SIMULATION OF MONSOON RAINFALL OVER BANGLADESH USING HIGH RESOLUTION WRF-ARW MODEL

M. Sc. Thesis

BY

KRISHNA HALDER

ROLL NO: 1455554

SESSION: JULY-2014

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the Department of Physics, Khulna University of Engineering & Technology, Khulna-9203.

DEPARTMENT OF PHYSICS

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DECLARATION

This is to certify that the thesis work entitled “Simulation of Monsoon Rainfall over Bangladesh using High Resolution WRF-ARW Model” has been carried out by Krishna Halder in the Department of Physics, Khulna University of Engineering & Technology, Khulna, Bangladesh. The above thesis work or any part of this work has not been submitted anywhere for the award of any degree or diploma.

Signature of Supervisor | Signature of Candidate

(Professor Dr. Md. Mahbub Alam) | Krishna Halder

<u>DEDICATED TO</u>

MY PARENTS

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Krishna Halder

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Nomenclature

ARW	:	Advanced Research WRF
BMD	:	Bangladesh Meteorological Department
BMJ	:	Betts-Miller-Janjic
CP	:	Cumulus Parameterization
FNL	:	Final Reanalysis
GrADS	:	Grid Analysis and Display System
KF	:	Kain-Fritch
MAE	:	Mean Absolute Error
MP	:	Microphysics
NCAR	:	National Center for Atmospheric Research
PBL	:	Planetary Boundary Layer
TRMM	:	Tropical Rain Measuring Mission
RMSE	:	Root Mean Square Error
CC	:	Correlation of Coefficients
UTC	:	Universal Time Co-ordinate
WDM5	:	WRF double moment 5-class
WDM6	:	WRF double-moment 6-class
WRF	:	Weather Research and Forecasting
WSM6	:	WRF Single-moment 6-class
YSU	:	Yonsei University Scheme

Abstract

In the present study, the Weather Research and Forecast (WRF-ARW V3.5.1) model have been used to simulate the station wise monsoon rainfall during 2010–2014 over Bangladesh. The initial and boundary conditions are drawn from the global operational analysis and forecast products of National Center for Environmental Prediction (NCEP-GFS) available at $1°\times1^{o}$ resolution. The model was configured in single domain, 6 km horizontal grid spacing with 161×183 grids in the east-west and north-south directions and 28 vertical levels. For the simulation of monsoon rainfall WSM6-class graupel scheme coupled with Kain-Fritsch (KF) cumulus parameterization (CP) scheme has been used. Initially the model was run 137 days for long term prediction starting with the initial condition of 0000 UTC of 17 May up to 0000 UTC of 1 October for the period 2010-2014. The model was also run 72 hours with every day 0000 UTC initial conditions for 124 days for the prediction of 24, 48 and 72 hours lead time rainfall in the monsoon season of 2014. In this research convective and non-convective rainfall have been simulated at 3 hourly interval then made daily and monthly total rainfall data for 24, 48, 72 hour and long term during the studied period. We have compared this data with the observed rainfall at 33 meteorological stations of BMD and TRMM rainfall.

It has shown that the performance of the model for 24, 48 and 72 hours predictions are reasonably well except northeast and southeast hilly regions. The distribution of 24 hours lead time predicted rainfall is almost similar all over the country except the higher rainfall area where model simulated rainfall is much more. The prediction deteriorates as the prediction time increases. The long term predictions of simulated rainfall are not matched with BMD observed rainfall. The pattern of TRMM and observed rainfall are almost similar but the value of TRMM observations is much lower than that of observed rainfall. The RMSE shows that the value for 24 hour prediction lies within 15-30 mm range except hilly regions. The MAE shows that the value for 24 hour prediction lies within 10-20 mm range except hilly regions. It has also been observed that where the rainfall has minimum the RMSE and MAE have also minimum.

Chapter I

Introduction

Weather is the state of the atmosphere, as determined by the simultaneous occurrence of several meteorological phenomena at a geographical locality. It is the state of the atmosphere, to the degree that it is hot or cold, wet or dry, calm or stormy, clear or cloudy. Weather, seen from an anthropological perspective, is something all humans in the world constantly experience through their senses, at least while being outside. Weather generally refers to day-to-day temperature and precipitation activity, whereas climate is the term for the statistics of atmospheric conditions over longer periods of time. More popularly, weather refers to a certain state of the atmosphere as it affects human's activities on the Earth's surface. It involves day-to-day changes in such atmospheric phenomena as temperature, humidity, precipitation; air pressure, wind and cloud cover etc. Climate is the condition of the atmosphere at a particular location over a long period of time from one month to many millions of years, but generally 30 years. Climate is the sum of atmospheric elements: solar radiation, temperature, humidity, clouds and precipitation, atmospheric pressure, and wind.

The life of man inhabiting the planet earth is influenced mostly by the climate among all the factors of our physical environment. It is therefore essential to know how climate will change over the coming years. Bangladesh has a tropical monsoon climate with significant variations in rainfall and temperature throughout the country. The mean annual temperature is about 25^{o}C, with extremes of 4 and 43^{o}C. Ground frosts can occur in the hills. Humidity ranges between 60% in the dry season and 98% during the monsoon. Most of the annual rainfall occurs in this season. The mean rainfall during the monsoon season ranges from 1000 to 3000 mm in the country. The maximum rainfall occurred at Sylhet in the northeastern part and along the coastline in the southern part and with a minimum in the west central part (Matsumoto, 1988; Hussain and Sultana, 1996). The rainfall actually exceeds 5000 mm near the Shillong Plateau (Ohsawa *et al.*, 1998). Because the Shilong Plateau works as a topographic barrier to prevailing southerly monsoon wind, the amount of rainfall is extremely high on the southern slope of the Shillong Plateau. The monsoon rainfall at Cherrapunji located on the southern slope of the Shillong Plateau and about 10-km away from the border of Bangladesh is, on an average, more than 8000 mm (Pant and Kumar, 1997).

Ahasan *et al.* (2015) conducted research on prediction of heavy rainfall event over Rangamati, Bangladesh using high-resolution MM5 model. The results show that the model performed all the Day-1, Day-2 and Day-3 predictions reasonably well. The predictions are more accurate for Day-2 and worse for Day-4. The prediction also deteriorates as the prediction time increases. The RMSE shows that the value for 24 h prediction lies within 10–20 mm range. Das *et al.,* (2012) studied simulation of seasonal monsoon rainfall over the SAARC Region by dynamical downscaling using WRF Model. Their findings suggest the large scale seasonal distributions of rainfall observed by different sources are simulated fairly well by the model.

Khaladkar *et al*., (2007) studied the performance of NCMRWF Models in predicting high rainfall spells during SW Monsoon Season. They showed that, in general, all the models predicted good rainfall activity along the west coast of India, which is consistent with the observations. Das *et al.,* (2008) studied skills of different mesoscale models over Indian region during monsoon season. They made a conclusion that the WRF is able to produce best all India rainfall prediction compared to observations in the day-1 forecast and, the MM5 is able to produce best all India rainfall forecasts in day-3 but ETA and RSM are able to depict the best distribution of rainfall maxima along the west coast of India.

Bhanu *et al*., (2012) conducted research on simulation of heavy rainfall events during retreat phase of summer monsoon season over parts of Andhra Pradesh. They noticed that, circulation features and rainfall quantities are validated with observed rainfall of IMD and satellite derived datasets of KALPANA-1. Prakash *et al.,* (2010) estimate the Indian summer monsoon rainfall using Kalpana-1 VHRR data and its validation using rain gauge and GPCP data. The results show that IMSRA technique qualitatively as well as quantitatively matches well with GPCP and TMPA-3B42 derived monthly rain products.

Pattanaik (2014) conducted research on Meteorological sub divisional level extended range forecast over India during southwest monsoon 2012. Although the individual models show useful skill in predicting the extended range forecast of monsoon, the MME forecast is found to be superior compared to these. For the country as a whole, the correlation coefficient (CC) between the observed and MME forecast rainfall departure is found to be statistically significant (99 % level) at least for 2 weeks (up to 18 days). Vitart and Molteni (2009) studied dynamical extended range prediction of early monsoon rainfall over India. They suggest that the high resolution extended range forecasts could be useful for the prediction a few weeks in advance of sub seasonal events, like the onset of the monsoon.

Rahman *et al*., (2013) studied the seasonal forecasting of Bangladesh summer monsoon rainfall using simple multiple regression models. The model showed better performance in their hind cast seasonal monsoon rainfall over Bangladesh. The experimental forecasts for the year 2008 summer monsoon rainfall based on the model were also found to be in good agreement with the observation. Ahasan *et al*., (2013) conducted research on simulation of high impact rainfall events over southeastern hilly region of Bangladesh using MM5 model. The model suggests that the highly localized high impact rainfall was the result of an interaction of the mesoscale severe convective processes with the large scale active monsoon system. Shahid (2010) studied rainfall variability and the trends of wet and dry periods in Bangladesh. The result shows a significant increase in the average annual and pre-monsoon rainfall of Bangladesh. The number of wet months is found to increase and the dry months to decrease in most parts of the country. Seasonal analysis of wet and dry months shows a significant decrease of dry months in monsoon and pre-monsoon.

The climatic change and its impacts on natural disasters have been studied by Karmakar and Nessa (1997). From the projected values of increasing rainfall during the southwest monsoon season they predicted that the rainfall is likely to increase by 12.74 mm and 23.36 mm by the year 2050 and 2100, respectively. Begum and Alam (2013) conducted research on climate change impact on rainfall over Bangladesh for last decades. The annual and monsoon rainfall is found in decreasing trend in recent times (1981-2010) whereas in increasing trend during the period of 1951-2011.

In the present study the Weather Research and Forecast (WRF-ARW V3.5.1) model has been used to simulate the monsoon (June – September) rainfall over Bangladesh for the period of 2010-2014. The objectives of this study are to examine whether the high resolution WRF model is capable of simulating the observed features of monsoon. The results have been compared with the observed station rainfall of Bangladesh Meteorological Department (BMD) and TRMM rainfall.

Chapter II

Literature Review

2.1 Monsoon

Monsoon is traditionally defined as a seasonal reversing wind accompanied by corresponding changes in precipitation but is now used to describe seasonal changes in atmospheric circulation and precipitation associated with the asymmetric heating of land and sea. Usually, the term monsoon is used to refer to the rainy phase of a seasonally changing pattern, although technically there is also a dry phase. Monsoon is a common weather phenomenon in Indian subcontinent. Bangladesh is situated in a very active monsoon region of the world**.** Bangladesh gets much rain during this season. The agro-economic activities of Bangladesh are seriously dependent on monsoon rain. Bangladesh is located over the vast delta of three great rivers, the Ganges, the Brahmaputra and the Meghna (GBM) with total area of about 144,000 sq. kms. The river area is 6.5 % and forest area is 15.6% of the country. The coastal line of the Bay of Bengal is 716 km to the south of the country. It is characterized by very flat plains, which dominate most of the country and never rise more than 10m above sea level. Although there are few mountains higher than 1000 m in the country, the Shillong Plateau of India and Chittagong Hill Tracts of Bangladesh, located near the northeastern and southeastern border with India respectively, have great effects on the amount of rainfall in the adjacent areas. The confluence of many geographical and orographical characteristics makes Bangladesh susceptible to different type of weather hazards.

Summer monsoon is the most important and vital season in Indian subcontinent. On an average, more than 70% of Bangladesh's annual rainfall occurs in the monsoon (June-September) season. The quantity of monsoon rainfall has a socio-economic impact on the peoples of Indian subcontinent. However, the numerical studies on the rainfall characteristics over Bangladesh are a few. The southwest monsoon makes its arrival at Bangladesh coast through the southeastern part, the mean date of onset is 2nd June, and it takes about 13 days (Ahmed and Karmakar, 1993) to reach the northwestern part of the country. The southwest monsoon begins its withdrawal from 30th September and the withdrawal is completed through the southeastern part of the country 17 days later. The impact of rainfall in Indian sub-continent is tremendous in monsoon season. In this season sometimes large amount of rainfall occurs in Nepal and Northeast of India, which causes flood in northeast India and Bangladesh.

The Bay of Bengal Branch of SW Monsoon flows over the Bay of Bengal heading towards NE India and Bengal, picking up more moisture from the Bay of Bengal. Its hits the Eastern Himalaya and provides a huge amount of rain to the regions of NE India, Bangladesh and West Bengal. Cherrapunji situated on the southern slopes of the astern Himalaya in Shillong, India is one of the wettest places on Earth.

The agriculture of Bangladesh is heavily dependent on the rains, especially crops. A delay of a few days in the arrival of the monsoon can, and does, badly affect the economy, as evidenced in the numerous droughts in Indian subcontinent. The monsoon is widely welcomed and appreciated by city-dwellers as well, for it provides relief from the climax of summer in June. Bangladesh and some regions of Indian like in Assam and places of West Bengal experiences heavy flood, which claims huge number of lives and huge loss of property and causes severe damage to economy.

The monsoon area has been defined by Ramage (1971) by the following criteria:

- The prevailing wind direction shifts by at least 120^o between January and July
- The average frequency of prevailing wind directions in January and July exceeds 40 percent.
- The mean resultant wind is at least one of the months exceeding 3 m/sec.
- Less than one cyclone-anticyclone alternation occurs every two years in either month in a 5^o latitude-longitude rectangle.

The monsoon normally reaches the coastal belt of Bangladesh by the last week of May to the first week of June and progressively engulfs the whole country through June. On an average 20-25 rainy days per month during June to August, decreasing to 12-15 days in September. With the advent of the monsoon, the extreme temperatures of summer fall appreciably throughout the country. Although the mean temperature falls hardly by one degree, the maximum temperature falls by 2-5^{o}C over most part of the country except the coastal belts where the fall is by 5-6^{o}C [WMO/UNDP/BGD/79/013, 1986].

2.1.1 Monsoon Wind

Since the temperature changes at sea are slower than those at land, during the daytime when a region is heated by the sun, the land will quickly absorb the heat from the sun and its temperature will quickly rise. This causes the land temperature to be higher than that at sea which in turn will affect the temperature of the air; the land area will be hotter while the sea surface will be cooler. This temperature difference will result in the flow of air. At this time, air from the cooler sea surface will flow toward the warmer land area, creating a cool “sea breeze”. At night the process will be reversed. Since the land loses heat faster than the sea, the land area will be cooler than the sea surface. As a result, air will flow from the land towards the sea, and a “land breeze” will thereby be formed. So in the course of a day, there will be both land and sea breezes. When we extend the timeline from a day to a season, the different winds created by these effects are called “monsoons”.

The land has a small heat capacity compared to ocean. As a result the absorption of solar radiation raises the surface temperature over the land much more rapidly than over the ocean. This surface warming leads to enhanced columns convection, and hence to latent heat releases which produces warm temperatures throughout the troposphere. As a result there is a pressure gradient force at the upper levels directed from the land to ocean. The divergent wind which develops in response to this pressure gradient causes a net mass transport out of the air cumulus above the continent and thereby generates a surface low over the continent. A compensating convergence wind then develops at low levels. This low level flow produces a convergence of moisture which serves to maintain the columns convection which is primarily energy source for the monsoon circulation.

2.1.2 Monsoon rainfall

The summer monsoon in Bangladesh prevails from early June to mid-October, with an average duration of 110 days in the west to 134 days in the south-east, and an average number of rainy days of 60 days in the west to 100 days in the northeast and south-east. Most summer monsoons have a dominant westerly component and a strong tendency to ascend and produce copious amounts of rain. The intensity and duration, however, are not uniform from year to year. Average summer monsoon rainfall ranges from 1200 mm in the west to 3000 mm in the north-east and south-east. During the wettest monsoon season at three stations the periods of consecutive rain days range from 8–10 days in the west to 30–40 days in the northeast. During the driest monsoon season at these stations the periods of consecutive rain days vary from 3–6 days in the west to 20– 30 days in the north-east. Frequency of consecutive rain days of various duration’s at these stations in the 35-yr period shows that episodes with duration of 1–3 days are most common. However, episodes of much longer consecutive rain days also occur, ranging from 10–19 days in the west to 18–35 days in the southeast and 20–44 days in the northeast.

The rainfall distribution in the principal rainy season of India, the southwest monsoon period, is lasting from June to September. Except in Kashmir and neighborhood, the extreme south Peninsula and the east coast areas, the annual rain is mainly accounted for the falls in this season. Orographic influence is dominant in the distribution of rainfall in this season, as the prevailing winds blow almost at right angles against the Western Ghats and the Khasi-Jaintia hills. There is rapid increase of rainfall to the north of a line running from Ahmednagar to Masuliptanam up to the southern slopes of the Vindhyas. In the north Indian plains, a minimum rainfall belt runs from northwest Rajasthan to the central parts of West Bengal, practically along the axis of the monsoon trough. Rainfall decreases generally from the hills of the western and Eastern Ghats towards the coast (Rao, 1976).

Rainfall decreases very rapidly southwards along west coast from 9.5^{o}N to Kanyakumari. The rainfall at Kanyakumari in this season is about the same as in the Great Indian Desert. Rainfall is only 20 mm in some places in the coastal strip in extreme south Tamil Nadu. With all the significant amounts of rainfall occurring over the Ghats, a saving feature of economic interest is that all the important rivers of south India emerge out of the western Ghats to flow east through the plains having rainfall of the order of that in west Rajasthan.

Hills and mountain ranges cause striking variations in rainfall distribution. On the southern slopes of the Khasi-Jaintia hills rainfall is over 8000 mm while to the north, in the Brahmaputra valley, it drops to about 1200 mm. Cherrapunji's annual rainfall of 11420 mm (at elevation of 1313 m) is obviously due to orographic lifting but its magnitude requires to be quantitavily explained. From the west coast, rainfall increases along the slopes of the Western Ghats and rapidly decreases on the eastern lee side. No definite information is available about the increase of rainfall with elevation and the height at which the rainfall attains the highest value. In the higher reaches of the Western Ghats, there are places with seasonal rainfall of 5000 mm. Within 80 km on the lee side, rainfall is only 400 mm (Rao, 1976).

Across northern India, a line of rainfall minimum runs from 28.5^{o}N, 75^{o}E to 25^{o}N, 88^{o}E which is paradoxically close to the monsoon trough. Area to the south of this rainfall minimum falls in the track of monsoon depressions which are responsible for much of the rainfall. In tracts further to north, there is probably the influence of the Himalayas in increasing the rainfall. Apart from this, there is also a decrease of rainfall from east to west, from about 1200 mm in West Bengal to less than 200 mm in the Great Indian Desert in west Rajasthan.

In the Himalayas, observations are extremely scanty, particularly from higher elevations where there is added difficulty of measuring snowfall. Rainfall measured in river valleys may not be representative of the hill slopes. Between the Great Himalayan Range and the plains, there is the Pir Panjal, the Siwalikland the Mahabharat Ranges. Most of the available observations are from these ranges. Rainfall increases up to the slopes of these foothills, presumably decreases on their northern slopes and increase again on the Himalayan slopes. Annual rainfall at Chaunrikharka (2,700 m) is 2280 mm and at Namche Bazar (3,300 m) only 940 mm. Both are in Nepal and the distance between the two is hardly 16 km. Therefore, we can tentatively conclude that above some elevation near 3 km, rainfall may decrease with height on the Himalayan range. In the eastern Himalayas, rainfall is more than in the western portions. In the east, annual rainfall of 4000 mm has been recorded but less than 2000 mm in the west (Rao, 1976).

Rainfall in the Andaman and Nicobar Islands during the southwest monsoon season is about 1400 to 1900 mm, while in Laccadives and Maldives in the Arabian Sea, it is only about 1000 mm though both the groups are in the same latitude belt. Calicut on the mainland in the west coast, however, gets 2330 mm more than the Bay Islands (Rao, 1976).

2.2 Classification of Rainfall

Bangladesh Meteorological Department (BMD) has been using the following classification:

- very light rain when the precipitation rate is < 0.25 mm/hour
- light rain when the precipitation rate is between 0.25 mm/hour-1.0 mm/hour
- moderate rain when the precipitation rate is between 1.0 mm/hour – 4.0 mm/hour
- heavy rain when the precipitation rate is between 4.0 mm/hour-16.0 mm/hour
- very heavy rain when the precipitation rate is between 16.0 mm/hour-50 mm/hour
- extreme rain when the precipitation rate is > 50.0 mm/hour

2.3 Weather Research & Forecasting Model

The Weather Research and Forecasting (WRF) Model is a next-generation mesoscale numerical weather prediction system designed to serve both atmospheric research and operational forecasting needs. It features two dynamical cores, a data assimilation system, and a software architecture facilitating parallel computation and system extensibility. The model serves a wide range of meteorological applications across scales from tens of meters to thousands of kilometers. The effort to develop WRF began in the latter part of the 1990's and was a collaborative partnership principally among the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration represented by the National Centers for Environmental Prediction (NCEP) and the Forecast Systems Laboratory (FSL) the Air Force Weather Agency (AFWA), the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration (FAA).

