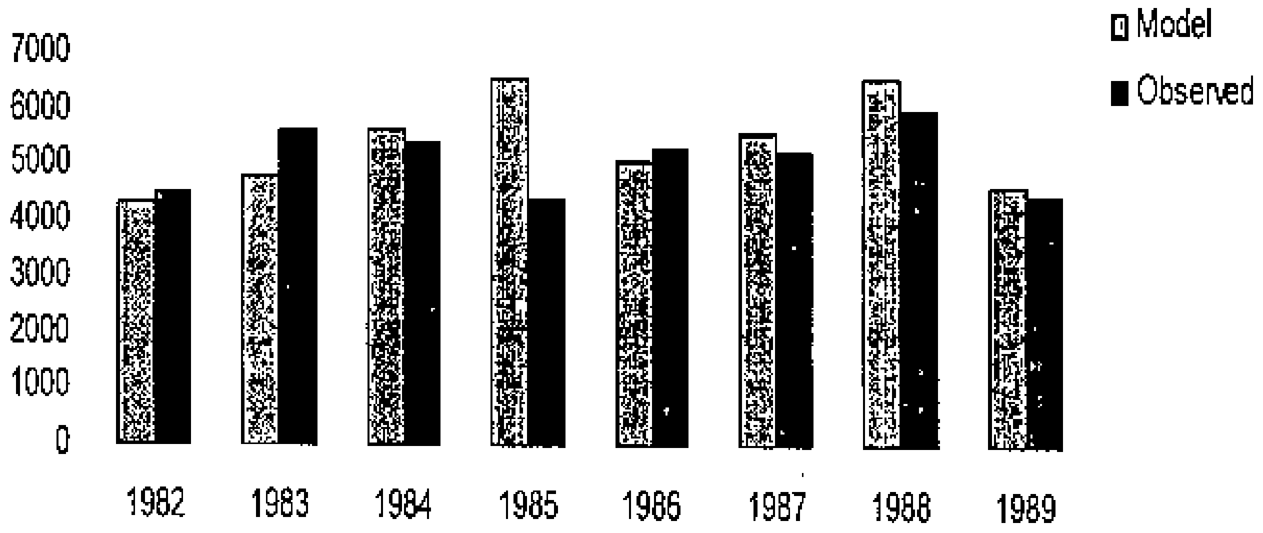

Fig. 5.1.6(ii): Annual Variation of Rainfall for Observed and RegCM model.

5.1.7 Year-to-year rainfall variation over Bangladesh for observed and RegCM model

Table 05: Seasonal rainfall estimated by RegCM model in Grell Fritsch and Chappell and observed rainfall

Rainfall for the year of 1982-1989.

Year	**Month**	**Observed rainfall (in mm)**		**Model Data(in mm)**			**Observed data (rainfall in mm)**		
		Observed	Model	Pre-monsoon	Monsoon	Post-monsoon	Pre-monsoon	Monsoon	Post-monso
1982	March	35.31	38 30						
	April	183 46	195.82						
	May	125 31	154 91						
	June	563.77	424.66						
	July	414 88	447.83	344.08	1841.04	76 69	389.02	1674.09	104.36
	August	555.04	576 42						
	September	307.35	225.17						
	October	41.77	65.95						
	November	34.92	38.41						
1983	March	91.85	85 57						
	April	196 12	108 19						
	May	391.12	435.97						
	June	353 88	464 99						
	July	493.50	450.66	679 08	1798.12	343.35	629.74	1492.95	222.56
	August	659 04	446 72						
	September	291.69	130.58						
	October	305 54	122 21						
	November	37 81	100 36						
1984	March	6.35	73.36						
	April	97.35	278.13						
	May	431.54	891 49						
	June	725.35	391.35						
	July	571.42	373 57	535 23	2076.50	149 31	1242.99	1390.71	140.90
	August	460.12	407.90						
	September	319.62	217 89						
	October	146.88	126.29						
	November	2.42	14 61						
1985	March	73.69	131 86						
	April	98.08	402.75						
	May	292 65	344.91						
	June	381 35	545.65						
	July	401 85	669.80	464.42	1420.50	115.27	879.52	1816 98	222.06
	August	356 12	385.43						
	September	281.19	216.11						

	October	89 62	63 43						
	November	25.65	158 63						
1986	March	8.08	80 92						
	April	173.27	239 03						
	May	201.42	316 10						
	June	370 31	552.97						
	July	514.62	479.00	382.77	1703.62	360.31	636.04	1442.31	200.88
	August	300 81	256 89						
	September	517.88	153 44						
	October	211 08	122.56						
	November	149 23	78 32						
1987	March	51.81	134 90						
	April	205.69	292 00						
	May	128 77	338.04						
	June	131.92	507.83						
	July	748.65	563 61	386.27	1887.00	129.69	764.94	1663.16	92.62
	August	648 69	321.08						
	September	357.73	270 64						
	October	88 00	56 37						
	November	41.69	36 25						
1988	March	62 81	163.42						
	April	130 23	175.45						
	May	419.00	596.22						
	June	601.62	989.77						
	July	487.15	303.77	612.04	1845 73	253 69	935.09	1693.05	299.11
	August	458.42	307.24						
	September	298.54	92.27						
	October	157.31	150.88						
	November	96.38	148.23						
1989	March	6 38	97.87						
	April	99.65	60 37						
	May	197.54	335 54						
	June	335.23	443 41						
	July	541 08	364.31	303.58	1412.12	323 00	493.78	1212.96	-366.81
	August	164.85	259 40						
	September	370.96	145 84						
	October	317.27	158 03						
	November	5.73	208.78						

Table 06: Month-to-month rainfall variation (mm) over Bangladesh for observed and RegCM model

Yearly Average Rainfall	Obs. Data(mm)	Model Data(mm)	Obs.(-) Model
Jan 1982-89	5.36	11.3	-5.94
Feb 1982-89	16.12	46.06	-23.94
Mar 1982-89	42.03	100.78	-58.75
Apr 1982-89	147.98	218.97	-70.99
May 1982-89	273.42	426.65	-153.23
Jun 1982-89	432.93	540.08	-107.15
July 1982-89	521.64	456.57	65.07
Aug 1982-89	450.38	370.14	80.24
Sep 1982-89	343.12	181.49	161.63
Oct 1982-89	169.68	108.22	61.46
Nov 1982-89	49.23	97.95	-48.72
Dec 1982-89	7.34	25.98	-18.64

Table 07: Seasonal rainfall variation of different years over Bangladesh for observed and RegCM model.

Yearly Seasonal RF(mm)	Observed data (rainfall in mm)			Model data (rainfall in mm)		
	Pre-monsoon	Monsoon	Post-monsoon	Pre-monsoon	Monsoon	Post-monsoon
1982	344.08	1841.64	76.69	389.02	1674.09	104.36
1983	679.08	1798.12	343.35	629.74	1492.95	222.56
1984	535.23	2076.50	149.31	1242.99	1390.71	140.90
1985	464.42	1420.50	115.27	879.52	1816.98	222.06
1986	382.77	1703.62	360.31	636.04	1442.31	200.88
1987	386.27	1887.00	129.69	764.94	1663.16	92.62
1988	612.04	1845.73	253.69	935.09	1693.05	299.11
1989	303.58	1412.12	323.00	493.78	1212.96	366.81

5.2.1 Temperature Validation

The year 1982-1989 was reasonably close to the climate averages for the region being considered. This regional climate modeling study is unique in that it has used daily observations to validate the model outputs. While the diurnal cycle is not explicitly analyzed with sub- daily observational data, it is implicitly addressed through the use of daily maximum and minimum air temperature data sets. The model has been able to simulate these spatial distributions, as well as their temporal evolution throughout the year.

In this study a regional climate model is employed to expand on modeling experiments of future climate change to address issues of (1) the timing and length of the growing season and (2) the frequency and intensity of extreme temperatures and precipitation. The study focuses on Bangladesh a climatically complex region that is vulnerable to changes in water supply and delivery. Statistically significant increases in daily minimum and maximum temperatures occur with a doubling of atmospheric carbon dioxide concentration. Increases in daily temperatures lead to increases in prolonged heat waves and length of the growing season. Changes in total and extreme precipitation vary depending upon geographic location.

Bangladesh is situated in the tropical belt and it has warm and humid climate in the summer and dry and cool weather in the winter Regional climatic differences in this flat country are minor. Three seasons are generally recognized: a hot, humid summer from March to June, a cool, rainy monsoon season from June to October; and a cool, dry winter from October to March. In general, maximum summer temperatures range between 32 °C and 38 °C. April is the warmest month in most parts of the country. January is the coldest month, when the average temperature for most of the country is 10 °C. The decrease in temperature during July and August is due to high precipitation activities from the southwest monsoon.

5.2.2 Temperature Validation for observed and RegCM model

The annual mean temperature have been shown in Fig. 5.2.2 (i) for some of the selected stations. The column bar shows the yearly mean temperature from 1982-1989 for the observed data and model data. For model data, the altitude of mean temperature variation decreases towards December and January from June of Bangladesh and yearly mean temperature variation increases towards June and July from December or January of Bangladesh compared with observed data.