The WRF model is an atmospheric simulation system which is designed for both operational and research use. WRF is currently in operational use at the National Oceanic and Atmospheric Administration (NOAA)'s national weather service as well as at the air force weather agency and meteorological services worldwide. Getting weather predictions in time using latest advances in atmospheric sciences is a challenge even on the fastest super computers. Timely weather predictions are particularly useful for severe weather events when lives and property are at risk. Microphysics is a crucial but computationally intensive part of WRF.

WRF offers two dynamical solvers for its computation of the atmospheric governing equations, and the variants of the model are known as WRF-ARW and WRF-NMM. The Advanced Research WRF (ARW) is supported to the community by the NCAR Mesoscale and Microscale Meteorology Division. The WRF-NMM solver variant was based on the Eta Model, and later Non hydrostatic Mesoscale Model, developed at NCEP. The WRF-NMM is supported to the community by the Developmental Test bed Center.

2.3.1 Microphysics schemes in WRF-ARW Model

Microphysics includes explicitly resolved water vapor, cloud and precipitation processes. The model is general enough to accommodate any number of mass mixing-ratio variables, and other quantities such as number concentrations. Four-dimensional arrays with three spatial indices and one species index are used to carry such scalars. Memory, i.e., the size of the fourth dimension in these arrays, is allocated depending on the needs of the scheme chosen, and advection of the species also applies to all those required by the microphysics option. In the current version of the ARW, microphysics is carried out at the end of the time-step as an adjustment process, and so does not provide tendencies.

The rationale for this is that condensation should be at the end of the time-step to guarantee that the final saturation balance is accurate for the updated temperature and moisture. However, it is also important to have the latent heating forcing for potential temperature during the dynamical sub-steps and this is done by saving the microphysical heating as an approximation for the next time-step as described.

2.3.1.1 Kessler Scheme

The Kessler scheme is a simple warm cloud scheme that includes water vapor, cloud water and rain. The microphysical process consists of the production, fall and evaporation of rain, the accumulation and auto conversion of cloud water and the production of cloud water from condensation. A warm-rain scheme has been used commonly in idealized cloud modeling studies. Kessler scheme is one moment scheme. The purpose of the scheme is to increase understanding of the roles of cloud conversion, accretion, evaporation, and entrainment processes in shaping the distributions of water vapor, cloud, and precipitation associated with tropical circulations. This scheme is idealized microphysics process without the consideration of ice phase and melting zone. Kessler scheme has been used widely in cloud modeling studies due to its simplicity. The equation represented the processes between cloud, vapor and rain are also much simplified compared with other scheme. Kessler scheme produced much heavier precipitation and can show unrealistic precipitation profiles in some studies.

2.3.1.2 Lin *et al.* Scheme

A sophisticated scheme that has ice, snow and graupel processes, suitable for real-data high-resolution simulations. Lin *et al.* (1983) scheme includes six classes of hydrometeors are included: water vapor, cloud water, rain water, cloud ice, snow, and graupel. All parameterization production terms are based on Lin *et al.* (1983). This is a relatively sophisticated microphysics scheme in WRF, and it is more suitable for use in research studies. The scheme is taken from Purdue cloud model and the details can be found in Chen and Sun *et al.* (2002) 2-D microphysics scheme. This is one of the first schemes to parameterize snow, graupel, and mixed-phase processes. It has been used extensively in research studies and in mesoscale NWP Model. The scheme includes ice sedimentation and time-split fall terms.

2.3.1.3 WRF Single Moment 3-class (WSM3) microphysics Scheme

The WSM3 microphysics scheme includes ice sedimentation and other new ice-phase parameterizations. In this scheme an analytical relation is used for ice number concentration that is based on ice mass content rather than temperature. The WSM3 scheme predicts three categories of hydrometers: water vapor, cloud water and rain water mixing ratio, which is a so-called simple-ice scheme. This scheme is computationally efficient for the inclusion of ice processes, but lacks super cooled water and gradual melting rates.

2.3.1.4 WRF Single Moment 5-class (WSM5) microphysics Scheme

WRF Single Moment 5-class (WSM5) microphysics scheme represents fallout of various types of precipitation, condensation and thermodynamics effects of latent heat release. The WSM5 scheme predicts five categories of hydrometrics: water vapor, cloud water, cloud ice, rain and snow. WSM5 allows super cooled water to exist and a gradual melting of snow falling below the melting layer. Therefore, to expedite the computation process, Graphics Processing Units (GPUs) appear an attractive alternative to traditional CPU architectures. The use of high resolution WRF enables us to compute microphysical processes for increasingly small clouds and water droplets. To implement WSM5 scheme on GPUs, the WRF code was rewritten into CUDA C, a high level data-parallel programming language used on NVIDIA GPU.

2.3.1.5 Ferrier Scheme

Ferrier scheme predicts changes in water vapor and condensate in the forms of cloud water, rain, cloud ice, and precipitation ice. Local storage arrays retain first-guess information that extract contributions of cloud water, rain, cloud ice, and precipitation ice of variable density in the form of snow, graupel, or sleet. The density of precipitation ice is expected from a local array that stores information on the total growth of ice by vapor deposition and accretion of liquid water. Sedimentation is treated by partitioning the time averaged flux of precipitation into a grid box between local storage in the box and fall out through the bottom of the box. Advection only of total condensate and vapor diagnostic cloud water, rain, & ice from storage arrays – assumes fractions of water & ice within the column are fixed during advection super cooled liquid water & ice melt.

2.3.1.6 WRF Single-Moment 6-class Microphysics Scheme (WSM6)

The WRF-single-moment-6-class (WSM6) microphysics scheme has been one of the options of microphysical process in the WRF model since August 2004. This scheme predicts the mixing ratios for water vapor, cloud water, cloud ice, snow, rain, and graupel. We attempt to improve such existing deficiencies in the WSM6 scheme by incorporating the prediction of number concentrations for warm rain species. A new method for representing mixed-phase particle fall speeds for the snow and graupel by assigning a single fall speed to both that is weighted by the mixing ratios, and applying that fall speed to both sedimentation and accumulation processes is introduced of the three WSM schemes, the WSM6 scheme is the most suitable for cloud-resolving grids, considering the efficiency and theoretical backgrounds (Hong *et al*., 2006). The WSM6 scheme has been developed by adding additional process related to graupel to the WSM5 scheme.

2.3.1.7 Thompson Scheme

A bulk microphysical parameterization (BMP) developed for use with WRF or other mesoscale models. The snow size distribution depends on both ice water content and temperature and is represented as a sum of exponential and gamma distributions. Furthermore, snow assumes a non-spherical shape with a bulk density that varies inversely with diameter as found in observations. A new scheme with ice, snow and graupel processes suitable for high-resolution simulations. This adds rain number concentration and updates the scheme from the one in Version 3.0 New Thompson et al. scheme in V3.1. Replacement of Thompson *et al*., (2007) scheme that was option 8 in V3.0 6-class microphysics with graupel, ice and rain number concentrations also predicted.

2.3.1.8 WRF Double-Moment 6-class Microphysics Scheme (WDM6)

The WRF double-moment 6-class microphysics scheme (WDM6) implements a double-moment bulk micro physical parameterization of clouds and precipitation and is applicable in mesoscale and general circulation models. The WDM6 scheme enables the investigation of the aerosol effects on cloud properties and precipitation processes with the prognostic variables of cloud condensation nuclei (CCN), cloud water and rain number concentrations. WDM6 extends the WRF single-moment 6-class microphysics scheme (WSM6) by incorporating the number concentrations for cloud and rainwater along with a prognostic variable of cloud condensation nuclei (CCN) number concentration. Moreover, it predicts the mixing ratios of six water species (water vapor, cloud droplets, cloud ice, snow, rain, and graupel), similar to WSM6. Prognostic water substance variables include water vapor, clouds, rain, ice, snow, and graupel for both the WDM6 and WSM6 schemes. Additionally, the prognostic number concentrations of cloud and rain waters, together with the CCN, are considered in the WDM6 scheme. The number concentrations of ice species such as graupel, snow, and ice are diagnosed following the ice-phase microphysics of Hong *et al.* (2004).

2.4 Cumulus Parameterization

These schemes are responsible for the sub-grid-scale effects of convective and/or shallow clouds. The schemes are intended to represent vertical fluxes due to unresolved up drafts and down drafts and compensating motion outside the clouds. They operate only on individual columns where the scheme is triggered and provide vertical heating and moistening profiles. Some schemes provide cloud and precipitation field tendencies in the column, and future schemes may provide momentum tendencies due to convective transport of momentum. The schemes all provide the convective component of surface rainfall. Cumulus parameterizations are theoretically only valid for coarser grid sizes, (e.g., greater than 10 km), where they necessary to properly release latent heat on a realistic time scale in the convective columns. Where the assumptions about the convective eddies being entirely sub-grid-scale break down for finer grid sizes, sometimes these schemes have been found to be helpful in triggering convection in 5-10 km grid applications. Generally they should not be used when the model can resolve the convective eddies itself. These schemes are responsible for the sub-grid-scale effects of convective and shallow clouds. The schemes are intended to represent vertical fluxes due to unresolved updrafts and downdrafts and compensating motion outside the clouds.

2.4.1 Kain-Fritsch (KF) Scheme

In the KF scheme the condensates in the updraft are converted into precipitation when their amount exceeds threshold value. In this scheme the convection consumes the convective available potential energy in a certain time scale. The KF scheme also includes the shallow convection other than deep convection. The shallow convection creates non-perceptible condensates and the shallowness of the convection is determined by a vertical extent of the cloud layer that is known by a function of temperature at LCL of rising air parcel. The KF scheme was derived from the Fritsch–Chappell, and its fundamental framework and closure assumptions are described by Fritsch and Chappell (1980). KF (1990) modified the updraft model in the scheme and later introduced numerous other changes, so that it eventually became distinctly different from the Fritsch–Chappell scheme. It was distinguished from its parent algorithm by referring to the more elaborate code as the KF scheme, beginning in the early 1990s. This is also deep and shallow convection sub-grid scheme using a mass flux approach with downdrafts and CAPE removal time scale. Updraft generates condensate and dump condensate into environment downdraft evaporates condensate at a rate that depends on RH and depth of downdraft leftover condensate accumulates at surface as precipitation.

2.4.2 Betts-Miller-Janjic (BMJ) Scheme

The BMJ cumulus parameterization scheme is a nudging type adjustment of temperature and humidity in grid scale. The scheme adjusts the sounding towards a pre-determined, post convective profile derived from climatology. This post convective profile has been defined by points at the cloud base, cloud top and freezing level. In this scheme there is no explicit updraft or downdraft and no cloud detrainment occur. Convection is initiated when soundings are moist through a deep layer and when CAPE and convective cloud depth thresholds are exceeded. Betts and Miller proposed a convective adjustment scheme that includes both deep and shallow convection. The deep convection in the Betts–Miller scheme is similar to the other adjustment schemes except that it uses empirically based quasi-equilibrium thermodynamic profiles as a reference state rather than a moist adiabatic. The basic shape of these quasi-equilibrium reference profiles is based on the numerous observations. The construction of the reference profiles and the specification of the relaxation timescale are two major components of the Betts–Miller scheme.

These points and thresholds can vary by season and between the tropics and extra tropics. Compared with the original sounding, the sounding modified to the post convective profile will note a net change in perceptible water as well as changes in net heating and cooling. Convection is initiated when soundings are moist through a deep layer and when CAPE and convective cloud depth thresholds are exceeded. Important vertical structures may be eliminated since the reference profiles are based on climatology. Convection only initiated for soundings with deep moisture profile. When convection is initiated the scheme often rains out to much water. This is because the reference profile is too dry for the forecast scenario or the transition to the reference profile was too rapid. Scheme does not account for the strength of CAPE inhibiting convective development. Scheme does not account for any changes below the cloud base.

2.5 Planetary Boundary Layer (PBL)

The PBL is the layer in the lower part of the troposphere with thickness ranging from a few hundred meters to a few kilometers within which the effects of the Earth’s surface are felt by the atmosphere. The PBL processes represent a consequence of interaction between the lowest layer of air and the underlying surface. The interactions can significant impact on the dynamics of the upper air flows. The influences of the small-scale eddy on large scale atmospheric circulations may be included in the model equations. Accurate depiction of meteorological conditions, especially within the PBL, is important for air pollution modeling, and PBL parameterization schemes play a critical role in simulating the boundary layer. It is a very important portion of the atmosphere to correctly model to provide accurate forecasts, e.g., air pollution forecasts (Deardorff 1972; Pleim 2007). As important as the PBL is, it has one basic property whose accurate and realistic prediction is paramount to its correct modeling: its height. After all, the height of the top of the PBL defines its upper boundary. This is critical since PBL parameterizations schemes in WRF-ARW models need to know the extent through which to mix properties such as heavy rainfall, relative humidity, outgoing long wave flux, downward long wave flux.

PBL schemes were developed to help resolve the turbulent fluxes of heat, moisture, and momentum in the boundary layer. Another important issue is the interaction between the atmosphere and the surface. The PBL schemes handle the latent and sensible heat fluxes into the atmosphere, the frictional effects with the surface and the strong sub–grid–scale mixing which takes place in the lower levels due to these processes.

2.5.1 Yonsei University (YSU) scheme

The Yonsei University (YSU) PBL is the next generation of the MRF, Non local-K scheme with explicit entrainment layer and parabolic K profile in unstable mixed layer. The YSU scheme is a bulk scheme that expresses non-local mixing by convective large eddies. Non-local mixing is achieved by adding a non-local gradient adjustment term to the local gradient. At the top of the PBL, the YSU scheme uses explicit treatment of the entrainment layer, which is proportional to the surface layer flux (Shin and Hong 2011; Hong *et al*. 2006).

2.6 Map Projection

Commonly, a map projection is a systematic transformation of the latitudes and longitudes of locations on the surface of a sphere or an ellipsoid into locations on a plane. Map projections are necessary for creating maps. All map projections distort the surface in some fashion. Depending on the purpose of the map, some distortions are acceptable and others are not; therefore, different map projections exist in order to preserve some properties of the sphere-like body at the expense of other properties. There is no limit to the number of possible map projections. More generally, the surfaces of planetary bodies can be mapped even if they are too irregular to be modeled well with a sphere or ellipsoid. Even more generally, projections are the subject of several pure mathematical fields, including differential geometry and projective geometry. However, map projection refers specifically to a cartographic projection.

2.6.1 Mercator projection

The Mercator projection is a cylindrical map projection presented by the Flemish geographer and cartographer Gerardus Mercator in 1569. It became the standard map projection for nautical purposes because of its ability to represent lines of constant course, known as rhumb lines_ loxodromes, as straight segments which conserve the angles with the meridians. While the linear scale is equal in all directions around any point, thus preserving the angles and the shapes of small objects, the Mercator projection distorts the size and shape of large objects, as the scale increases from the Equator to the poles, where it becomes infinite. Although the Mercator projection is still used commonly for navigation, due to its unique properties, cartographers agree that it is not suited to general reference world maps due to its distortion of land area. Mercator himself used the equal-area sinusoidal projection to show relative areas. As a result of these criticisms, modern atlases no longer use the Mercator projection for world maps or for areas distant from the equator, preferring other cylindrical projection or forms of equal-area projection. The Mercator projection is still commonly used for areas near the equator, however, where distortion is minimal.

2.7 Arakawa Staggered C-grids

The Arakawa grid system depicts different ways to represent and compute orthogonal physical quantities on rectangular grids used for Earth system models for meteorology and oceanography. For example, the Weather Research and Forecasting Model use the Arakawa Staggered C-Grid in its atmospheric calculations when using the ARW core. The staggered Arakawa C-grid further separates evaluation of vector quantities compared to the Arakawa B-grid. E.g., instead of evaluating both east-west (u) and north-south (v) velocity components at the grid center, one might evaluate the u components at the centers of the left and right grid faces, and the v components at the centers of the upper and lower grid faces.

Chapter III

Methodology

3.1 Model Setup

In the present study the Weather Research and Forecast (WRF-ARW Version 3.5.1) model have been used to simulate the monsoon rainfall over Bangladesh. Advance Research WRF (ARW) is a dynamic solver which is compatible with WRF system to simulate broad spectrum of meteorological phenomena. Weather Research and Forecast model consists of fully compressible non-hydrostatic equations and different prognostic variables. The model vertical coordinate is terrain following hydrostatic pressure and the horizontal grid is Arakawa C-grid staggering. The model has different microphysics options but in this research WSM6-class graupel scheme has been used. The WSM6 scheme contains prognostic equations for cloud water, rainwater, cloud ice, snow, and graupel mixing ratio. The model has integrated by using initial and lateral boundary conditions (LBCs) from NCEP-FNL analysis at six hourly intervals. Surface layer is treated using Monin-Obukhov and planetary boundary layer (PBL) is treated with Yonsei University scheme. Dudhia (1989) scheme has been used for short wave radiation and Rapid Radiative Transfer Model (RRTM) for long wave (Mlawer *et al.* 1997). Kain-Fritsch (KF) (1993) cumulus parameterization (CP) scheme has been used for simulating the monsoon rainfall.

3.2 Model Domain and Configuration

The model has been configured in single domain, 6 km horizontal grid spacing with 161×183 grids in the east-west and north-south directions and 30 vertical levels. Time step of integration is set to 36 seconds for maintaining computational stability as the model uses third-order Runge-Kutta time integration scheme. The model has been integrated for 137 days starting from the initial conditions at 0000UTC of 17 May to ending at 0000 UTC of 01 October during 2010-2014. However, the results are presented for June-September to avoid the spin-up effects of the first 15 days. The model has also been run during the monsoon season of 2014 with everyday 0000 UTC initial conditions for the prediction of 24, 48 and 72 hours. The model domain is given in Fig. 3.1. The detail of the model and domain configuration is given in Table 1:

Table 1: WRF Model and Domain Configurations

Dynamics	Non-hydrostatic
Number of domain	1
Central points of the domain	Central Lat.: 22.80°N, Central Lon.: 90.70°E
Horizontal grid distance	6 km
Integration time step	36 s
Number of grid points	X-direction 161 points, Y-direction 183 points
Map projection	Mercator
Horizontal grid distribution	Arakawa C-grid
Nesting	One way
Vertical co-ordinate	Terrain-following hydrostatic-pressure co-ordinate (30 sigma levels up to 100 hPa)
Time integration	3rd order Runge-Kutta
Spatial differencing scheme	6th order centered differencing
Initial conditions	Three-dimensional real-data (FNL: 1° × 1°)
Lateral boundary condition	Specified options for real-data
Top boundary condition	Gravity wave absorbing (diffusion or Rayleigh damping)
Bottom boundary condition	Physical or free-slip
Diffusion and Damping	Simple Diffusion
Microphysics	WSM 6-class graupel Sch. (Hong and Lim, 2006)
Radiation scheme	Dudhia (1989) for short wave radiation/ RRTM long wave Mlawer *et al.* (1997)
Surface layer	Monin-Obukhov similarity theory Scheme (Hong and Pan, 1996)
Land surface parameterization	5 Layer Thermal diffusion Scheme (Ek *et al*., 2003)
Cumulus parameterization schemes	Kain-Fritsch (KF) Scheme, (Kain and Fritsch, 1990, 1993; Kain, 2004)
PBL parameterization	Yonsei University Scheme (YSU) (Hong *et al.*, 2006)

Fig. 3.1: WRF Model Domain for Monsoon rainfall prediction in Bangladesh

3.3 Data and Methodology

Final Reanalysis (FNL) data ($1^o x 1^o$) collected from National Centre for Environment Prediction (NCEP) is used as initial and lateral boundary Conditions (LBCs) which is updated at six hours interval i.e. the model is initialized with 0000, 0600, 1200 and 1800 UTC initial field of corresponding date. Tropical Rainfall Measuring Mission (TRMM)-3B42RT-daily rainfall data sets were downloaded from their website (http://lake.nascom.nasa.gov) while daily rain gauge data of 33 stations has been collected from Bangladesh Meteorological Department (BMD) all over Bangladesh. There is limited no. of meteorological observation stations in the northeastern and southwestern regions of Bangladesh. For this reason we have added 8 more points in the Bangladesh Map to collect rainfall data. We have extracted convective and non-convective rainfall data from WRF Model output at 33 BMD station points with additional 8 points in the northeastern and southwestern regions of Bangladesh. We have also extracted TRMM rainfall data from above mentioned 41 points during the monsoon season of 2010-2014. From WRF Model run we made 3 hourly outputs during the study period. This 3 hourly rainfall data converted into monthly rainfall data of June, July, August and September during 2010-2014. For collecting 24, 48 and 72 hour model rainfall data the WRF model has been run with every day initial condition starting from 0000 UTC of 30 May to 0000 UTC of 30 September 2014. We have considered 24 hours as 1st day of model run, 48 hours as 2nd day of model run and 72 hours as 3rd day of model run.

Txt format data from ctl file of WRF model output has been found using Grid Analysis and Display System (GrADS). These txt data have been converted into Microsoft Excel format and then plotted using SURFER Software. The monthly rainfall data has been plotted of June, July, August and September using 24, 48 and 72-hour lead time prediction for the year 2014 and also using 137 day prediction during 2010-2014. The RMSE and MAE have been calculated for 33 meteorological stations, because there is not any observational data for others. The RMSE and MAE of rainfall have been calculated for long time prediction using Microsoft Excel and then plotted using SURFER Software during 2010-2014. The RMSE and MAE for 24, 48, 72-hour predicted rainfall have also been plotted using the same procedure for the year 2014. The CC between observed and 24, 48, 72-hour and 137 days predicted rainfall has been obtained using Microsoft Excel and then plotted using SURFER Software.

3.4 Root mean square error (RMSE)

The Root Mean Square Error (RMSE) (also called the root mean square deviation, RMSD) is a frequently used measure of the difference between values predicted by a model and the values actually observed from the environment that is being modeled. These individual differences are also called residuals, and the RMSE serves to aggregate them into a single measure of predictive power. The RMSE of a model prediction with respect to the estimated variable is defined as the square root of the mean squared error:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model,i})^2}{n}}$$

Where X_{obs} is observed values and X_{model} is modeled values at time/place i.

The RMSE values can be used to distinguish model performance in a calibration period with that of a validation period as well as to compare the individual model performance to that of other predictive models.

3.5 Mean absolute error (MAE)

The MAE measures the average magnitude of the errors in a set of forecasts, without considering their direction. It measures accuracy for continuous variables. The MAE is the average over the verification sample of the absolute values of the differences between forecast and the corresponding observation. The MAE is a linear score which means that all the individual differences are weighted equally in the average. In statistics, the mean absolute error is a quantity used to measure how close forecasts or predictions are to the eventual outcomes. The mean absolute error is given by

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n} |f_i - y_i| = \frac{1}{n}\sum_{i=1}^{n} |e_i|.$$

As the name suggests, the mean absolute error is an average of the absolute errors $|e_i| = |f_i - y_i|$, where f_i is the prediction and y_i the true value. Note that alternative formulations may include relative frequencies as weight factors.

The mean absolute error is a common measure of forecast error in time series analysis, where the terms "mean absolute deviation" is sometimes used in confusion with the more standard definition of mean absolute deviation.

3.6 Coefficient of Correlation (CC)

The ratio of the explained variation to the total variation is called the coefficient of determination. If there is zero explained variation (i.e., the total variation is all unexplained), this ratio is 0. If there is zero unexplained variation (i.e., the total variation is all explained), the ratio is 1. In other cases the ratio lies between 0 and 1. Since the ratio is always nonnegative, we can denote it by r^2. The quantity r, called the coefficient of correlation or briefly correlation coefficient, is given by

$$r = \pm\sqrt{\frac{Explained \quad Variation}{Total \quad Variation}} = \pm\sqrt{\frac{\sum (Y_{est} - \bar{Y})^2}{\sum (Y - \bar{Y})^2}} \qquad (1)$$

and varies between –1 and +1. The + and – signs are used for positive linear correlation and negative linear correlation, respectively. R is a dimensionless quantity; that is, it does not depend on the units employed.

The total variation of Y is defined as $\sum (Y - \bar{Y})^2$; that is, the sum of the squares of the deviations of the values of Y from the mean $\bar{Y}$. This can be written

$$\sum (Y - \bar{Y})^2 = \sum (Y - Y_{est})^2 + \sum (Y_{est} - \bar{Y})^2 \qquad (2)$$

The first term on the right of equation (2) is called the unexplained variation, while the second term is called the explained variation.

Here Y_{est} represent the value of Y for given values of X as estimated from equation $Y = a_0 + a_1 X$ and a measure of the scatter about the regression line of Y on X is supplied by the quantity

$$s_{Y.X} = \sqrt{\frac{\sum (Y - Y_{est})^2}{N}} \tag{3}$$

and the scatter about the regression line of X on Y is

$$s_{X.Y} = \sqrt{\frac{\sum (X - X_{est})^2}{N}} \tag{4}$$

By using the equations (2) and (3) and the fact that the standard deviation of Y is

$$s_Y = \sqrt{\frac{\sum (Y - \bar{Y})^2}{N}} \tag{5}$$

We find that equation (1) can be written, disregarding the sign as

$$r = \sqrt{1 - \frac{s_{Y.X}^2}{s_Y^2}} \tag{6}$$

or $$s_{Y.X} = s_Y \sqrt{1 - r^2} \tag{7}$$

Similar equations exist when X and Y are interchanged (Spiegel and Stephens, 1999).

Chapter IV

Results and Discussions

4.1 Rainfall distribution

Station wise monthly average observed rainfall and 137 days prediction of monsoon seasonal (June-September) rainfall have been analysed during 2010-2014 all over Bangladesh. WRF model has been used to predict 24, 48 and 72 hours rainfall for the prediction of monthly rainfall of June, July, August and September for 2014. We have run WRF model with everyday 0000 UTC initial conditions for 72 hours for the prediction of monsoon seasonal rainfall of 2014 and also run the model for 137 days prediction with the initial condition at 0000 UTC of 17 May for the year 2010-2014.

4.1.1 Observed, TRMM and 137 days predicted rainfall of June and July 2010

The observed, TRMM and 137 days predicted rainfall of June 2010 has been presented in Figure 4.1.1(a-c). From Fig. 4.1.1a, the rainfall has recorded maximum in the south southeastern and northeastern region of the country. At Sandwip, Teknaf and Sylhet about 900, 800 and 850 mm rainfall has recorded. The rainfall is found minimum at Ishurdi, Chuadanga and Rajshahi regions about 150 mm during the month of June. The observed rainfall has decreased from Sandwip towards the west, east and northerly regions and from Teknaf towards Rangamati. The observed rainfall has recorded 300 mm in the central region of the country.

The TRMM rainfall of June 2010 (Fig. 4.1.1b) all over Bangladesh has recorded maximum in the northeastern and southeastern region. At Sylhet and Cox's Bazar region, the rainfall was derived 320 and 350 mm respectively. TRMM rainfall has decreased from northeastern towards western region and the minimum rainfall has found at Chuadanga, Jessore, Ishurdi and Rajshahi regions. The southwestern region i.e. Khulna, Patuakhali and Mongla the TRMM rainfall has derived of about 80-150 mm. From Cox's Bazar region, the TRMM rainfall has been decreased towards Rangamati.

The 137 days prediction of rainfall of June 2010 (Fig. 4.1.1c) has simulated maximum in the southeastern and northeastern region of Bangladesh. The rainfall has found 2500 and 3000 mm at Sylhet and Teknaf regions respectively. Simulated rainfall has decreased from northeastern region towards west and southwestern region of Bangladesh. The simulated rainfall has also decreased form Teknaf towards Rangamati region and from Sandwip towards west and east also. The minimum rainfall has been predicted in the southwestern part i.e. Mongla and Khulna and its value was 200-300 mm. The rainfall has simulated around 500-700 mm in the central region of the country.

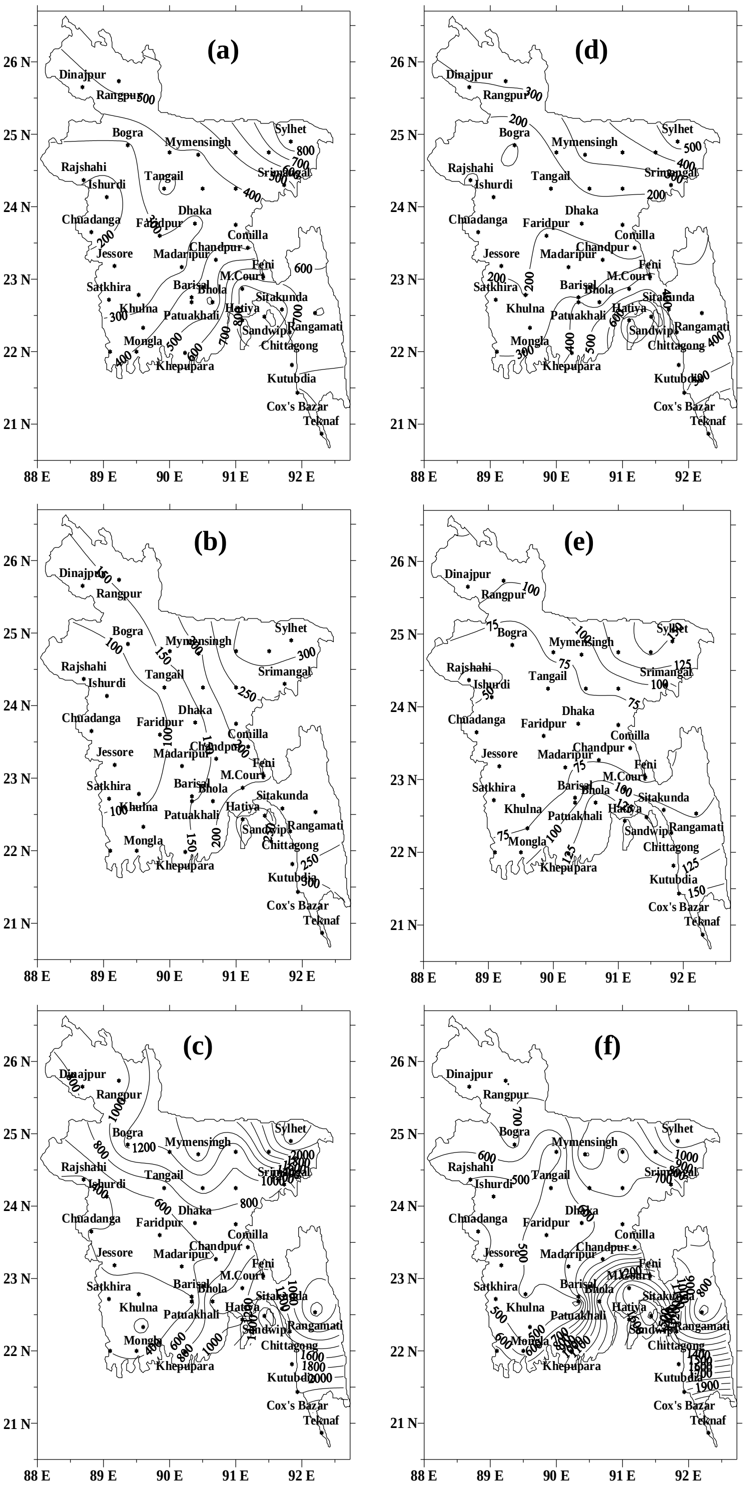

Fig. 4.1.1: Distribution of station average Observed, TRMM and Model simulated rainfall for the month of (a-c) June and (d-f) July 2010 respectively all over Bangladesh

From the analysis of observed, TRMM and 137 days prediction of June 2010 rainfall, the rainfall is found maximum in northeastern and southeastern regions and minimum in the west and southwest regions of the country. The pattern of observed, TRMM and model simulated rainfall are almost similar but the value of TRMM is much lower and simulated rainfall is much higher than that of observed rainfall.

The observed, TRMM and simulated rainfall of July 2010 has been presented in Fig. 4.1.1(d-f). The observed rainfall (Fig. 4.1.1d) has recorded maximum in the south-southeastern and northeastern region of the country. The rainfall has been observed 700, 800 and 550 mm at Sandwip, Teknaf and Sylhet regions respectively. The minimum rainfall has recorded in the western part of the country i.e. Chuadanga and Rajshahi regions of about 100 mm. The observed rainfall in Khulna, Patuakhali and Mongla has been recorded at about 200-400 mm. The observed rainfall has decreased from northeast and south southeast towards the western region. The observed rainfall has been recorded at Dhaka, Faridpur and Madaripur of about 200-300 mm.

TRMM derived rainfall of July 2010 (Fig. 4.1.1e) is found maximum in the south southeastern and northeastern region of the country. The rainfall has observed about 130, 190 and 150 mm at Sandwip, Teknaf and Sylhet regions respectively. TRMM rainfall has decreased from northeastern towards western region and the minimum rainfall has found at Rajshahi and Ishurdi regions. The TRMM rainfall has derived of about 50-100 mm at Khulna, Patuakhali, Mongla and the central region of the country. The TRMM rainfall has decreased from Teknaf region towards the northern part of the country.

The 137 days predicted rainfall of July 2010 (Fig. 4.1.1f) has simulated maximum in the south southeastern and northeastern regions of the country. The rainfall at Sylhet and Teknaf has found 1200 and 2800 mm respectively. Simulated rainfall has decreased from northeastern and southeastern regions towards west southwestern region of Bangladesh. The minimum rainfall has found at Patuakhali, Rajshahi and Dinajpur regions. In the central region of the country such as Dhaka and Faridpur the rainfall has simulated around 500-600 mm.

From the analysis of observed, TRMM and 137 days predicted rainfall of July 2010, it can be seen that the rainfall is found maximum in the northeastern and southeastern region and minimum in the west, southwest and central regions of the country. The pattern of observed, TRMM and model simulated rainfall are almost similar but the value of TRMM is much lower and simulated rainfall is much higher than that of observed rainfall.

4.1.2 Observed, TRMM and 137 days predicted rainfall of August and September 2010

The observed, TRMM and simulated rainfall of August 2010 has been presented in Fig. 4.1.2(a-c). The observed rainfall (Fig.4.1.2a) has recorded maximum in the northeastern and southeastern regions of the country. The significant amount of rainfall has found 500, 650 and 700 mm at Sandwip, Sylhet and Teknaf regions respectively. The minimum rainfall has found at Chuadanga and Rajshahi regions only about 100 mm and Bhola and Madaripur regions were 150 mm. The observed rainfall has recorded in Khulna, Patuakhali and Mongla was 200-250 mm. The rainfall has decreased from northeast towards west and southwestern region.

The TRMM rainfall of August 2010 (Fig. 4.1.2b) has derived maximum in the northeastern and southeastern region. The rainfall has found 140, 100 and 170 mm at Sandwip Teknaf and Sylhet regions respectively. TRMM rainfall has decreased from northeastern towards western and southwestern region and minimum rainfall has derived at Khulna region. The TRMM rainfall has decreased from Sandwip region towards the western part of the country.

The 137 days predicted rainfall of August 2010 (Fig. 4.1.2c) has predicted maximum in the south southeastern and northeastern region of the country. The rainfall has simulated 1100 and 1500 mm at Sylhet and Teknaf respectively. Simulated rainfall has decreased from northeastern region towards west and southwest region. The simulated rainfall has also decreased form Teknaf towards Rangamati region and from Sandwip towards west and east also. The minimum rainfall has predicted in the central and western regions of the country.

From the analysis of rainfall distribution for August 2010, the rainfall is found maximum in northeastern and southeastern region and minimum in the west and south southwest regions of the country. The distribution pattern of TRMM, Model simulated and observed rainfalls are almost similar but the TRMM (Model simulated) was much lower (higher) than that of observed rainfall. The rainfall for 137 days prediction has simulated much higher value in south southeastern and northeastern region than those of observed and TRMM rainfall.

The observed, TRMM and 137 days predicted rainfall of September 2010 has been presented in Fig. 4.1.1(d-f). The observed rainfall (Fig. 4.1.2d) has recorded maximum in the

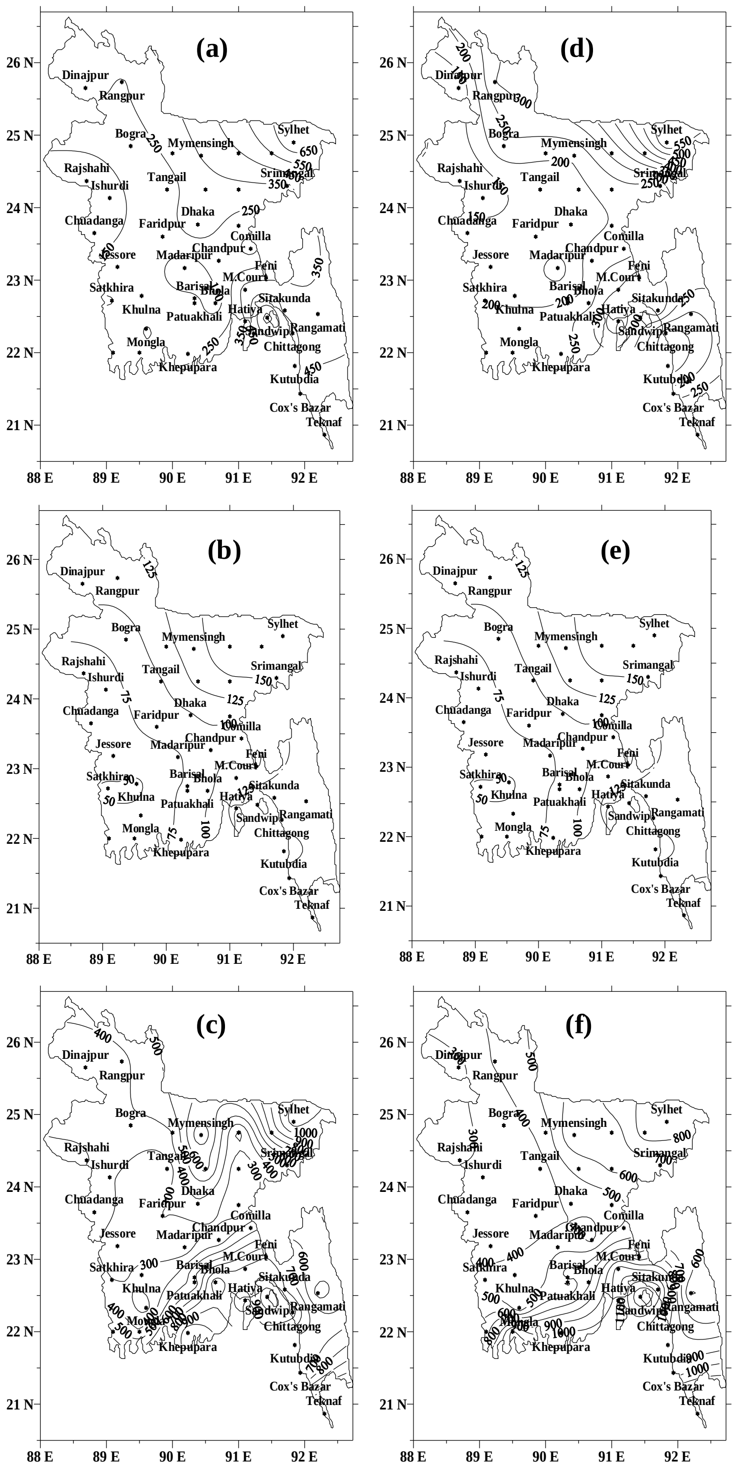

Fig. 4.1.2: Distribution of station average Observed, TRMM and Model simulated rainfall for the month of (a-c) August and (d-f) September 2010 respectively all over Bangladesh

northeastern and southeastern region of the country. The observed rainfall has found 400 and 550 mm at Teknaf and Sylhet respectively. The observed rainfall has decreased from northeastern region towards west and southwestern region. The minimum rainfall has been observed in the west northwestern region of the country and at Rajshahi, Dinajpur and Ishurdi regions only about 150 mm. The rainfall has been recorded in Khulna, Patuakhali and Mongla was about 200-250 mm.

Fig. 4.1.2(e) represents the distribution of TRMM derived rainfall for the month of September 2010 all over Bangladesh. The maximum rainfall has derived in north northeastern region i.e. Sylhet was about 210 mm. TRMM rainfall has decreased from northeastern towards western and southern region. The minimum rainfall has derived in the central, western and eastern regions of the country were about 60 mm.

The 137 days predicted rainfall of September 2010 (Fig. 4.1.2f) has simulated maximum in the south southeastern region of the country. The significant amount of rainfall has also simulated in the northeastern part of Bangladesh. The rainfall has simulated 900 and 1500 mm at Sylhet and Teknaf regions respectively. Simulated rainfall has decreased from northeastern and southeastern region towards west. The minimum rainfall has predicted in the western and northwestern region i.e. Dinajpur, Rajshahi, Ishurdi and its value was almost 300 mm. In the central region of the country such as Dhaka, Tangail and Faridpur the rainfall has simulated around 400-500 mm.