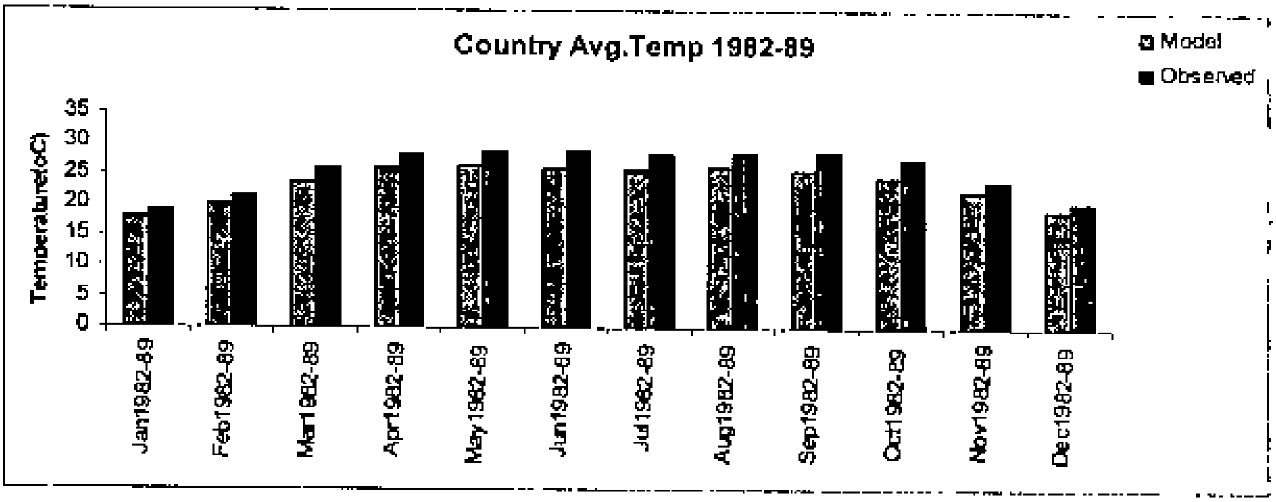

Fig. 5.2.2(i): Country average temperature for observed and RegCM model.

From Fig. 5.2.2 (i), it is seen that maximum mean temperature is obtained in May with a few sites. The sites are Dhaka, Faridpur and Tangail located in the central part of Bangladesh where the peak is obtained in April. Relatively high temperature is maintained from March to October and low temperature is found to occur for the period during December to February.

Similarly, for model temperature, it is also seen that the primary maximum mean temperature is obtained in May and secondary maximum mean temperature in October most of the year in Bangladesh.

5.2.3 Year-to-year station-wise country average temperature variation for observed and RegCM model over Bangladesh

The yearly station-wise country average temperature of 26 stations of Bangladesh for the period of 1982-89 have been analyzed and presented in Fig. 5.2.3 (a-h). It can be seen that country average temperature is of unimodal nature for observed and model temperature except in 1982, 1987 and 1989. The following features are obtained for observed and model temperature.

The schematic diagram is shown in Fig. 5.2.3 (a) for the year 1982, the highest temperature about 29.5°C is measured by BMD at Dhaka, Faridpur, Khulna, Patuakhali and Satkhira for observed data which is about 20% higher compare to RegCM model data. In this year model performance in almost each station underestimates compare to observed temperature. Analyses of the differences between model results and observed suggestions, we get the temperature fields are more acceptable the RegCM model compared to observed data. The lowest temperature at Mymensingh about 20% lower compare to RegCM model.