From the analysis of rainfall distribution of September 2010, the rainfall is found maximum in northeastern region of the country and minimum in the west, south southwest and central region. The distribution pattern of TRMM, Model simulated and observed rainfalls are almost similar but the TRMM (Model simulated) was much lower (higher) than that of observed rainfall. The rainfall for 137 days prediction has simulated much higher value in south southeastern and northeastern region than those of observed and TRMM rainfall.

4.1.3 Observed, TRMM and 137 days predicted rainfall of June and July 2011

The observed, TRMM and 137 days predicted rainfall of June 2011 has been presented in Fig. 4.1.3(a-c). The observed rainfall of June (Fig. 4.1.3a) has recorded maximum in the south southeastern region of the country i.e. Sandwip and Teknaf about 700 and 1100 mm respectively. The significant amount of rainfall has also recorded in Sylhet about 600 mm. The northwestern part of the country such as Bogra and Rangpur regions the minimum rainfall has recorded around 300 mm in this month. The observed rainfall has decreased from northeast and southeast region towards the west north western regions. In the central region of the country Dhaka, Faridpur and Comilla the rainfall has recorded of about 300-400 mm.

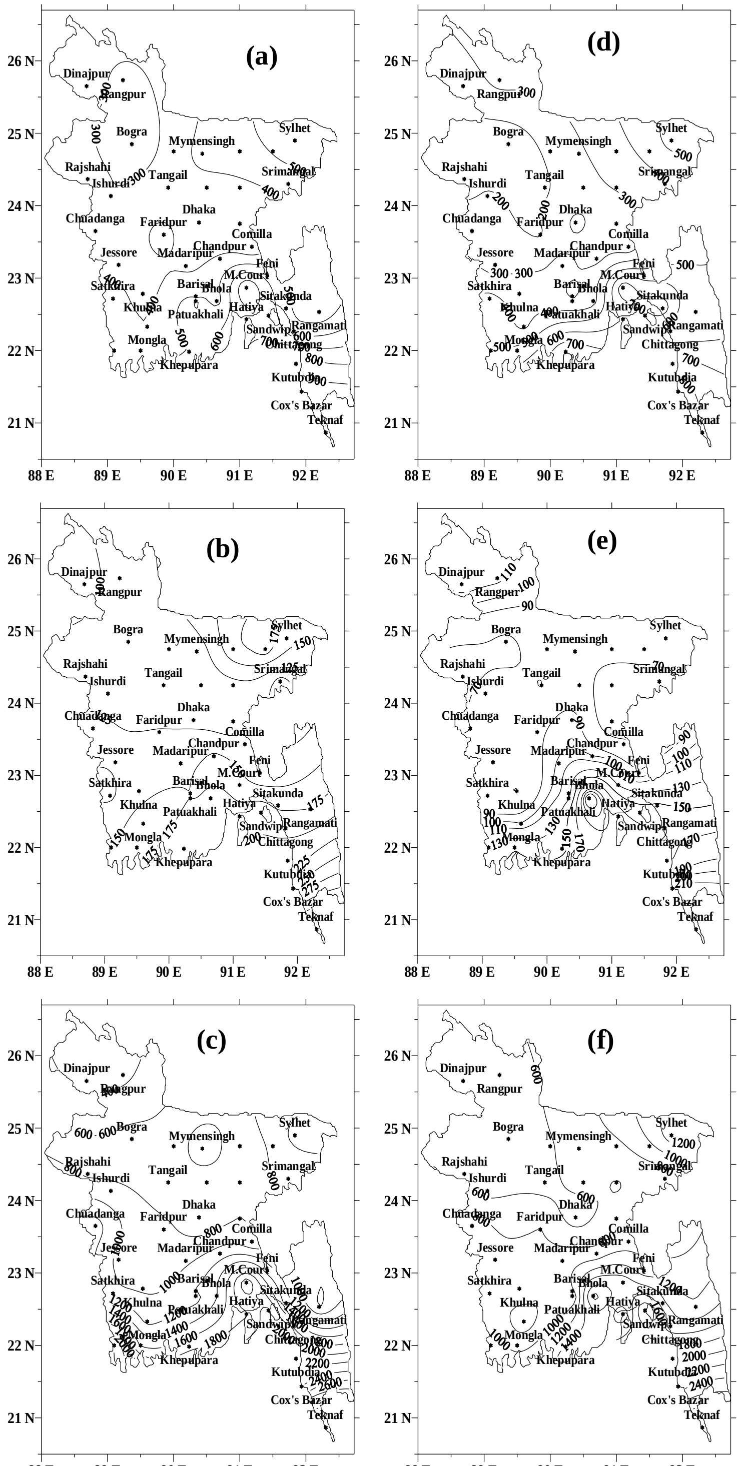

Fig. 4.1.3: Distribution of station average Observed, TRMM and Model simulated rainfall for the month of (a-c) June and (d-f) July 2011 respectively all over Bangladesh

The TRMM rainfall of June 2011 (Fig. 4.1.3b) has derived maximum in the south southeastern region. 200 and 380 mm rainfall has derived at Sandwip and Teknaf respectively. The significant amount of rainfall is observed in northeastern region and its value was 190 mm. TRMM rainfall has decreased from northeastern and south southeastern towards western region and the minimum rainfall is observed in the northwestern region i.e. Dinajpur.

The 137 days prediction of rainfall of June 2011 (Fig. 4.1.3c) has simulated maximum in the south southeastern regions of the country. The rainfall has simulated at Khepupara and Teknaf regions of about 1700 and 3900 mm respectively. Simulated rainfall has decreased from south southeastern region towards northwestern region. The simulated rainfall has also decreased form Teknaf towards Rangamati region and from Sandwip towards west and east also. The minimum rainfall has simulated at Rangpur and Dinajpur and its value almost 300 mm.

From the analysis of observed, TRMM and 137 days prediction of rainfall for June 2011, it can be emphasize that the rainfall is found maximum in northeastern and southeastern region and minimum in the west and northwestern regions of the country. The distribution pattern of TRMM, Model simulated and observed rainfalls are almost similar but the TRMM (Model simulated) was much lower (higher) than that of observed rainfall. The rainfall for 137 days prediction has simulated much higher value in south southeastern and northeastern region than those of observed and TRMM rainfall.

The observed, TRMM and 137 days simulated rainfall of July 2011 has been presented in Fig. 4.1.3(d-f). The observed rainfall of July (Fig. 4.1.3d) has recorded maximum in the south southeastern region of the country i.e. Sandwip and Teknaf of about 700 and 800 mm. The significant amount of rainfall has also observed in the northeastern region i.e. Sylhet of about 500 mm. The observed rainfall has decreased from northeastern and southeastern region towards west of Bangladesh. The minimum rainfall is recorded in the western part of the country such as Bogra and Rangpur region only about 200 mm. In the central region of the country Dhaka, Faridpur and Comilla the rainfall is recorded of about 200-300 mm.

The TRMM rainfall of July 2011 (Fig. 4.1.3e) has derived maximum in the south southeastern region. In Hatiya and Teknaf region only about 230 and 250 mm rainfall is observed. The western region of the country i.e. Ishurdi, Rajshahi and Bogra the minimum rainfall 60-70 mm is also observed. The observed rainfall has decreased from south southeast towards western region. The TRMM rainfall is derived of about 70-130 mm in the southwestern region i.e. Khulna, Patuakhali and Mongla.

The 137 days prediction of rainfall of July 2011 (Fig.4.1.3f) has simulated maximum in south southeastern region of Bangladesh. The significant amount of rainfall has simulated in the northeastern region. The rainfall has found 1200 and 3200 mm at Sylhet and Teknaf regions respectively. Simulated rainfall has decreased from northeastern and southeastern region towards west northwestern region. The minimum rainfall has found in the northwestern region i.e. Rangpur, Dinajpur and its value was almost 500 mm. In the central region of the country such as Dhaka, Faridpur the predicted rainfall has simulated around 600-700 mm.

From the analysis of observed, TRMM and 137 days prediction of rainfall for July 2011, it can be emphasize that the rainfall is found maximum in northeastern and southeastern region and minimum in the central, west and northwestern regions of the country. The distribution pattern of TRMM, Model simulated and observed rainfalls are almost similar but the TRMM (Model simulated) was much lower (higher) than that of observed rainfall. The rainfall for 137 days prediction has simulated much higher value in south southeastern and northeastern region than those of observed and TRMM rainfall.

4.1.4 Observed, TRMM and 137 days predicted rainfall of August and September 2011

The observed, TRMM and 137 days simulated rainfall of August 2011 has been presented in Fig. 4.1.4(a-c). The observed rainfall of August (Fig.4.1.4a) has recorded maximum in the south southeastern region of the country. In Cox's Bazar and Sandwip regions the observed rainfall was about 1100 mm. In Jessore, Chandpur and Madaripur regions only about 300 mm rainfall were recorded which has minimum during the month of August 2011. The observed rainfall in Khulna, Patuakhali and Mongla is recorded about 500-600 mm. The observed rainfall has decreased from Sandwip towards the north, east and west also and from Teknaf region towards Rangamati.

The TRMM derived rainfall of August 2011 (Fig. 4.1.4b) is found maximum in the south southeastern region i.e. Cox's Bazar. In Sandwip and Teknaf region only about 270 and 320 mm rainfall is observed. TRMM rainfall has decreased from north and south southeast towards southwest and the minimum rainfall is observed in Khulna region. The minimum rainfall is also observed in the southwestern and northwestern region i.e. the rainfall derived at Khulna and Satkhira were about 120 mm. The observed rainfall has decreased from Teknaf towards Rangamati and Sandwip towards northwestern region of the country.

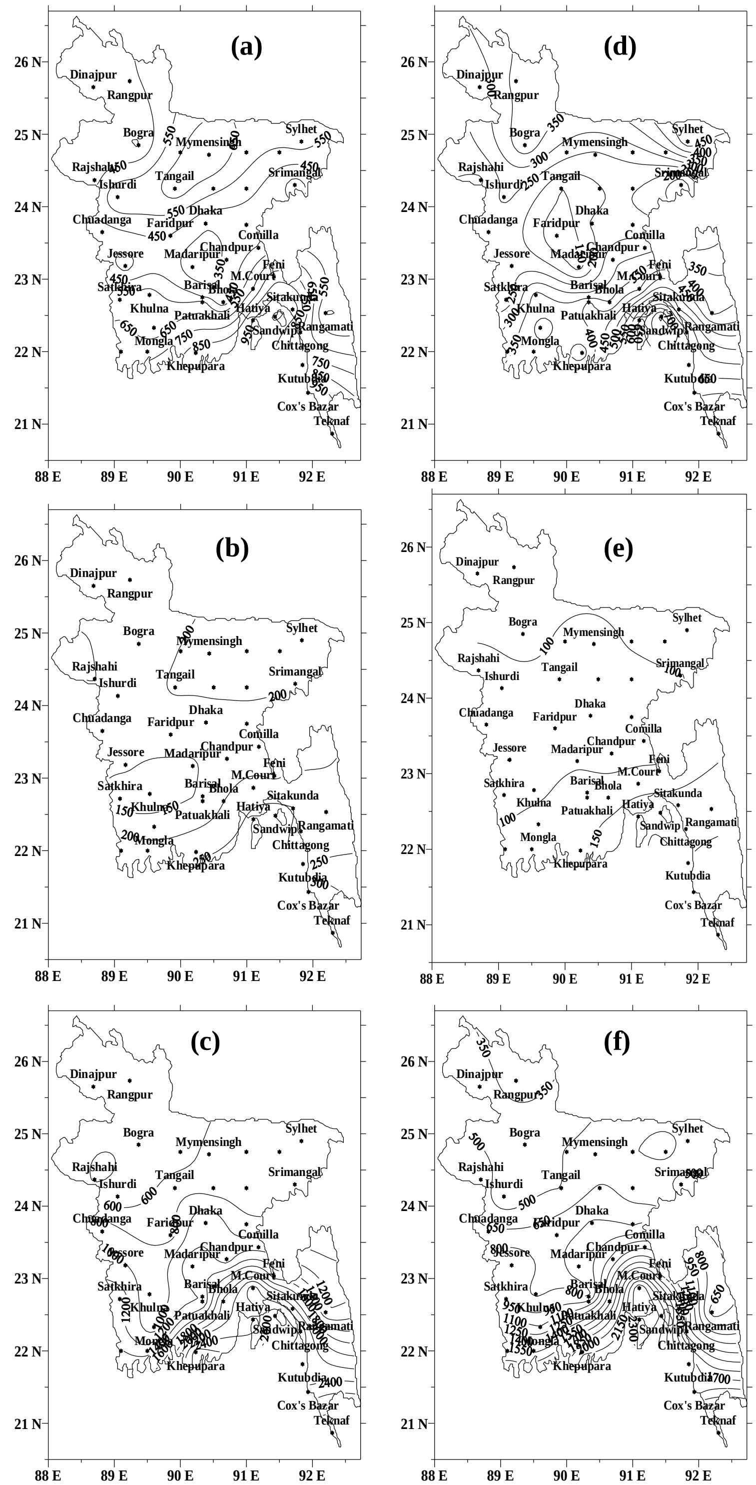

Fig. 4.1.4: Distribution of station average Observed, TRMM and Model simulated rainfall for the month of (a-c) August and (d-f) September 2011 respectively all over Bangladesh

The 137 days prediction of rainfall of August 2011 (Fig.4.1.4c) has simulated maximum in the south southeastern region of the country. The highest and lowest rainfall has found 3400 and 400 mm at Teknaf and Rajshahi respectively. The simulated rainfall has decreased form Teknaf towards Rangamati region and from Sandwip towards west and east also. In the central region of the country such as Dhaka, Comilla, Faridpur and Madaripur regions the rainfall has simulated around 800-1200 mm.

From the analysis of observed, TRMM and 137 days prediction of rainfall for August 2011, it can be emphasize that the rainfall is found maximum in southeastern region and minimum in the central, west and northwestern regions of the country. The distribution pattern of TRMM and observed rainfall are almost similar but the value of TRMM rainfall is much lower than that of observed rainfall. The rainfall for 137 days prediction has simulated much higher value in south southeastern and northeastern region than those of observed and TRMM rainfall. Simulated rainfall distribution is found minimum in the northwestern region but the minimum has found for observed and TRMM rainfall in the central region of the country.

The observed, TRMM and 137 days predicted rainfall of September 2011 has been presented in Fig. 4.1.4(d-f). The observed rainfall of September (Fig.4.1.4d) has recorded maximum in the southeastern and northeastern region of the country. The significant amount of rainfall 450, 750 and 800 mm has been observed at Sylhet, Sandwip and Teknaf regions respectively. The minimum rainfall has observed at Tangail, Faridpur, Madaripur and Srimangal regions and its value around 150 mm. The rainfall has decreased from Teknaf towards Rangamati region.

TRMM rainfall of September 2011 (Fig. 4.1.4e) has derived maximum in the south southeastern region of Bangladesh. In Sandwip and Cox’s Bazar regions only about 200 and 260 mm rainfall has been derived. TRMM rainfall has increased from central region towards the surrounding area of Bangladesh. The minimum rainfall has derived in central region i.e. Dhaka and its value is 70 mm. The TRMM rainfall has decreased from Teknaf towards the northern part of the country.

The 137 days predicted rainfall of September 2011 (Fig. 4.1.4f) has simulated maximum in the south southeastern region of the country. The rainfall has simulated 2800 and 2300 mm at Teknaf and M. Court regions respectively. Simulated rainfall has decreased from south southwestern region towards north northwestern region of the country. The rainfall has also decreased form Teknaf towards Rangamati region and from Hatiya towards west and east also. The minimum rainfall has predicted in the northwestern region i.e. Rangpur and its value was 350 mm. In the central region of the country such as Dhaka, Madaripur and Faridpur the rainfall has simulated around 650-800 mm.

From the analysis of observed, TRMM and 137 days prediction of rainfall for September 2011, it can be emphasize that the rainfall is found maximum in southeastern region and minimum in the central, west and northwestern regions of the country. The distribution pattern of TRMM and observed rainfall are almost similar but the TRMM rainfall is much lower than that of observed rainfall. The rainfall for 137 days prediction has simulated much higher value in south southeastern region than those of observed and TRMM rainfall. Simulated rainfall distribution is found minimum in the northwestern region but the minimum has found for observed and TRMM rainfall in the central region of the country. The similar distribution pattern has seen for observed, TRMM and 137 days predicted rainfall for the month of August and September.

4.1.5 Observed, TRMM and 137 days predicted rainfall of June and July 2012

The observed, TRMM and 137 days predicted rainfall of June 2012 has been presented in Fig. 4.1.5(a-c). The observed rainfall of June (Fig.4.1.5a) has recorded maximum in the southeastern and northeastern region of the country. At Sylhet and Teknaf regions about 1100 and 1200 mm rainfall has recorded in the month of June 2012. The rainfall has been recorded minimum from central to western region i.e. at Dhaka, Faridpur, Madaripur, Bogra, Rajshahi, Ishurdi, Chuadanga and Jessore and the minimum value of about 200 mm in this month. The rainfall has decreased from eastern towards western region of the country.

The TRMM rainfall of June 2012 (Fig. 4.1.5b) has derived maximum in the northeastern and southeastern region of Bangladesh. At Sylhet and Teknaf regions the rainfall has derived of about 300-400 mm. The TRMM rainfall has decreased from eastern towards western region of the country. The rainfall is found minimum at Ishurdi, Chuadanga and Jessore regions only about 50 mm. In this month the TRMM rainfall has almost one third to that of observed rainfall all through the country.

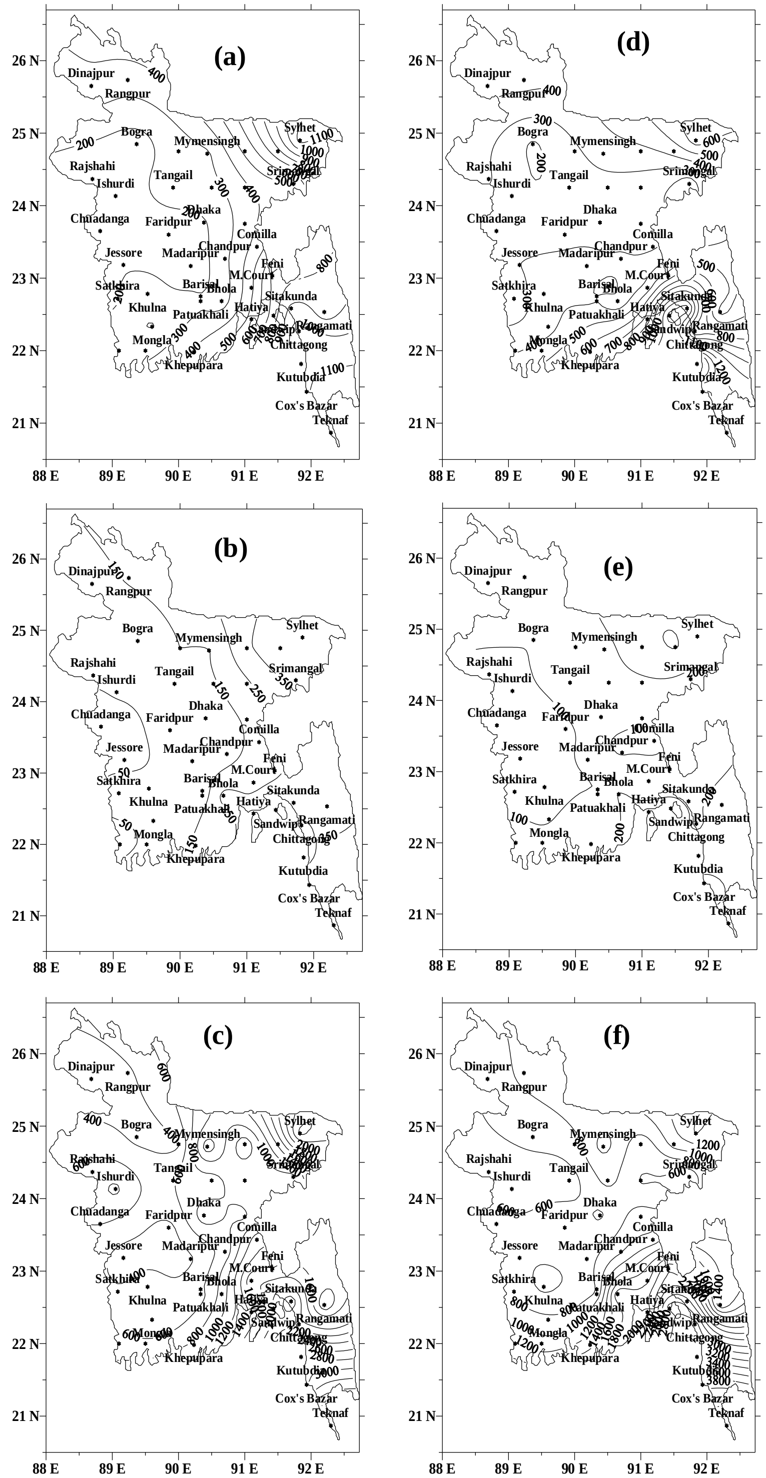

Fig. 4.1.5: Distribution of station average Observed, TRMM and Model simulated rainfall for the month of (a-c) June and (d-f) July 2012 respectively all over Bangladesh

The 137 days prediction of rainfall of June 2012 (Fig.4.1.5c) has simulated maximum in south southeastern and northeastern region of the country. The rainfall has simulated at Sylhet and Teknaf regions about 2200 and 4000 mm respectively. Simulated rainfall has decreased from northeastern and southeastern region towards west, southwest regions of Bangladesh. The rainfall has simulated minimum in northwestern and southwestern regions. The rainfall has simulated almost 400 mm at Rangpur, Dinajpur, Jessore, Faridpur and Madaripur regions.