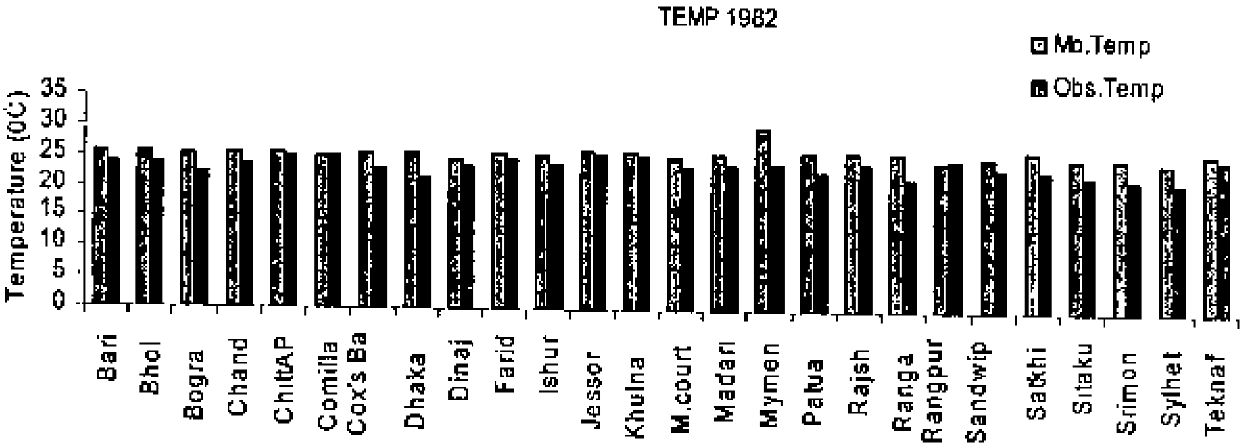

Fig. 5.2.3(a): Station-wise country average temperature for observed and RegCM model.

The variation of yearly station-wise temperature over Bangladesh for the year 1983 is shown in Fig. 5.2.3 (b), the highest temperature about 28°C is at Cox'sbazar, Jessore, Madripur, Mymensingh, Rangamati, Sandwip and Teknaf by BMD collection which is about 15% higher compare to RegCM model temperature. The lowest temperature about 24°C at Dhaka, Rangamati and Srimongal are found by RegCM model that underestimates compare to observed data. The performance of BMD collections are always preceding ahead compared to net data. The annual average temperature collected by BMD is about 27.5°C for the whole year.

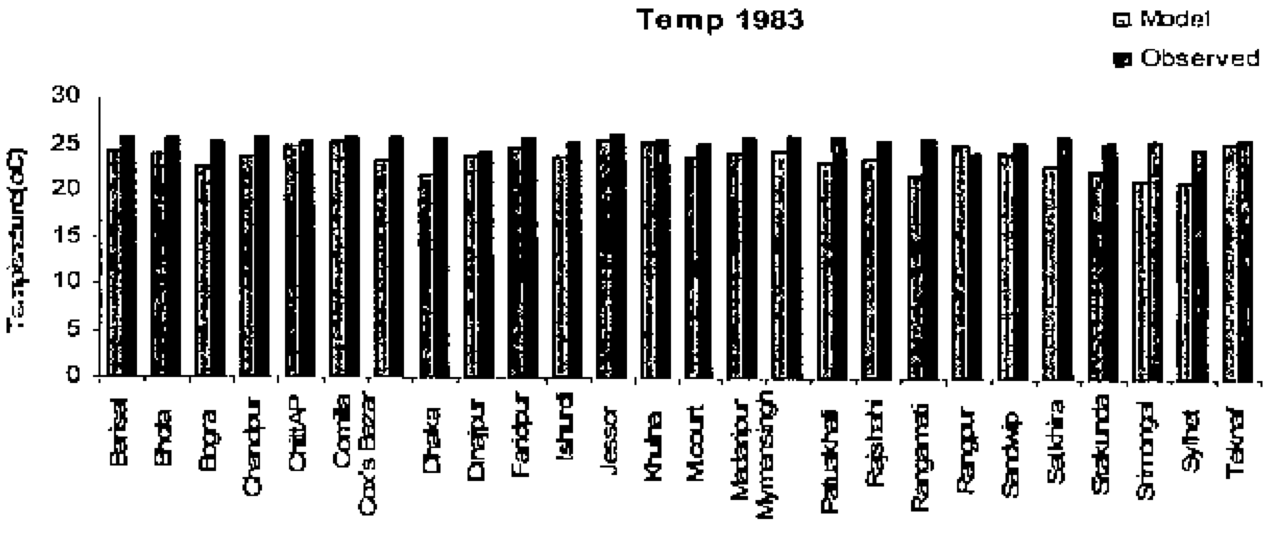

Fig.5.2.3 (b): Station-wise country average temperature for observed and RegCM model.

The station-wise annual average temperature variation over Bangladesh for the year 1984 is shown in Fig. 5.2.3(c), the highest temperature about 29°C is observed at Bhola, Cox'sbazar, Dhaka, Madaripur, Patuakhali, Satkhira and Teknaf which is approximately 20% higher than RegCM model temperature. The lowest temperature collected by BMD is about 24°C at Rangpur and Sitakunda which underestimates the RegCM model. The annual average temperature for the whole year is about 28°C for observed data whereas the average performance of RegCM model data is sufficiently better for the year 1984.The results of the pattern are not uniform at station-to-station due to the cause of heterogeneous characteristics.