From the analysis of observed, TRMM and 137 days prediction of rainfall for June 2012 is found maximum in northeastern and southeastern region and minimum in the west, southwest and northwest regions of the country. The distribution pattern of TRMM, observed and simulated rainfall are almost similar but the value of TRMM is much lower and model simulated rainfall is much higher than that of observed rainfall.

The observed, TRMM and 137 days simulated rainfall of July 2012 has been presented in Fig. 4.1.5(d-f). The observed rainfall of July (Fig. 4.1.5d) is found maximum in the southeastern region of Bangladesh. The rainfall has been recorded at Sandwip, Teknaf and Kutubdia regions were 1200, 1400 and 1500 mm respectively. The significant amount of rainfall has recorded in the northeastern region i.e. Sylhet about 600 mm but which is much lower than that of southeastern region. The minimum rainfall has been observed in the central region at Bogra and Srimangal regions of about 200 mm. The observed rainfall has decreased from Sandwip towards the western and northern region of the country.

The TRMM rainfall of July 2012 (Fig. 4.1.5e) has derived maximum in southeastern i.e. Cox's Bazar and northeastern region i.e. Sylhet about 250 mm. In Sandwip and Teknaf region only about 200-300 rainfall is observed. The TRMM rainfall has decreased from northeastern and southeastern towards western region of Bangladesh. The rainfall is recorded minimum in Rajshahi, Ishurdi, Chuadanga, Jessore, Satkhira, Khulna, Patuakhali and Mongla regions only about 100 mm.

The 137 days prediction of rainfall of July 2012 (Fig. 4.1.5f) has simulated maximum in the south southeastern part of the country. The significant amount of rainfall has also simulated in the northeastern part of Bangladesh. The rainfall at Teknaf and Sylhet was 4800 and 1400 mm respectively. Simulated rainfall has decreased from northeastern and south southeastern region towards western region. The simulated rainfall has also decreased form Teknaf towards Rangamati region and from Sandwip towards west and east also. The minimum rainfall has found at Srimangal, Rajshahi and Ishurdi regions. The rainfall has simulated around 600-800 mm in the central region of the country such as Dhaka, Faridpur and Madaripur regions.

From the analysis of observed, TRMM and 137 days prediction of rainfall for July 2012, the rainfall is found maximum in northeastern and southeastern region and minimum in the west, southwest, northwest and central regions of the country. The pattern of TRMM and observed rainfall are almost similar but the value of TRMM observations is much lower than that of observed rainfall. The rainfall for 137 days prediction has seen much higher value than those of observed and TRMM rainfall.

4.1.6 Observed, TRMM and 137 days predicted rainfall of August and September 2012

The observed, TRMM and 137 days simulated rainfall of August 2012 has been presented in Fig. 4.1.6(a-c). The observed rainfall of August (Fig. 4.1.6a) is found maximum in the southeastern and northeastern region of the country. The rainfall has been recorded in Sandwip, Kutubdia and Sylhet region only about 900, 500 and 700 mm respectively. The minimum rainfall has been observed in the western part of the country i.e. Rangpur, Dinajpur, Bogra, Rajshahi, Ishurdi and Chuadanga regions. The observed rainfall has decreased from northeast towards west and from southeast towards western region. In the central region of the country such as Dhaka, Faridpur and Madaripur the rainfall has recorded of about 200-300 mm. The TRMM rainfall of August 2012 (Figure 4.1.6b) has derived maximum in the southeastern and northeastern region. TRMM rainfall has decreased from northeastern region towards western region. The minimum rainfall is recorded at Chuadanga, Rajshahi, Jessore and Ishurdi region only about 50-75 mm.

The 137 days prediction of rainfall of August (Fig. 4.1.6c) has simulated maximum in the south southeastern part of the country. The significant amount of rainfall has simulated at Teknaf was 4200 mm. Simulated rainfall has decreased from southeastern region towards north northwestern region. The minimum rainfall has predicted at Srimangal, Mymensingh, Tangail, Bogra, Dinajpur and Rangpur and its value was 400 mm.

From the analysis of observed and TRMM rainfall for August 2012, the rainfall is found maximum in northeastern and southeastern region and minimum in the west northwestern region of the country. The pattern of TRMM and observed rainfall are almost similar but the value of TRMM observations is much lower than that of observed rainfall. The rainfall for 137 days prediction has simulated maximum in south southeastern region and minimum in north northwestern region. The rainfall for 137 days prediction has seen much higher value than those of observed and TRMM rainfall in south southeastern region.

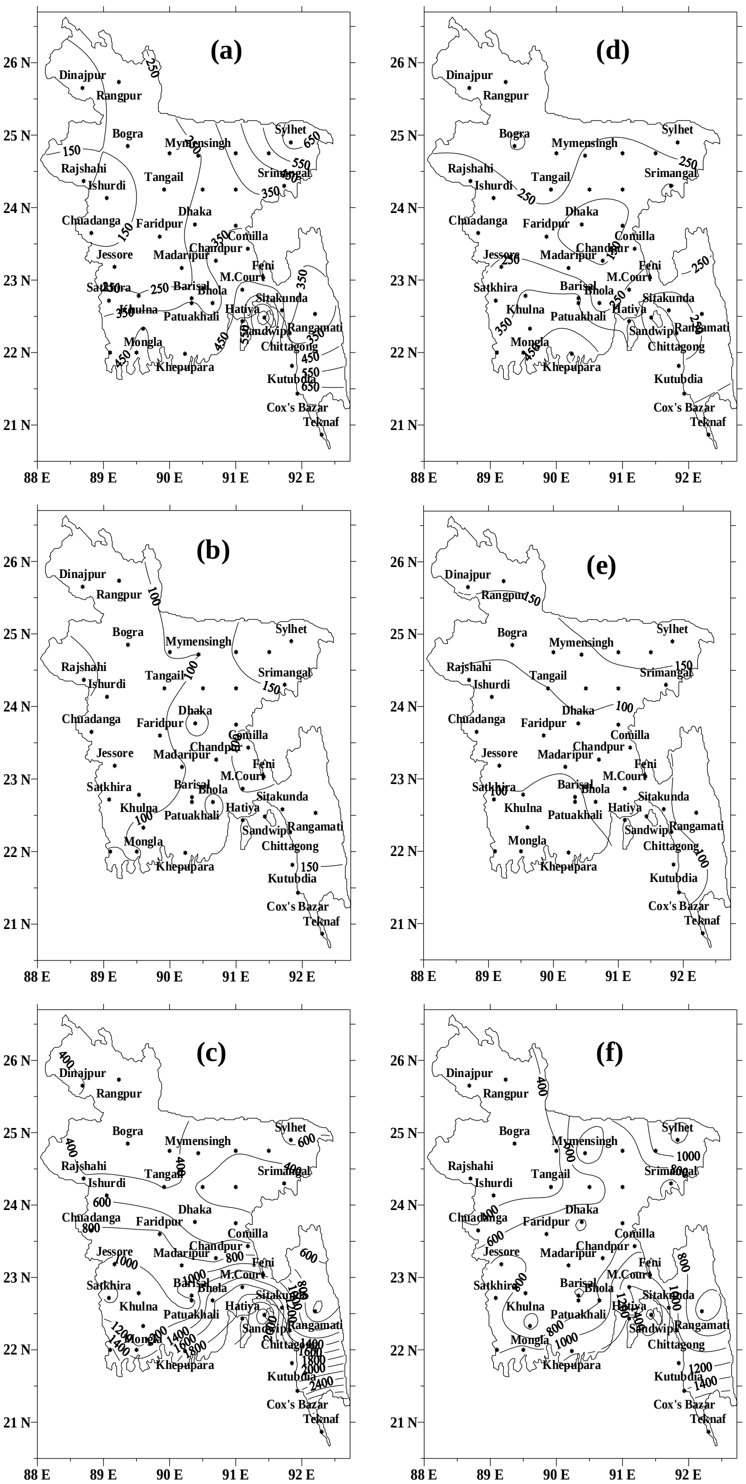

Fig. 4.1.6: Distribution of station average Observed, TRMM and Model simulated rainfall for the month of (a-c) August and (d-f) September 2012 respectively all over Bangladesh

The observed, TRMM and 137 days predicted rainfall of September 2012 has been presented in Fig. 4.1.2(d-f). The observed rainfall has (Fig. 4.1.6d) found maximum in the south southwestern region of the country i.e. Mongla, Patuakhali and Khepupara region and its value was 550 mm at Khepupara. The rainfall has recorded in the northeastern region i.e. Sylhet about 300 mm. In the central region of the country i.e. Dhaka and Chandpur region the observed rainfall is about 150 mm which is considered minimum. The observed rainfall has decreased from south towards the central region of the country.

The TRMM rainfall of September 2012 (Figure 4.1.6e) is found maximum in the north northeastern region i.e. Sylhet and its value was 175 mm. In Sandwip and Teknaf region about 80 and 100 mm rainfall is recorded. The TRMM rainfall is found minimum in the central region of the country and the minimum value at about 75 mm at Kutubdia, Chuadanga and Bhola.

The 137 days prediction of rainfall of September 2012 (Fig.4.1.26f) has simulated maximum in the south southeastern part of the country. The significant amount of rainfall has also simulated in the northeastern part of Bangladesh. The rainfall at Teknaf and Sylhet were 2200 and 1200 mm respectively. Simulated rainfall has decreased from northeastern region towards northwestern region. The minimum rainfall has found in northwestern region i.e. Dinajpur, Rangpur, Bogra, Rajshahi and Tangail regions and its value was almost 300-400 mm.

From the analysis of observed and TRMM rainfall for September 2012, the rainfall is found maximum in northeastern and southeastern regions and minimum in the central region of the country. The distribution pattern of TRMM and observed rainfall are almost similar. The rainfall for 137 days prediction has simulated maximum in south southeastern region and minimum in northwestern region. The rainfall for 137 days prediction has seen much higher value than those of observed and TRMM rainfall.

4.1.7 Observed, TRMM and 137 days predicted rainfall of June and July 2013

The observed, TRMM and 137 days simulated rainfall of June 2013 has been presented in Fig. 4.1.7(a-c). The observed rainfall of June 2013 (Fig. 4.1.7a) has recorded maximum in the southeastern and northeastern regions of the country. The rainfall has recorded of about 700, 800 and 1100 mm at Sylhet, Teknaf and Kutubdia regions respectively. Observed rainfall has decreased from northeastern and southeastern towards west and southwest region of the country. The minimum rainfall has found in western region of the country i.e. Jessore, Ishurdi, Chuadanga and Rajshahi regions only about 200 mm. The rainfall of about 200-400 mm has been observed in the central region of the country.

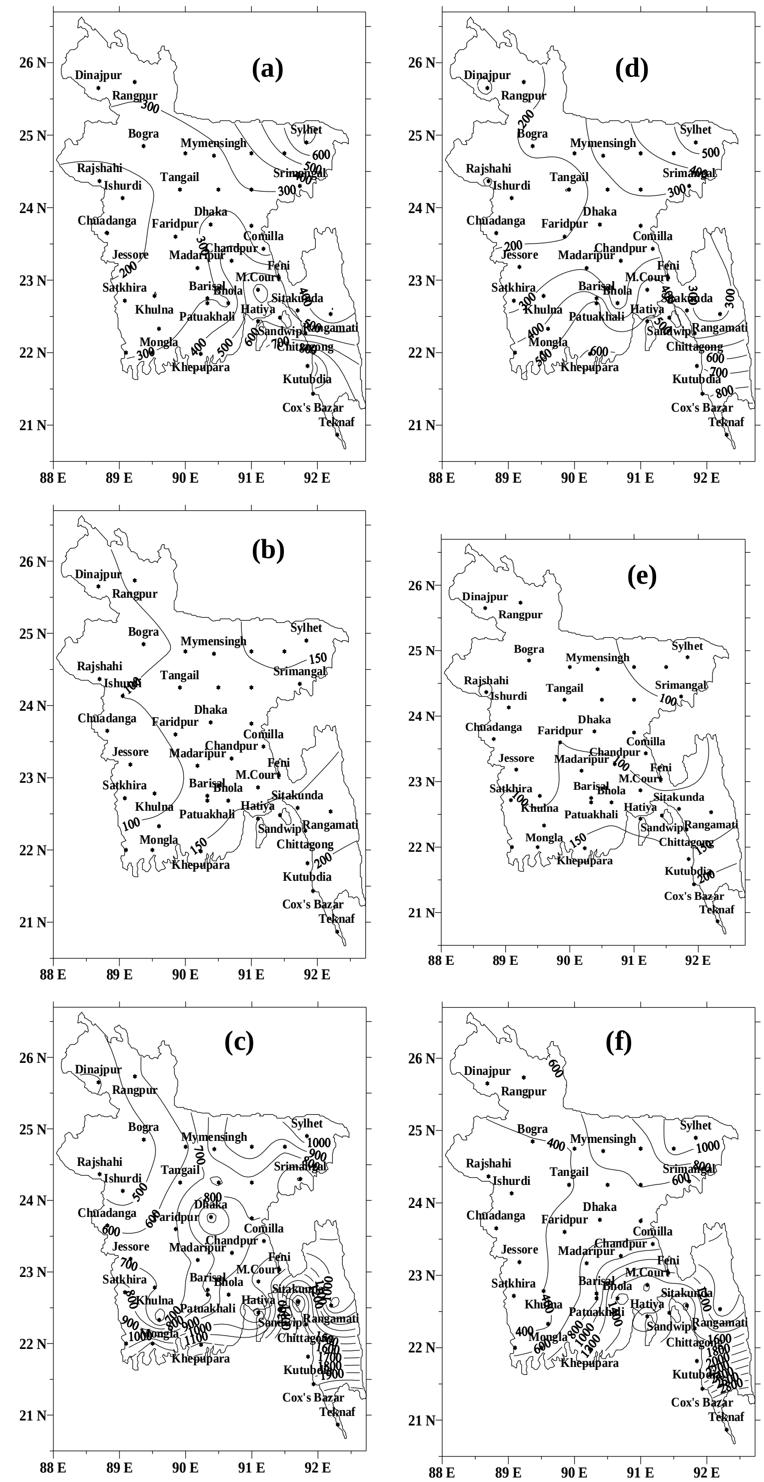

Fig. 4.1.7: Distribution of station average Observed, TRMM and Model simulated rainfall for the month of (a-c) June and (d-f) July 2013 respectively all over Bangladesh

TRMM rainfall of June 2013 (Fig. 4.1.7b) has derived maximum in the south southeastern and northeastern region of Bangladesh. The maximum rainfall has been recorded at Sylhet, Sandwip and Teknaf regions only about 160, 170 and 240 mm respectively. The TRMM rainfall has decreased from southeastern and northeastern towards western region. The TRMM rainfall has observed minimum in the western part of the country i.e. Chuadanga, Rajshahi and Jessore region of about 80 mm.

The simulated rainfall for the month of June 2013 (Fig. 4.1.7c) has simulated maximum in the south-southeastern, central and northeastern regions of the country. The rainfall has simulated 1000 and 2600 mm at Sylhet and Teknaf regions respectively. Simulated rainfall has decreased from northeastern region towards northwest and form Teknaf towards Rangamati region. The rainfall is found minimum at the northwestern region i.e. Rajshahi, Ishurdi and Dinajpur and its value almost 400-500 mm.

From the analysis of observed, TRMM and 137 days prediction of rainfall for June 2013, the rainfall is found minimum in the west and northwest regions of the country. The highest value has found in the south southeastern region. The pattern of observed and TRMM rainfall are almost similar but the value of TRMM observations is much lower than that of observed rainfall.

The observed, TRMM and 137 days prediction of rainfall of July 2013 has been presented in Fig. 4.1.7(d-f). The observed rainfall of July 2013 (Figure 4.1.7d) has recorded maximum in the southeastern and northeastern region of the country. The rainfall has been recorded of about 600 and 1100 mm at Sylhet and Teknaf regions respectively. The observed rainfall has decreased from northeastern region towards west and southeastern region towards west and northwest. The western part of the country has been recorded about 100-200 mm rainfalls at Rajshahi, Ishurdi and Dinajpur regions which have minimum during the month of July 2013. In the central region of the country i.e. Dhaka, Faridpur and Madaripur the observed rainfall has been recorded of about 200-300 mm.

The TRMM rainfall of July 2013 (Figure 4.1.7e) has derived maximum in the south southeastern and northeastern region of the country. At Sylhet and Teknaf regions the rainfall derived of about 165 and 310 mm rainfall respectively. The TRMM rainfall has decreased from northeastern and southeastern towards western region. The minimum rainfall is derived at Rajshahi region and its value at about 85 mm. In the central region of the country such as Dhaka, Faridpur and Madaripur the rainfall is derived of about 80-110 mm.

The 137 days prediction of rainfall of July 2013 (Fig. 4.1.7f) has simulated maximum in the south southeastern region of the country and significant amount of rainfall has also found in the northeastern region. The simulated rainfall has found at Sylhet and Teknaf regions 1000 and 4300 mm respectively. Simulated rainfall has decreased from northeastern region towards west and from southeastern region towards west northwest region of Bangladesh. The simulated rainfall has also decreased form Teknaf towards Rangamati region and from Sandwip towards west and east also.

From the analysis of 137 days prediction of rainfall for July 2013, the rainfall is found minimum in the west and northwest regions of the country. The maximum value has observed in south southeastern and northeastern region. The 137 days predicted rainfall has seen much higher value those of observed and TRMM rainfall. The pattern of TRMM and observed rainfall are almost similar but the value of TRMM observations is much lower than that of observed rainfall.

4.1.8 Observed, TRMM and 137 days predicted rainfall of August and September 2013

The observed, TRMM and 137 days predicted rainfall of August 2013 has been presented in Fig. 4.1.8(a-c). The observed rainfall of August 2013 (Fig. 4.1.8a) has recorded maximum in the southeastern and northeastern region of the country. The highest rainfall has found at Sylhet and Teknaf regions of about 500 and 800 mm respectively. The observed rainfall has decreased from northeastern and southeastern region towards west of the country. The minimum rainfall has observed in the central region i.e. Tangail and Ishurdi and Chuadanga. From Sandwip the observed rainfall has decreased towards all around and from Teknaf the rainfall has decreased towards Rangamati region.

TRMM rainfall of August 2013 (Fig. 4.1.8b) has derived maximum in the south southeastern and northeastern region of the country. The TRMM rainfall has found at Sylhet and Teknaf region about 140 and 240 mm respectively. The TRMM rainfall has decreased from northeastern and southeastern region towards western region. The TRMM rainfall has derived minimum in the central region. The observed rainfall has decreased from Teknaf region towards Rangamati.

The 137 days prediction of rainfall for the month of August 2013 (Fig. 4.1.8c) has predicted maximum in the south southeastern region of the country.

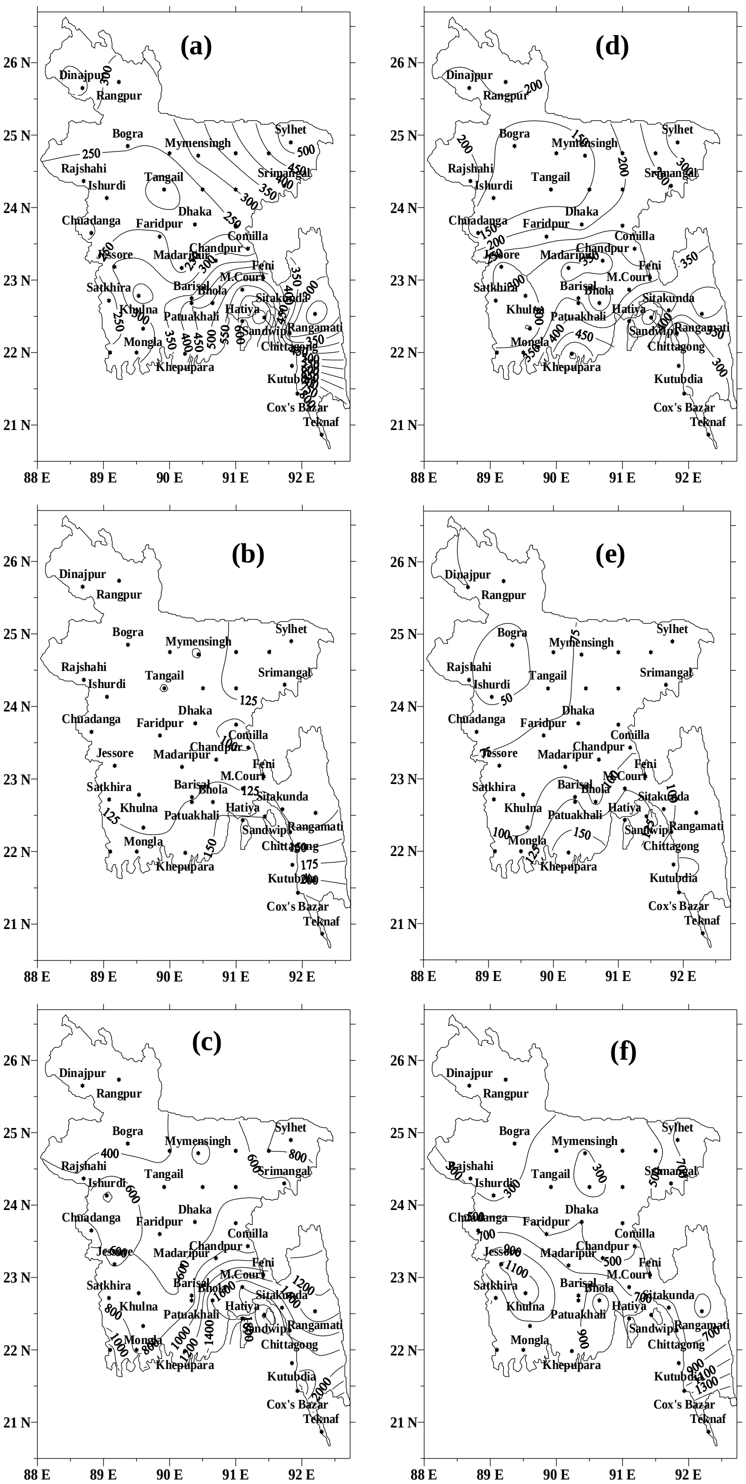

Fig. 4.1.8: Distribution of station average Observed, TRMM and Model simulated rainfall for the month of (a-c) August and (d-f) September 2013 respectively all over Bangladesh

The rainfall has simulated 900 and 3400 mm at Sylhet and Teknaf regions respectively. The simulated rainfall has decreased from northeastern and southeastern region towards west and northwest region. The 137 days rainfall has predicted minimum in northwestern region i.e. Rangpur, Dinajpur and Bogra around 400 mm.

From the analysis of observed, TRMM and 137 days predicted rainfall of August 2013, the rainfall is found maximum in northeastern and south southeastern regions. The minimum rainfall has found in the west, north northwest and central regions of the country. The 137 days predicted rainfall has been predicted much higher rain those of observed and TRMM rainfall. The pattern of TRMM and observed rainfall are almost similar but the value of TRMM (predicted) observations is much lower (higher) than that of observed rainfall.

The observed, TRMM and simulated rainfall of September 2013 (Fig. 4.1.8d) has recorded maximum in the northeastern and south southeastern region. The maximum rainfall has observed at Khepupara and its value was about 550 mm. The observed rainfall has decreased from northeastern towards western region of Bangladesh. The minimum rainfall has found in the central to western region of the country i.e. Mymensingh, Tangail, Ishurdi, Bogra and Chuadanga regions.

TRMM rainfall for the month of September 2013 (Fig. 4.1.8e) has derived maximum in the southern region of the country. The TRMM rainfall has derived about 90 and 170 mm at Sylhet and Khepupara regions respectively. The observed rainfall has decreased from southern region towards north and from northeastern towards western region and minimum rainfall has recorded at Bogra, Rajshahi and Ishurdi region only about 50 mm.

The 137 days prediction of rainfall for the month of September 2013 (Fig. 4.1.8f) has simulated maximum in the southeastern and southwestern region. The rainfall at Khulna and Teknaf has simulated 1000 and 2400 mm respectively. Simulated rainfall has decreased from southeastern region towards northwest, from south towards north and from northeastern region towards west. The minimum rainfall has found in the northwestern region i.e. Rangpur, Dinajpur, Rajshahi, Ishurdi regions and its value were almost 200-300 mm.

From the analysis of observed, TRMM and 137 days model simulated rainfall for September 2013, the rainfall is found minimum in the north northwestern regions of the country. The rainfall for 137 days prediction has simulated maximum in southeastern region and lowest in northwestern region. The 137 days predicted rainfall has been predicted much higher rain those of observed and TRMM rainfall. The pattern of TRMM and observed rainfall are almost similar but the value of TRMM (predicted) observations is much lower (higher) than that of observed rainfall.

4.1.9 Observed, TRMM and Simulated Rainfall of June 2014

The BMD observed, TRMM and model simulated rainfall for 24, 48, 72 hour and 137 days for the month of June 2014 all over Bangladesh has been presented in figure 4.1.9(a-f) respectively. Fig. 4.1.9(a) represents the station wise monthly average observed rainfall for the month of June 2014. Figure shows that the south-southeastern part of the country has recorded maximum amount of rainfall and highest rainfall observed in Chittagong at 1300 mm. In Sandwip and Teknaf region only about 1200 and 900 mm rainfall is observed. The significant amount of rainfall has also observed in the northeastern region i.e. Sylhet about 600 mm. The minimum rainfall is recorded in the west-northwestern region of the country i.e. Ishurdi and Chuadanga region only about 200-300 mm rainfall during the month of June 2014. The observed rainfall has decreased from Chittagong region towards eastern and northwestern region of the country.

Figure 4.1.9(b) shows that the highest TRMM rainfall recorded in the south southeastern part i.e. Chittagong about 300 mm. In Sandwip and Teknaf region about 300 and 250 mm rainfall were recorded. The maximum rainfall also recorded in the northeastern region i.e. Sylhet only about 200 mm. The TRMM rainfall has decreased from northeastern towards western region of the country. The minimum rainfall recorded in the western part of the country i.e. Rajshahi, Satkhira and Chuadanga region only about 100 mm during the month of June 2014. The TRMM rainfall has decreased from Teknaf region towards the northern part of the country i.e. Rangamati. In the middle part of the country Dhaka, Faridpur and Madaripur the rainfall derived of about 150 mm.

The 24 hours prediction of WRF model rainfall for the month of June 2014 has been presented in Fig. 4.1.9(c). The highest rainfall simulated towards the south southeastern part and the significant amount of rainfall also simulated in the northeastern part of the country i.e. Sylhet. The 24 hour total rainfall simulated at Teknaf and Sylhet were 2700 and 700 mm respectively. Simulated rainfall has decreased from northeastern region towards west and southwestern region of Bangladesh. The minimum rainfall was found at Rajshahi, Ishurdi and Chuadanga region which were almost 200 mm. The 24 hour predicted rainfall also decreases form Teknaf towards north i.e. Rangamati region and from Sandwip towards west and east also. In the central region of the country such as Dhaka, Tangail, Mymensingh and Faridpur the 24 hour predicted rainfall was simulated around 400-500 mm.

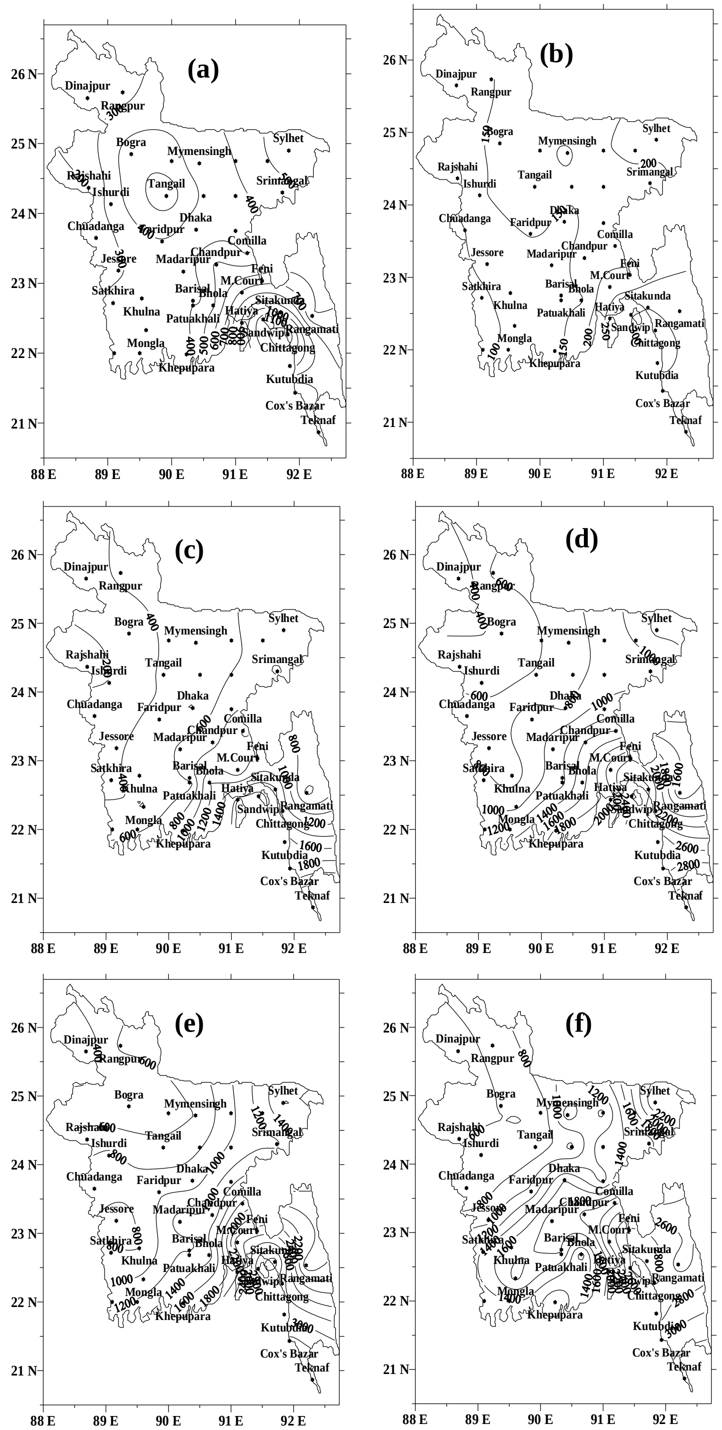

Fig. 4.1.9: Distribution of station average (a) observed, (b) TRMM, (c) 24, (d) 48, (e) 72 hours and (f) 137 days model simulated rainfall of June 2014 all over Bangladesh

Rainfall of June for 48 hour prediction (Fig. 4.1.9d) has simulated maximum in the south southeastern region and the significant amount of rainfall has simulated in the northeastern region of the country. The total rainfall June 2014 has simulated at Sylhet and Teknaf region of about 1200 and 3000 mm respectively. Simulated rainfall has increased from west towards northeastern and south southeastern region of Bangladesh.

The minimum rainfall has found in western, northwestern region such as Dinajpur, Bogra, Rajshahi, Ishurdi region which is almost 400-500 mm. The rainfall has decreased form Teknaf towards north i.e. Rangamati region and from Sandwip towards west and east also. In the central region of the country such as Dhaka, Tangail, Mymensingh the rainfall has simulated around 600-700 mm.

72 hour prediction of June rainfall (Fig. 4.1.9e) has simulated maximum in the south southeastern region and the significant amount of rainfall has also simulated in the northeastern region of the country. The 72 hour rainfall has simulated 1600 and 3300 mm at Sylhet and Teknaf regions respectively. Simulated rainfall has increased from west towards northeastern and south southeastern region of Bangladesh. The 72 hour lead time predicted rainfall is found minimum in west, northwestern region i.e. Dinajpur, Bogra region which is around 400 mm. The rainfall has decreased form Teknaf towards north i.e. Rangamati region and from Sandwip towards west and east also. The rainfall has simulated around 600-900 mm in the central region of the country such as Dhaka, Tangail, Mymensingh and Faridpur region.

The 137 days prediction of rainfall of June 2014 (Fig. 4.1.9f) has simulated maximum in the south southeastern region i.e. Teknaf, Sitakunda. The significant amount of rainfall has also simulated in the northeastern region of the country. The rainfall has found 2400 and 3400 mm at Sylhet and Teknaf regions respectively. 137 days simulated rainfall has increased from northwest towards northeast and south southeastern region and decreased from Teknaf towards Rangamati region of Bangladesh. The minimum amount of rainfall has found in the northwestern region of Bangladesh. The rainfall has simulated around 1000 mm in the central region of the country.

From the analysis of 24, 48, 72 hours and 137 days prediction of rainfall for June 2014, it has found that the rainfall was minimum in the west and north northwestern regions of the country. The maximum rainfall has simulated in south southeastern and northeastern region. The pattern of TRMM and observed rainfall are almost similar but the value of TRMM is much lower than that of observed rainfall. The rainfall for 137 days prediction has seen much higher value than those of 24, 48 and 72 hours prediction. Nevertheless, the basic features of observed and simulated rainfall distributions in all the data sets are almost similar but the value of model simulated rainfall is much higher than observed rainfall in the south southeastern region. The difference between predicted and observed rainfall were minimum where the observed rainfall is minimum.

4.1.10 Observed, TRMM and Simulated Rainfall of July 2014

The BMD observed, TRMM and model simulated rainfall for 24, 48, 72 hour and 137 days prediction for the month of July 2014 all over Bangladesh has been presented in figure 4.1.10(a-f) respectively. The observed rainfall of July 2014 (Fig. 4.1.10a) has recorded the highest rainfall in the south-southeastern part of the country i.e. Teknaf at about 900 mm. 500-700 mm rainfall were observed in Sandwip and Cox's Bazar region. In this month the significant amount of rainfall was also observed in Jessore region at about 400 mm. The observed rainfall has decreased from northeastern region towards west-northwestern region of the country. The minimum rainfall has seen in the western part of the country such as Chuadanga, Ishurdi and Rangpur region at about 100-200 mm in this month. From Teknaf region the observed rainfall decreased towards Rangamati. The rainfall has recorded 200-250 mm in the central region of the country.

The TRMM rainfall of July 2014 (Fig. 4.1.10b) has recorded maximum in the south southeastern region i.e. Teknaf about 240 mm. In Sandwip and Bhola region about 150 and170 mm rainfall is recorded. The amount of rainfall has recorded in the northeastern region i.e. Sylhet about 130 mm. The TRMM rainfall has decreased from northeastern and south southeastern region towards western region of the country. The minimum rainfall has recorded in the western part of the country i.e. Rajshahi, Bogra, Rangpur and Chuadanga region about 60-70 mm rainfall during this month. From Teknaf region TRMM rainfall has decreased towards the northern part of the country i.e. Rangamati. In the central region of the country Dhaka, Faridpur and Madaripur the rainfall has recorded of about 80-100 mm.

The 24 hours prediction of rainfall of July 2014 (Fig. 4.1.10c) all over Bangladesh has simulated maximum in south southeastern region and the significant amount of rainfall has found in northeastern region i.e. Sylhet. The rainfall has simulated 800 and 2500 mm at Sylhet and Teknaf region respectively. Simulated rainfall has decreased from northeastern and south southeastern region towards western region of Bangladesh and minimum rainfall

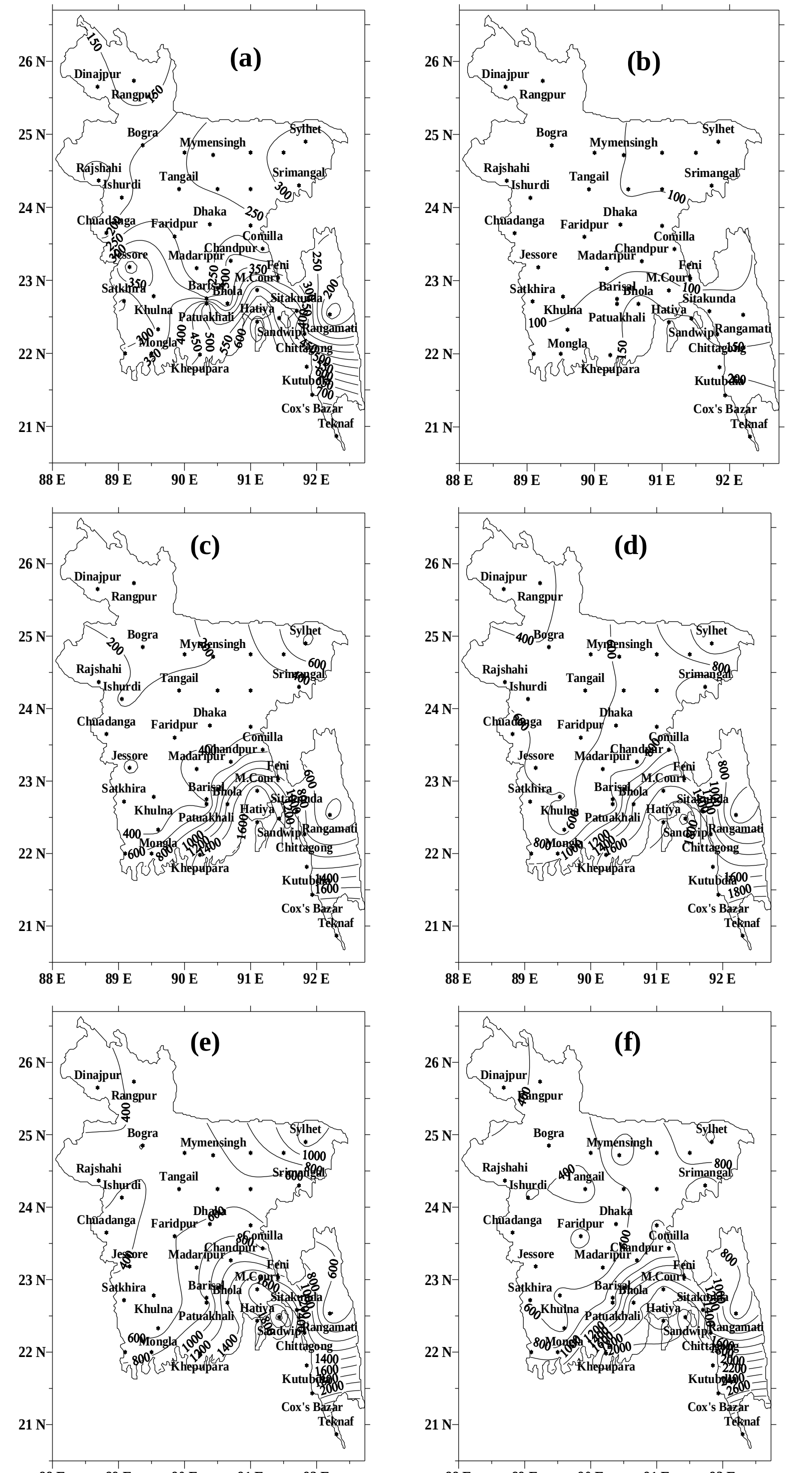

Fig. 4.1.10: Distribution of station average (a) observed, (b) TRMM, (c) 24, (d) 48, (e) 72 hours and (f) 137 days model simulated rainfall of July 2014 all over Bangladesh

was found at Bogra, Rangpur, Dinajpur, Rajshahi and Ishurdi region. The rainfall has simulated around 200-300 mm in the central region of the country such as Dhaka, Tangail, Mymensingh and Faridpur regions. The 48 hour prediction of model simulated rainfall of July 2014 (Fig. 4.1.10d) has simulated maximum in south southeastern and the significant amount of rainfall has simulated in northeastern region of the country i.e. Sylhet. The rainfall has found 1000 and 3000 mm at Sylhet and Teknaf respectively. Simulated rainfall has decreased from northeastern region towards west and from south southeastern region towards western region of Bangladesh. The minimum rainfall was found 300-400 mm at Bogra, Rangpur and Dinajpur region. The 48 hour rainfall has simulated around 500-600 mm in the central region of the country such as Dhaka, Tangail, Mymensingh and Faridpur region.