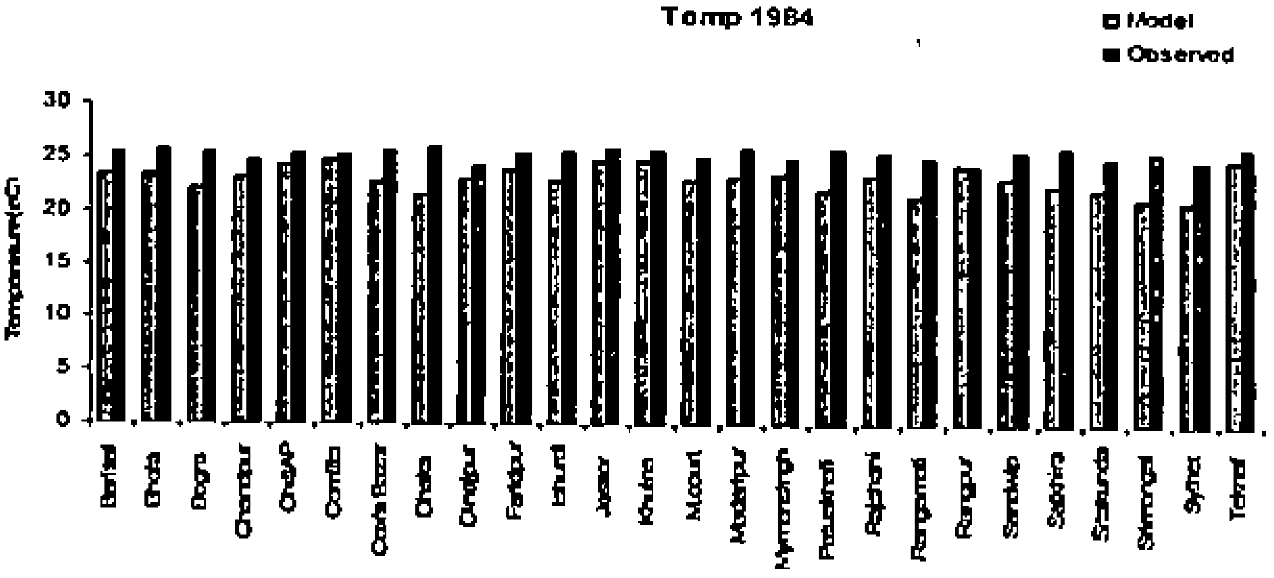

Fig.5.2.3(c): Station-wise country average temperature for observed and RegCM model.

The highest temperature is observed by BMD in Barisal, Dhaka and Patuakhali which is about 29.2°C and it is approximately 20% higher than RegCM model temperature as shown in Fig. 5.2.3 (d). The similarities in seen at Bhola, Jessore, Satkhira and Teknaf for the whole year 1985 where model data underestimates in differently. The lowest temperature is detected by RegCM model at Dhaka, Rangamati, Srimongal and Sylhet which is about 30% lesser compared to annual collection of BMD. The average annual temperature is measured by BMD is about 27°C for the whole year in Bangladesh.