The 72 hour prediction of rainfall of July 2014 (Fig. 4.1.10e) has simulated maximum in the south southeastern and the significant amount of rainfall has simulated in the northeastern region of Bangladesh i.e. Sylhet. The rainfall has simulated 1200 and 3400 mm at Sylhet and Teknaf respectively. Simulated rainfall has decreased from northeastern towards western region of the country. The minimum rainfall has found 300 mm at Dinajpur and Chuadanga region. The rainfall has decreased form Teknaf towards north i.e. Rangamati region and from Sandwip towards west and east also. The rainfall has simulated around 500-600 mm in the central region of the country such as Dhaka, Tangail and Faridpur region.

The 137 days prediction of rainfall of July 2014 all over Bangladesh (Fig. 4.1.10f) has simulated maximum in the northeastern and south southeastern region. The rainfall has found 4300 and 1000 mm at Teknaf and Sylhet region. Simulated rainfall has decreased from northeastern region towards west and also decreased form Teknaf towards north i.e. Rangamati region and from Sandwip towards west and east also. The 137 days predicted rainfall of July is found minimum at Tangail, Dinajpur and its value was 400 mm. In the central region of the country such as Dhaka, Faridpur the rainfall has simulated around 700-800 mm.

From the analysis of 24, 48, 72 hours and 137 days prediction of rainfall for July 2014, it has found that the rainfall was minimum in the west, north northwest, southwest and central regions of the country. The maximum rainfall has simulated in the south southeastern region and also northeastern region. The pattern of TRMM and observed rainfall are almost similar but TRMM rainfall is much lower than that of observed rainfall. The rainfall for 137 days prediction has seen much higher value than those of 24, 48 and 72 hours lead time prediction. Nevertheless, the basic features of observed and simulated rainfall distributions in all the data sets are almost similar but the value of model simulated rainfall is much greater than observed rainfall in south southeastern region.

4.1.11 Observed, TRMM and Simulated Rainfall of August 2014

The BMD observed, TRMM and model simulated rainfall for 24, 48, 72 hour and 137 days for the month of August 2014 all over Bangladesh has been presented in figure 4.1.11(a-f) respectively. From Fig. 4.1.11(a), the highest rainfall has observed in the southeastern region i.e. Teknaf at about 1000 mm. In Sandwip and Chittagong region the rainfall was recorded at 950 and 700 mm respectively. The significant amount of rainfall also recorded in the northeastern region of the country i.e. Sylhet about 800 mm. The observed rainfall has decreased from northeastern region towards west and southwestern region of the country. The minimum rainfall has observed in the western part of the country i.e. Satkhira, Jessore and Dinajpur region at about 200 mm during the month of August 2014. From Teknaf the observed rainfall has decreased towards Rangamati and from Sandwip the observed rainfall has decreased towards all around. In the middle part of the country the rainfall were recorded of about 300-400 mm in this month.

The TRMM rainfall of August 2014 (Fig. 4.1.11b) has derived maximum in the northeastern region i.e. Sylhet about 270 mm. The significant amount of rainfall has recorded in the south southeastern part of the country. The rainfall has recorded at Sandwip and Teknaf region about 200 and 220 mm. The TRMM rainfall has decreased from northeastern towards west and southwestern region of Bangladesh. The minimum rainfall has recorded in the southwestern region i.e. Khulna, Satkhira and Mongla about 80 mm. The TRMM rainfall has recorded about 100-140 mm in the middle part of the country i.e. Dhaka, Faridpur and Madaripur.

Figure 4.1.11(c) illustrated the 24 hour prediction of model simulated rainfall for the month of August 2014 all over Bangladesh. The highest rainfall simulated towards the south southeastern part of the country. The maximum rainfall also simulated in the northeastern region of Bangladesh. The rainfall simulated at Teknaf and Sylhet about 2000 and 900 mm respectively. Simulated rainfall has decreased from northeastern region towards west and southwestern region of Bangladesh and minimum rainfall was found at Rajshahi, Ishurdi and Chuadanga region which was almost 200 mm. The rainfall has simulated around 400-500 mm in the central region of the country such as Dhaka, Tangail, Mymensingh and Faridpur.

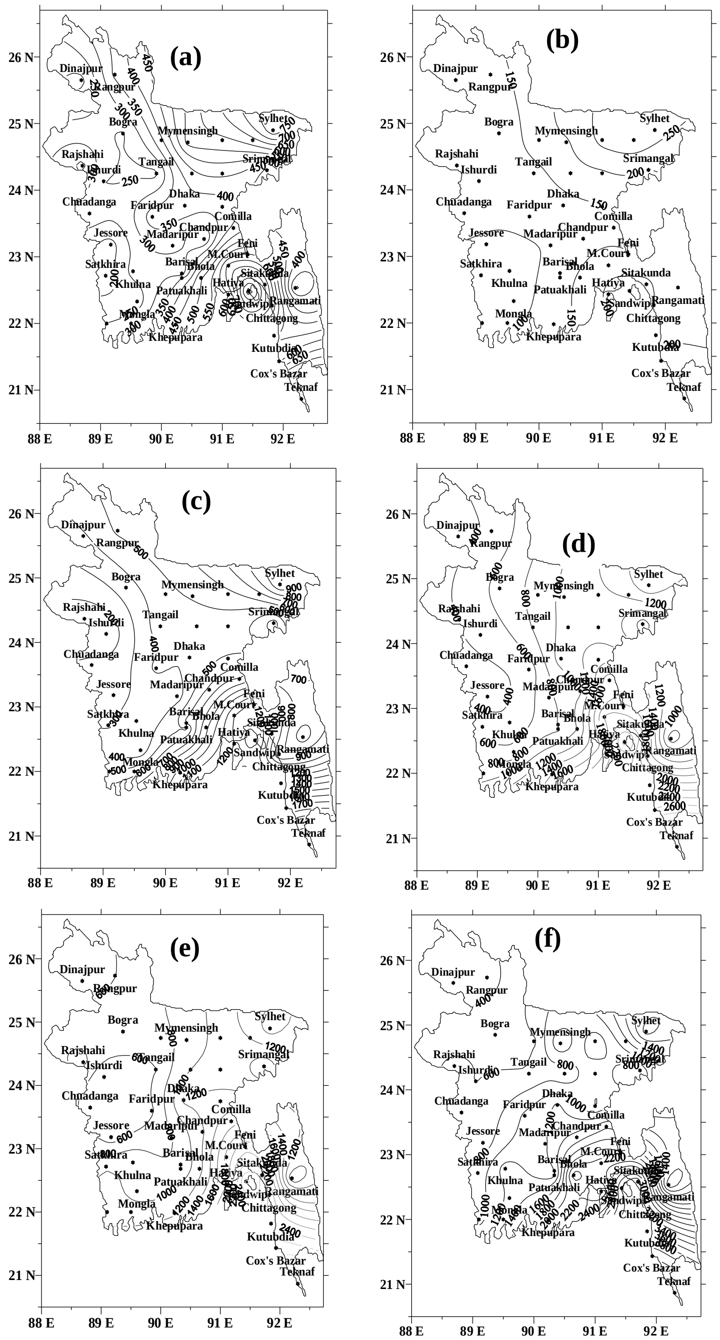

Fig. 4.1.11: Distribution of station average (a) observed, (b) TRMM, (c) 24, (d) 48, (e) 72 hours and (f) 137 days model simulated rainfall of August 2014 all over Bangladesh

The 48 hour prediction of rainfall of August 2014 (Fig. 4.1.11d) has simulated maximum in south-southeastern region of the country. The rainfall has simulated 3700, 2600 and 2400 mm at Teknaf, Cox's Bazar and Sandwip respectively. Simulated rainfall decreased from Sandwip towards east and west-northwest direction and also from Sylhet towards westward direction. The minimum rainfall was simulated at Jessore, Dinajpur and Chuadanga region which were almost 300 mm. The 48 hour predicted rainfall also decreased form Cox's Bazar towards Rangamati region. The predicted rainfall pattern is almost similar to that of observed but the simulated rainfall was much higher than that of observed in the southeastern region of the country.

The 72 hour prediction of rainfall for the month of August 2014 (Fig. 4.1.11e) all over Bangladesh has simulated maximum towards the south-southeastern region of the country. The rainfall has simulated 3200, 2700 and 2800 mm at Teknaf, Cox's Bazar and Sandwip respectively. Simulated rainfall decreased from Sandwip towards east and west-northwest direction and also from Cox's Bazar towards north-northeastward direction. The minimum rainfall was simulated at Jessore, Dinajpur, Ishurdi and Chuadanga region which were almost 500 mm.

The 137 days prediction of rainfall of August 2014 (Fig.4.1.11f) all over Bangladesh has simulated maximum towards the south-southeastern region and also the northeastern region of the country. The highest rainfall simulated at Teknaf, Cox's Bazar, Sandwip and Sylhet were 4600, 4200, 3200 and 1900 mm respectively. Simulated rainfall decreased from Sandwip towards east and west-northwestward direction and also from Cox's Bazar towards north-northeastward direction. The minimum rainfall was simulated at Rangpur-Dinajpur region which was almost 300 mm. For 137 days prediction minimum rainfall has seen in the northwestern region but minimum observed rainfall has found in the western part of the country.

From the analysis of 24, 48, 72 hours and 137 days prediction of rainfall for August 2014, it has found that the rainfall simulated minimum in the west, northwest and southwest regions of the country. The highest value has simulated in south southeastern region and maximum in northeastern region. The pattern of TRMM and observed rainfall are almost similar but the value of TRMM observations is much lower than that of observed rainfall and the highest value of observed rainfall found in north eastern region and minimum in western region. The rainfall for 137 days prediction has seen much higher than those of 24, 48 and 72 hours prediction. Nevertheless, the basic features of observed and simulated rainfall distributions in all the data sets are almost similar but the value of model simulated rainfall is much greater than observed rainfall in south southeastern region.

4.1.12 Observed, TRMM and Simulated Rainfall of September 2014

The BMD observed, TRMM and model simulated rainfall for 24, 48, 72 hour and 137 days for the month of September 2014 all over Bangladesh has been presented in Fig. 4.1.12(a-f) respectively. The observed rainfall of September 2014 (Fig. 4.1.12a) is found maximum in the northeastern region and decreased towards west-southwestern region of the country. The highest amount of rainfall recorded at Sylhet was 700 mm. The minimum rainfall recorded from central region towards west and southwestern region of the country. The minimum rainfall was observed at Chuadanga and Rajshahi region only about 150 mm. The maximum rainfall also recorded in northwestern region i.e. Rangpur and its value was about 500 mm. The observed rainfall recorded at Barisal, Bhola, Patuakhali, Khepupara and Mongla was about 250-300 mm.

The TRMM rainfall of September 2014 (Fig. 4.1.12b) has derived maximum in northeastern region i.e. Sylhet about 220 mm. In Teknaf and Sandwip regions about 100 and 110 mm rainfall was recorded. The TRMM derived rainfall has decreased from northeastern region towards west and southwestern region similarly as observed by BMD. The minimum rainfall derived in Chuadanga, Rajshahi, Jessore and Mongla was about 60 mm. In the central region of the country i.e. Dhaka, Faridpur and Tangail the rainfall was derived of about 80-120 mm.

The 24 hour lead time prediction of rainfall of September 2014 (Fig. 4.1.12c) all over Bangladesh has simulated maximum in the south southeastern and northeastern region of Bangladesh. The rainfall has simulated 600 and 700 mm at Sylhet and Teknaf respectively. Simulated rainfall has decreased from northeastern region towards west and southwestern region and minimum rainfall has found at Jessore, Faridpur, Rangamati and Patuakhali region similarly as observed by BMD. The rainfall has also decreased form Teknaf towards Rangamati region and from Sandwip towards west and east also. In the central region of the country such as Dhaka, Tangail, Mymensingh the rainfall has simulated around 200 mm. The 24 hour lead time predicted rainfall almost matched with the observed rainfall.

The 48 hour prediction of rainfall of September 2014 (Fig. 4.1.12d) has simulated maximum in south southeastern and northeastern region of Bangladesh. The rainfall has simulated about 900 mm at Teknaf and Sylhet. Simulated rainfall has decreased from northeastern region towards west and southwestern region and minimum rainfall has found at Jessore, Khulna and Patuakhali region. In the central region of the country such as Dhaka, Tangail, Mymensingh the 48 hour predicted rainfall has simulated around 300 mm. The 48 hour lead time predicted rainfall almost matched with the observed rainfall.

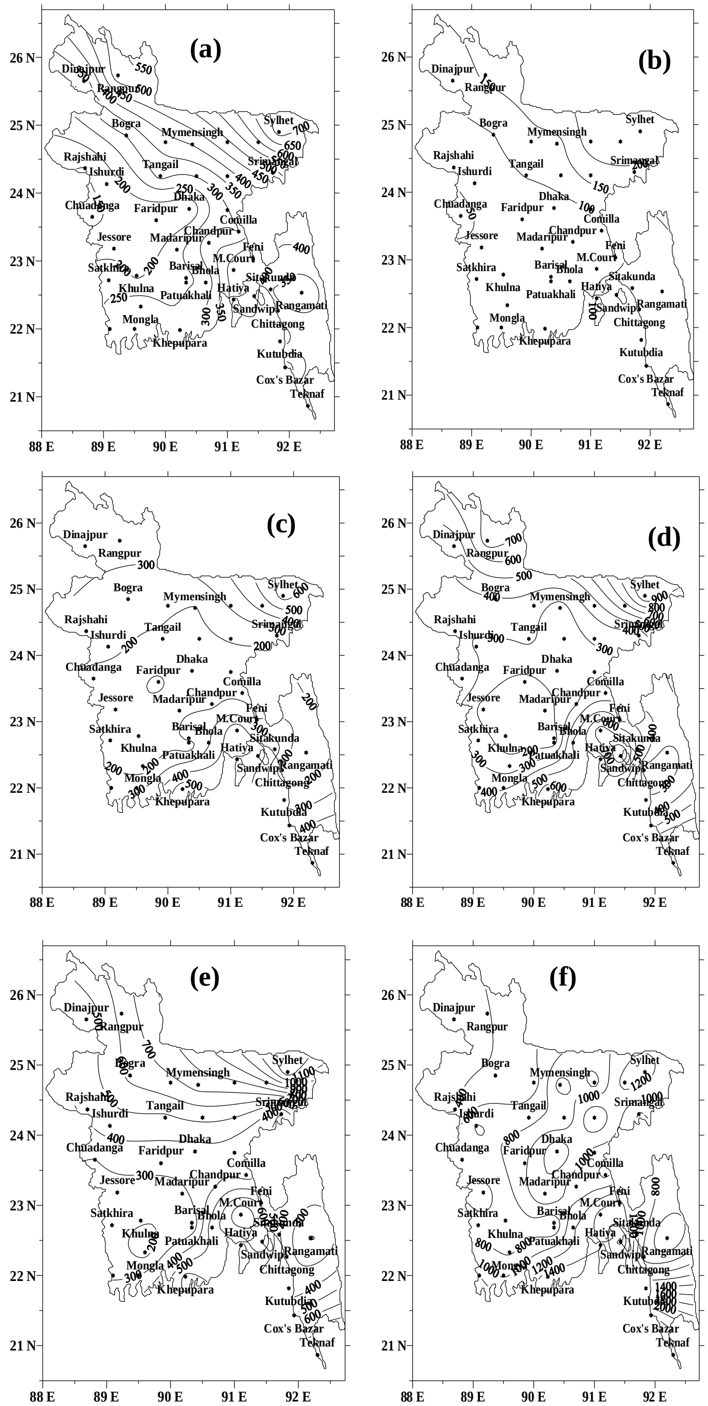

Fig. 4.1.12: Distribution of station average (a) observed, (b) TRMM, (c) 24, (d) 48, (e) 72 hours and (f) 137 days model simulated rainfall of September 2014 all over Bangladesh

The 72 hour lead time prediction of rainfall for the month of September 2014 (Fig. 4.1.12e) has simulated maximum in the northeastern and southeastern region of Bangladesh. The rainfall has simulated 1000 and 1100 mm at Teknaf and Sylhet respectively. Simulated rainfall has decreased from northeastern region towards west and southwestern region of Bangladesh. The rainfall is found minimum at Mongla, Khulna and Rangamati region which was almost 200 mm. The rainfall has also decreased form Teknaf towards Rangamati region and from Sandwip towards west and east also. In the central region of the country such as Dhaka, Tangail, Mymensingh the 72 hour predicted rainfall has simulated around 400-700 mm.

The 137 days prediction of rainfall of September 2014 (Fig. 4.1.12f) has simulated maximum in the south southeastern and the significant amount of rainfall has simulated in the northeastern region of Bangladesh. The rainfall has found 1300 and 2700 mm at Sylhet and Teknaf regions respectively. Simulated rainfall has decreased from northeastern region towards west and southwestern region. The minimum rainfall has found at the northwestern region i.e. Bogra, Dinajpur, Rajshahi, Rangpur and its value was almost 300-400 mm. In the central region of the country such as Dhaka, Tangail and Faridpur the rainfall has simulated around 700-900 mm. for 137 days prediction the simulated rainfall was much higher than that of observed rainfall.

It has found from 24, 48 and 72 hours lead time prediction of rainfall for September 2014 that the rainfall has minimum in the west, southwest and central regions of the country and the maximum value has simulated in northeastern region. The pattern of model simulated rainfall, TRMM and observed rainfall are almost similar but the value of TRMM derived rainfall was much lower than that of observed rainfall. The 24, 48 and 72 hours lead time predicted rainfall was almost similar all over the country but the higher rainfall area has simulated much higher with the time progression. The rainfall for 137 days prediction has seen much higher value in south southeastern region than those of 24, 48, 72, and observed rainfall.

4.2 Root Mean Square Error (RMSE) of Rainfall

4.2.1 RMSE of Rainfall of Monsoon 2010

The RMSE of rainfall for 137 days prediction of June, July, August and September 2010 at different stations of Bangladesh are presented in Fig. 4.2.1(a-d). The RMSE of rainfall of

June 2010 for 137 days prediction (Fig. 4.2.1a) is found minimum in the west-southwestern region and the lowest value has found at Khulna region. The minimum value 20-30 mm of RMSE has found at Dinajpur, Rajshahi, Ishurdi, Chuadanga, Barisal and Rangamati regions. The RMSE of rainfall is found maximum in the northeastern, south southeastern region and the maximum value has seen at Bogra, Bhola, Sandwip, Kutubdia and Teknaf regions. The RMSE of rainfall has increased from southwestern towards north northeastern and southeastern regions of Bangladesh.

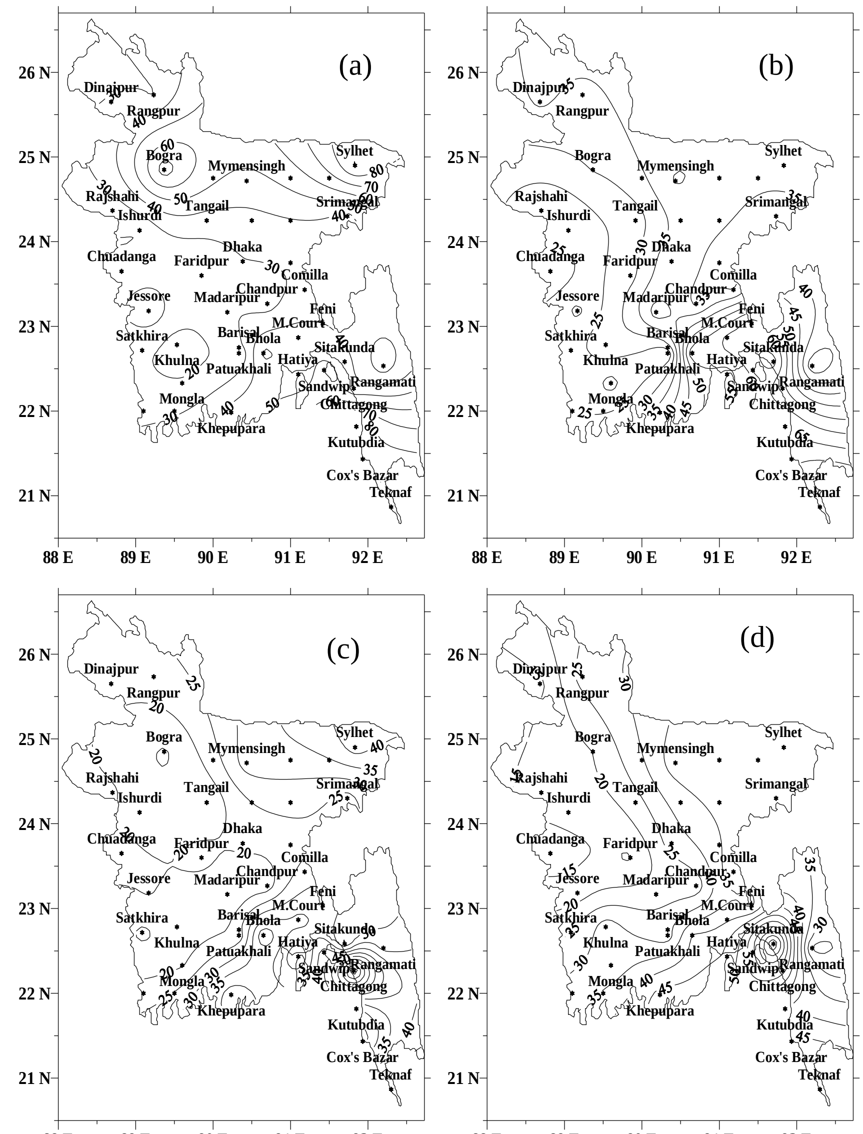

Fig. 4.2.1: Distribution of RMSE of rainfall for 137 days prediction for (a) June, (b) July, (c) August and (d) September 2010 all over Bangladesh

The RMSE of rainfall for 137 days prediction of July 2010 (Fig. 4.2.1b) is found minimum in the west-southwest region and the lowest value has seen in Mongla and Jessore regions was

20 mm. The RMSE of rainfall has increased from west towards northwestern region and from southwest towards east and southeastern regions of Bangladesh. The RMSE of rainfall is found maximum in the south southeastern region i.e. Sitakunda, Kutubdia and Teknaf regions and its maximum value was 85 mm at Teknaf. The minimum value of RMSE has found at Satkhira, Rajshahi, Ishurdi and Chuadanga regions.