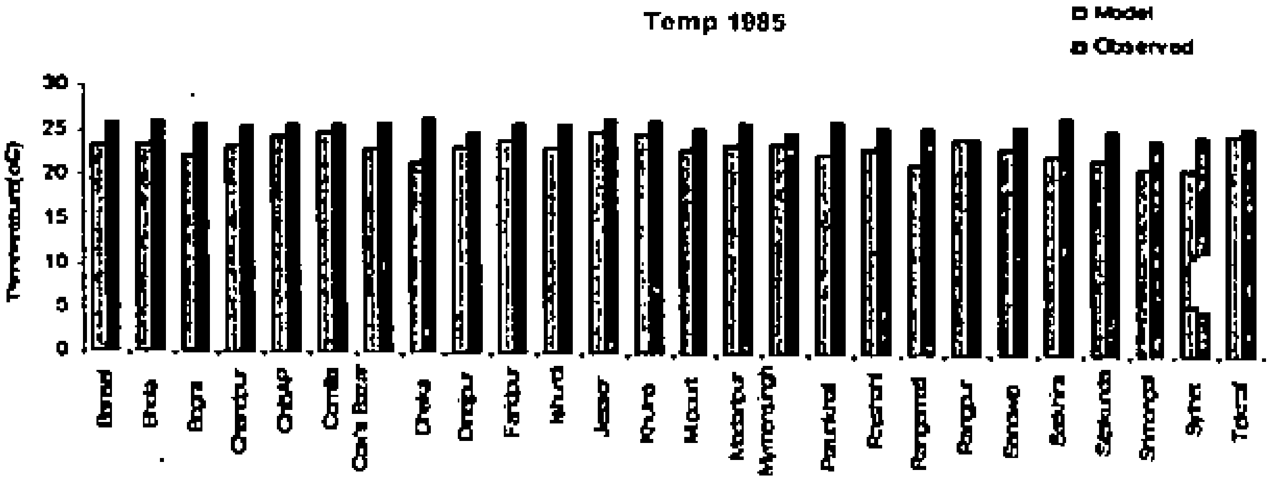

Fig.5.2.3 (d): Station-wise country average temperature for observed and RegCM model.

In Fig. 5.2.3 (c) for the year 1986, the highest temperature approximately 28.5°C is measured by BMD at Dhaka, Patuakhali, Satkhira and Teknaf for observed data which is about 20% higher compared to RegCM model data. In this year the model performance is good in almost each station although it underestimates compared to observed data. The lowest temperature is seen by RegCM model at Dhaka, Rangamati and Sylhet which is approximately 23°C.

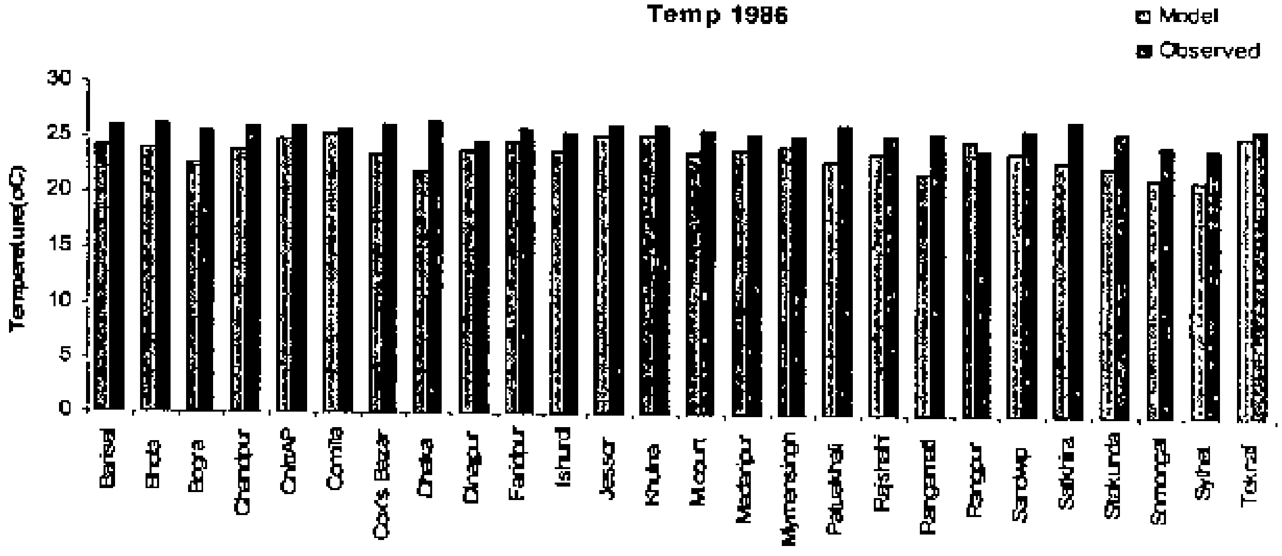

Fig.5.2.3 (e): Station-wise country average temperature for observed and RegCM model.

The schematic diagram is shown in Fig. 5.2.3 (f) for the year 1987, the highest temperature approximately 28.5°C is measured by BMD at Barisal, Bhola, Dhaka, Satkhira and Teknaf which is about 20% higher than compared to RegCM model data. The lowest temperature about 24°C is detected by BMD for the year 1987 at Sylhet. In this year model performance is different for different stations. The highest temperature is detected by model about 26.5°C at Khulna and Teknaf, and lowest temperature about 23°C at Dhaka.

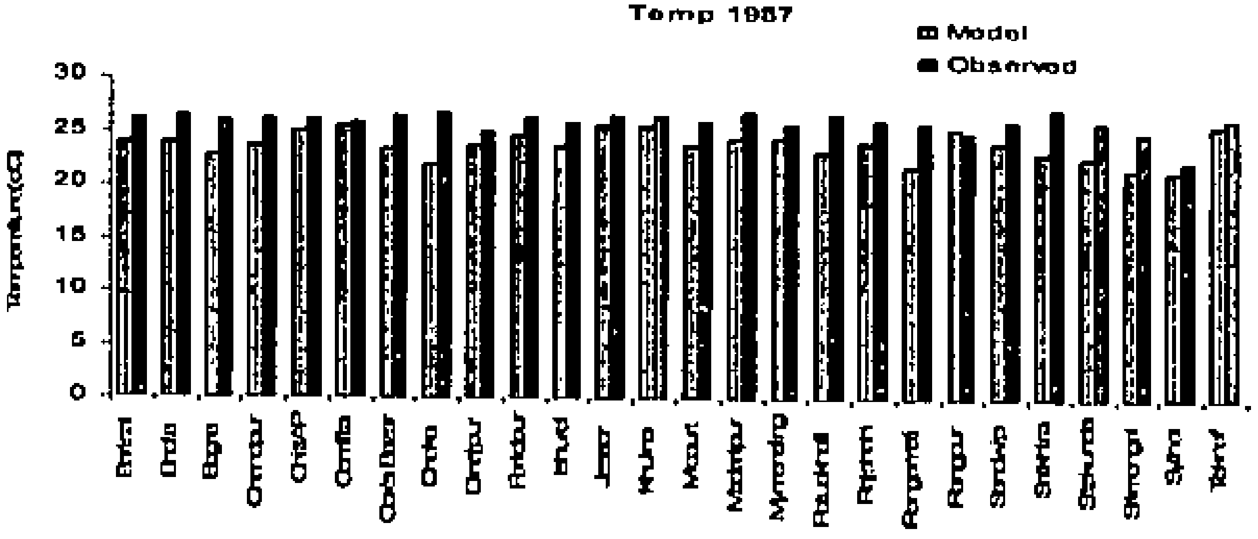

Fig.5.2.3 (f): Station-wise country average temperature for observed and RegCM model.

The station-wise annual average temperature for the year 1988 is shown in Fig. 5.2.3 (g), the highest temperature about 29°C is measured by BMD which is approximately 20% higher compare to RegCM model. The similarities are seen for the whole year in almost each station by BMD observation. The highest temperature about 28 is shown by RegCM model at Jessore, Khulna, Rangpur and Teknaf for the year 1988 that is almost equal in amount compared to BMD. The lowest temperature about 24°C is shown by RegCM model at Dhaka and Rangamati.

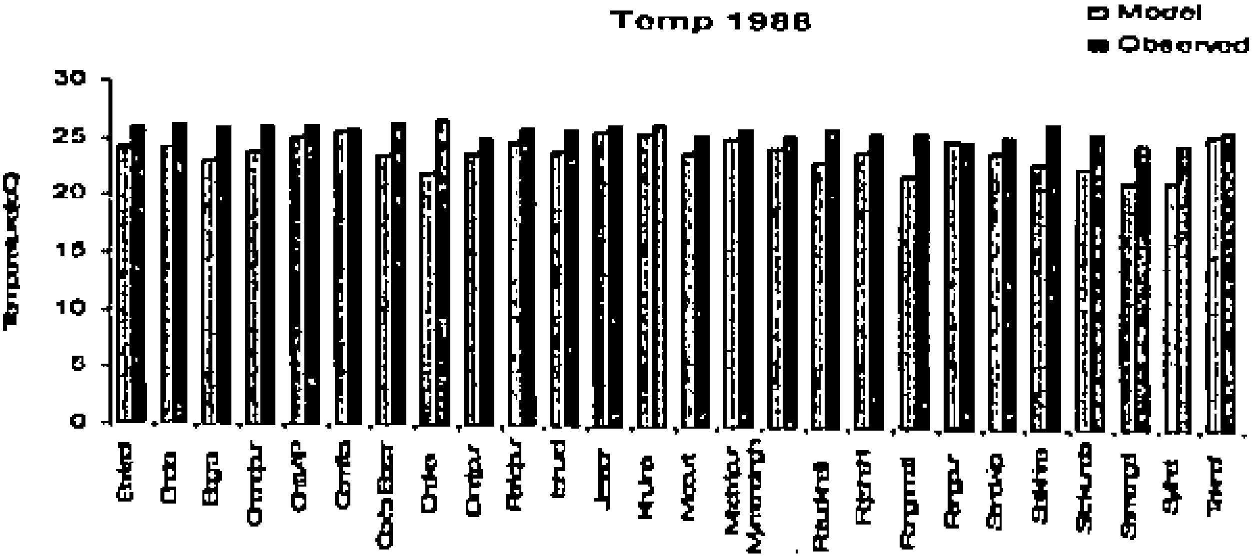

Fig. 5.2.3(g): Station-wise country average temperature for observed and RegCM model.

The schematic diagram is shown in Fig. 5.2.3 (h) for the year 1989, the station-wise highest temperature about 29.5°C is shown by BMD at Dhaka, Patuakhali, Satkhira and Teknaf which is approximately 20% higher compared to RegCM model data. The similarities are seen in almost all stations by BMD whereas the variation is observed in RegCM model performance in different stations.

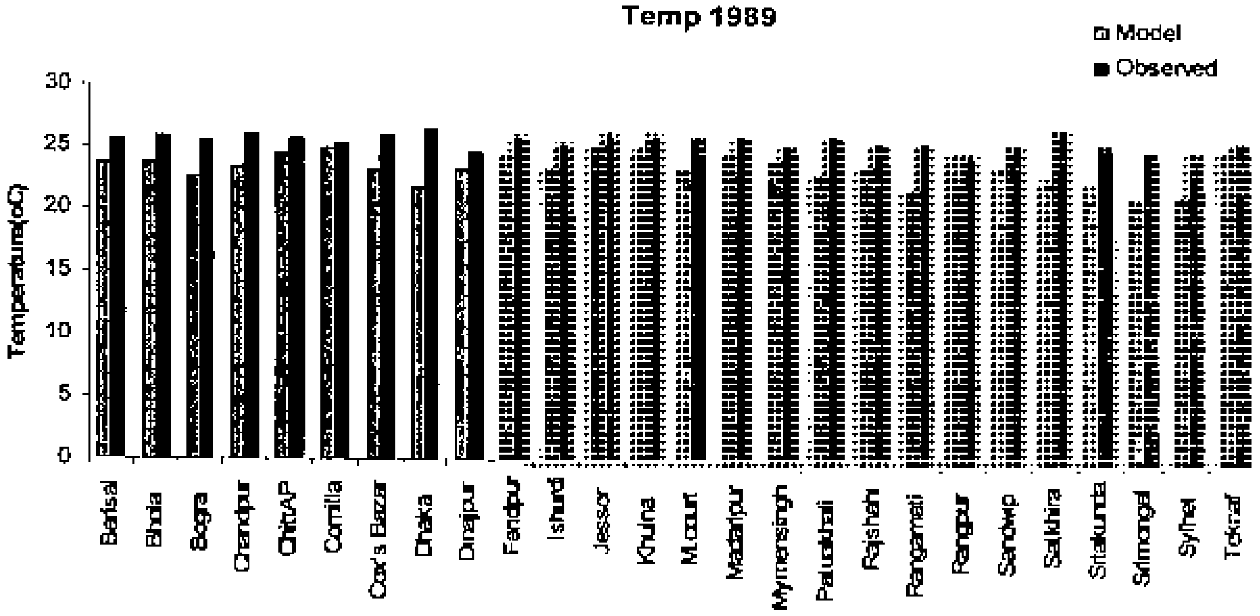

Fig.5.2.3 (h): Station-wise country average temperature for observed and RegCM model.

Discussion and Conclusions

This research has attempted to evaluate the ability of available RegCM model algorithm to depicted rainfall and temperature in 60 km resolution by comparing the model results with surface air temperature and rain-gauge rainfall at 26 sites throughout Bangladesh. Rainfalls compared for Pre-monsoon, Monsoon and Post-monsoon during the period of 1982-89. It is found that GFC option is much better to simulate rainfall in Bangladesh. It is also found that GFC option simulated surface air temperature has a significant cold bias of 2°C, i.e., if approximately 2°C is added with the model data (in GFC option) then it is fitted with the observed data in Bangladesh. Mathematically, it can be expressed that temperature,

$$T_{observe} = T_{model} + 2^{\circ}C$$

For analyses the spatial distribution of rainfall variation between RegCM model data and observed data (BMD), months, seasons and years have been used in this study for eight years (1982-89). The pros and cons is observed among the RegCM model data and observed data (BMD), the overall satisfactory results is obtained. Sometimes, the RegCM model to detect something whereas in the same moment BMD observation shows no rainfall. It means that sometimes falls calculation is obtained by the model. The economic development depends on the weather and climate conditions of a country. Therefore, simulation capability is to be improved. Once the model data is calibrated and validated with observed data, then only simulation will help the planners of the country. In this connection, validation of the modal is required and, then generation of future scenarios for the climate change impact studies is to be done very soon to meet up the demand of the present climate change issues. More analysis is needed using high resolution model run and various ensembles.

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