The RMSE of rainfall for 137 days prediction of August 2010 (Fig. 4.2.1c) is found minimum in the western, central, northwestern and southwestern regions and lowest value has found at Satkhira, Bogra and Madaripur regions. The RMSE of rainfall has increased from west towards northeast and from southwest towards eastern region of Bangladesh. The RMSE of rainfall is found maximum in the southeastern regions. The maximum value of RMSE has found at Sylhet, Sandwip and Chittagong regions.

The RMSE of rainfall of September 2010 for 137 days prediction (Fig. 4.2.1d) is found minimum in the west-northwestern region and the lowest value has found at Chuadanga region. The minimum value of RMSE has found at Faridpur, Jessore, Rajshahi, Ishurdi, Bogra and Dinajpur regions. The RMSE of rainfall has increased from western towards eastern and south southeastern regions of Bangladesh. The RMSE of rainfall is found maximum in the south southeastern region i.e. Khepupara, Teknaf and Sitakunda and its value was 45, 55 and 80 mm respectively. It has found that the RMSE is found minimum for the month of July, August and September 2010 all over Bangladesh except southeastern region. The RMSE of June 2010 has found higher values than that of other month.

4.2.2 RMSE of Rainfall of Monsoon 2011

The RMSE of rainfall of June 2011 for 137 days prediction (Fig. 4.2.2a) is found minimum in the north-northwestern regions and the lowest value was at Rangpur region. The RMSE of rainfall has increased from north northwestern region towards south southeastern regions of Bangladesh. The RMSE of rainfall is found maximum in the south southeastern region i.e. Mongla, Bhola, M. Court, Teknaf and its value was 60-115 mm respectively. The RMSE is found minimum at Mymensingh, Tangail, Sylhet, Bogra, Rangpur and Dinajpur regions and the value was 15-35 mm.

The RMSE of rainfall for 137 days prediction of July 2011 (Fig. 4.2.2b) is found minimum in the central to northwestern region and the lowest value has seen at Bogra region. The minimum value 25-35 mm of RMSE has found at Mymensingh, Tangail, Dhaka, Faridpur, Rajshahi, Ishurdi, Bogra, Rangpur and Dinajpur regions. The RMSE of rainfall has increased from northwest towards northeastern and west, south southeastern regions of Bangladesh. The RMSE of rainfall is found maximum in the western and southeastern regions.

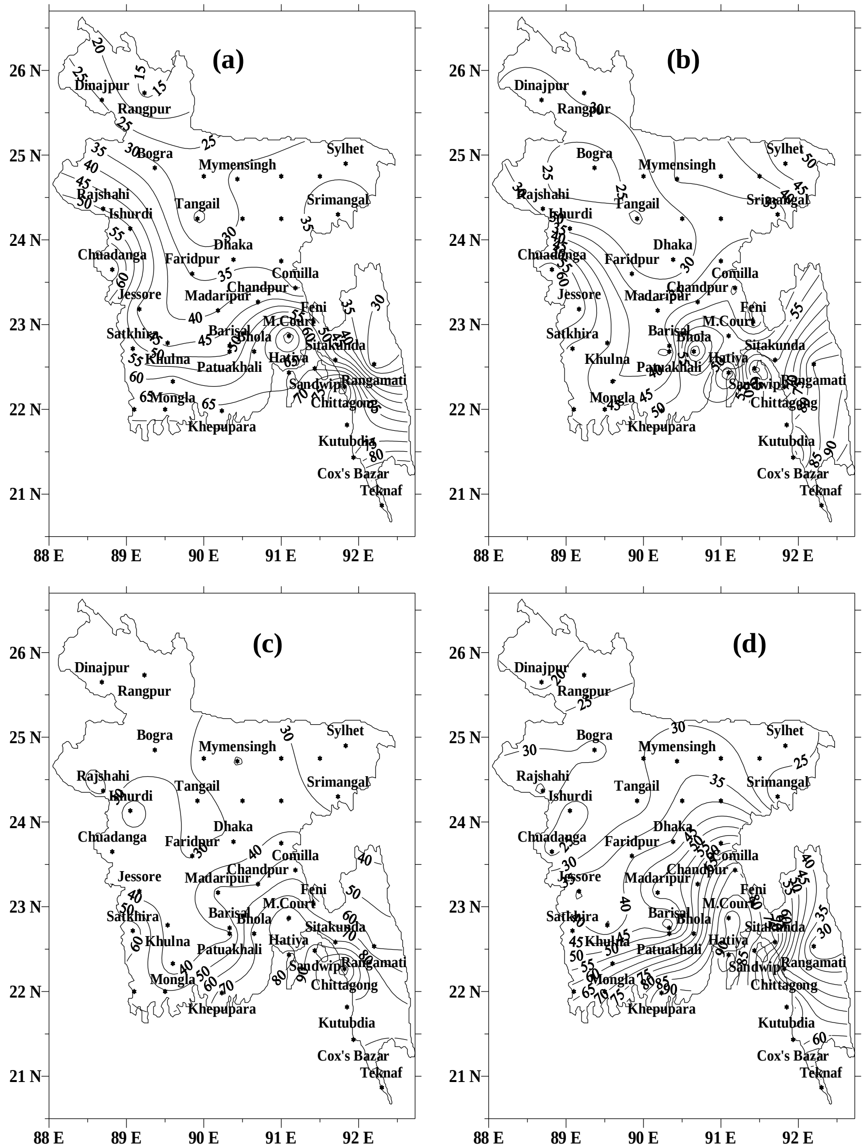

Fig. 4.2.2: Distribution of RMSE of rainfall for 137 days prediction for (a) June, (b) July, (c) August and (d) September 2011 all over Bangladesh

The RMSE of rainfall of August 2011 for 137 days prediction (Fig. 4.2.2c) is found minimum in the western, northwestern and northeastern regions. The minimum value 20-40 mm of RMSE has found at Sylhet, Srimangal, Dhaka, Tangail, Faridpur, Bogra, Rangpur, Dinajpur and Chuadanga regions. The lowest value has found at Rajshahi region. The RMSE of rainfall has increased from central region towards south-southeastern region of Bangladesh.

The RMSE of rainfall is found maximum in the south southeastern region i.e. Bhola, M. Court, Sandwip and Chittagong and its value has 70, 85, 95 and 120 mm respectively.

The RMSE of rainfall for 137 days prediction of September 2011 (Fig. 4.2.2d) is found minimum in the west northwest and northeastern regions and the lowest value at Dinajpur. The RMSE of rainfall has increased from north towards south-southeastern region and maximum has found in the south southeastern region. The maximum value of RMSE has found at Hatiya, Comilla, Sitakunda, Kutubdia and Teknaf regions. The minimum value 20-30 mm of RMSE has found at Sylhet, Srimangal, Tangail, Rajshahi, Ishurdi, Bogra, Rangpur, Dinajpur and Rangamati regions. It has found that the RMSE is found minimum for the month of June, July, August and September 2010 in the central to northern region.

4.2.3 RMSE of Rainfall of Monsoon 2012

The RMSE of rainfall for 137 days prediction of June 2012 (Fig. 4.2.3a) is found minimum in the north-northwestern and southwestern regions and the lowest value has simulated in Madaripur region. The RMSE of rainfall is found maximum in the western, northeastern and southeastern regions. The minimum value 20-40 mm of RMSE has found at Bogra, Mymensingh, Jessore, Khulna, Mongla, Faridpur, Rangpur and Dinajpur regions.

The RMSE of rainfall of July 2012 for 137 days prediction (Fig. 4.2.3b) is found minimum in the central to western and northeastern regions and lowest value has found in Srimangal region. The RMSE of rainfall has increased from western towards northwestern region and south-southeastern regions of Bangladesh. The RMSE of rainfall is found maximum in the southeastern region and the highest value has simulated at Bhola, Sitakunda, Teknaf were 65, 70 and 120 mm respectively. The minimum 20-30 mm of RMSE has found at Tangail, Madaripur, Khulna, Rajshahi and Ishurdi regions.

The RMSE of rainfall for 137 days prediction of August 2012 (Fig. 4.2.3c) is found minimum in the north-northwestern and northeastern regions and the lowest value has found at Rangpur region. The value of RMSE of rainfall has increased from northwest towards south southwestern and southeastern regions of Bangladesh. The RMSE of rainfall is found maximum at Khulna, Hatiya, Sitakunda, Sandwip and Teknaf regions. The minimum value 20-25 mm of RMSE has found at Mymensingh, Tangail, Rajshahi, Bogra, Rangpur and Dinajpur regions.

The RMSE of rainfall of September 2012 for 137 days prediction (Fig. 4.2.3d) is found minimum in the southwestern and northwestern regions. The RMSE of rainfall has increased from northwestern towards northeastern region and from southwest towards southeastern region of Bangladesh. The RMSE of rainfall is found maximum in the northeastern and southeastern region. The maximum value has simulated at Sylhet, Sitakunda, Sandwip, Teknaf were 55, 60, 75 and 85 mm respectively. The minimum value 15-30 mm of RMSE has found at Rangamati, Srimangal, Tangail, Mymensingh, Rajshahi, Rangpur, Bogra and Ishurdi regions.

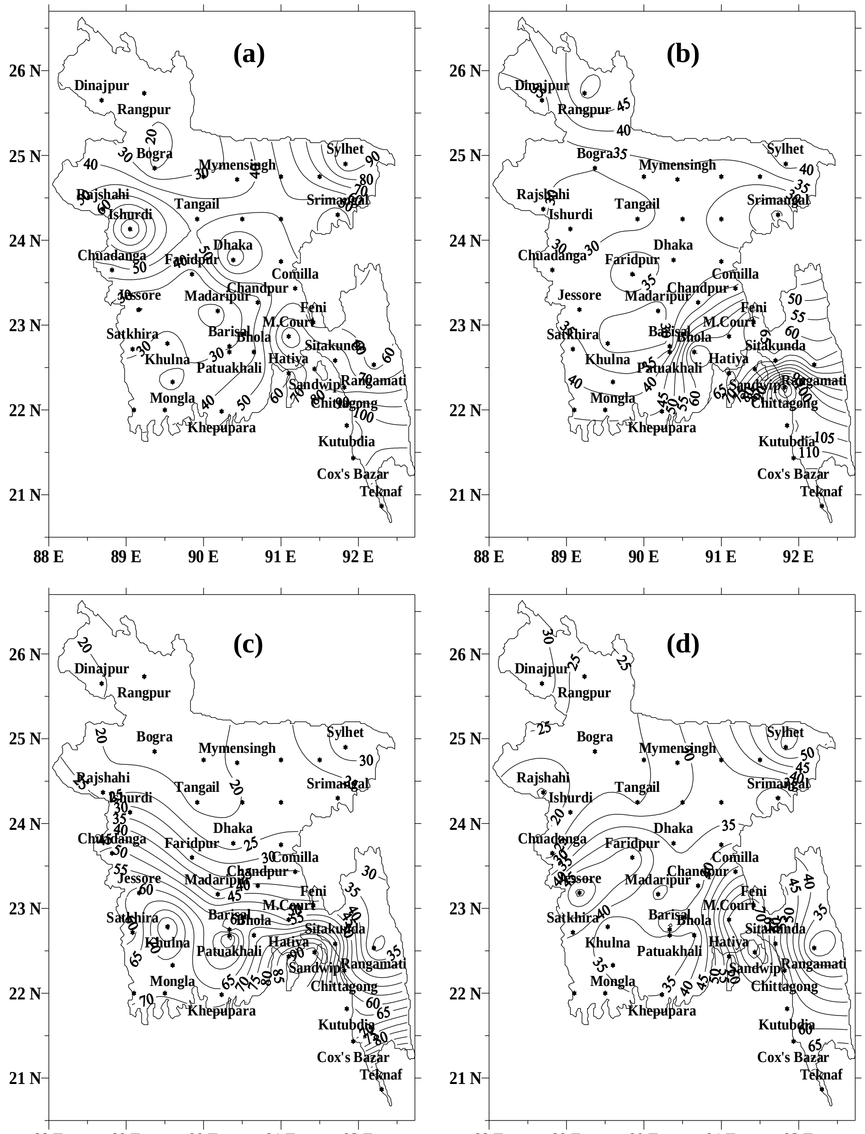

Fig. 4.2.3: Distribution of RMSE of rainfall for 137 days prediction for (a) June, (b) July, (c) August and (d) September 2012 all over Bangladesh

4.2.4 RMSE of Rainfall of Monsoon 2013

The RMSE of rainfall of June 2013 for 137 days prediction (Fig. 4.2.4a) is found minimum in northwestern region of the country. The RMSE of rainfall has increased from northwest towards northeast and southeastern region. The RMSE of rainfall is found maximum in the southwestern, northeastern and southeastern region. The maximum value of RMSE has found at Sylhet, Satkhira and Teknaf region and its value has 60, 65 and 85 mm respectively. The minimum value 25-35 mm of RMSE has found at Mymensingh, Faridpur, Mongla, Bogra, Rangpur and Dinajpur regions.

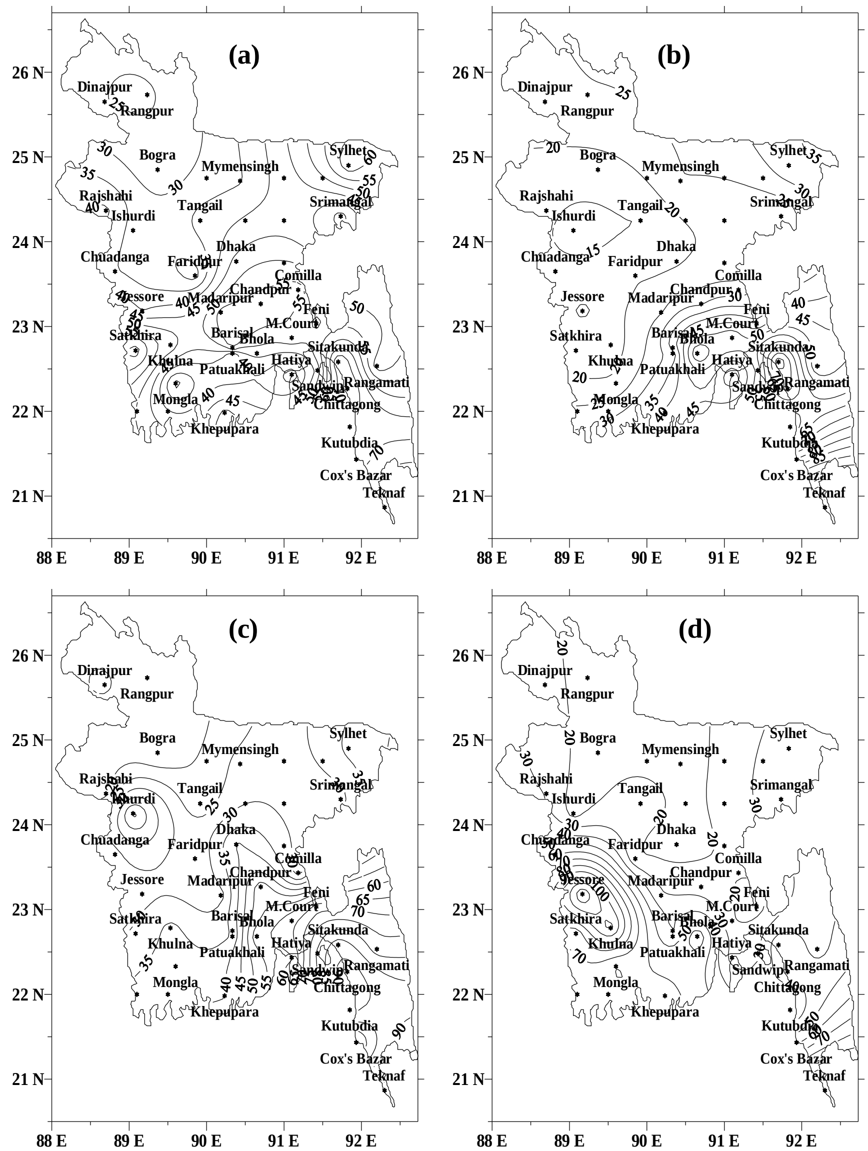

Fig. 4.2.4: Distribution of RMSE of rainfall for 137 days prediction for (a) June, (b) July, (c) August and (d) September 2013 all over Bangladesh

The RMSE of rainfall for 137 days prediction of July 2013 (Fig. 4.2.4b) is found minimum in the western, northwestern and southwestern region. The minimum value 15-25 mm of RMSE has found at Mymensingh, Tangail, Ishurdi, Rajshahi, Jessore, Khulna, Rangpur and Dinajpur regions. The value of RMSE of rainfall using 137 days prediction has increased from west towards northeastern region and south-southeastern region of Bangladesh. The RMSE is found maximum in the northeastern and south southeastern region. The maximum value has found at Bhola, Sitakunda, Teknaf was 60, 80 and 120 mm respectively.

The RMSE of rainfall of August 2013 for 137 days prediction (Fig. 4.2.4c) is found minimum in the north northwestern region. The minimum value 15-25 mm of RMSE has found at Mymensingh, Tangail, Rajshahi, Rangpur, Bogra and Dinajpur regions. The RMSE of rainfall using 137 days prediction has increased from northwestern towards northeastern region and south-southeastern region and is found maximum in the Kutubdia and Cox's Bazar region.

The RMSE of rainfall for 137 days prediction of September 2013 (Fig. 4.2.4d) is found minimum in the north and northwestern region. The RMSE of rainfall is found maximum in the southwest and southeastern regions and the highest value has simulated in Jessore region. The RMSE of rainfall has increased from central region towards western region and southeastern region of Bangladesh. The minimum value 15-25 mm of RMSE has found at Mymensingh, Dhaka, Comilla Ishurdi, Bogra, Rangpur, Feni and M. Court regions.

4.2.5 RMSE of Rainfall for Monsoon 2014

4.2.5.1 RMSE of Rainfall of June 2014

The RMSE of rainfall for 24, 48, 72 hours and 137 days prediction for June 2014 at different stations of Bangladesh are presented in Fig. 4.2.5(a-d). The RMSE of rainfall for 24 hour prediction (Fig. 4.2.5a) of June 2014 is found minimum in the west, northwest and southwestern region of Bangladesh and the minimum value at Rajshahi was 10 mm. The RMSE of rainfall have increased from central region towards south-southeast and from western towards the central region. The RMSE of rainfall is found maximum in the southeastern region i.e. Teknaf and its value was 125 mm. The RMSE lies between 30-40 mm all through the country except southeastern region.

The RMSE of rainfall for the month of June 2014 for 48 hour prediction (Fig. 4.2.5b) is found minimum in the western, northwestern and northern region of the country. The RMSE of rainfall using 48 hour predictions have increased from north-northwestern region towards south-southeastern region of the country. The RMSE of rainfall is found maximum in the south southeastern region i.e. Teknaf, Feni and its value were 140 and 105 mm respectively. The minimum value of RMSE has found at Mymensingh, Bogra, Rangpur, Dinajpur and Rajshahi regions were 20-35 mm.

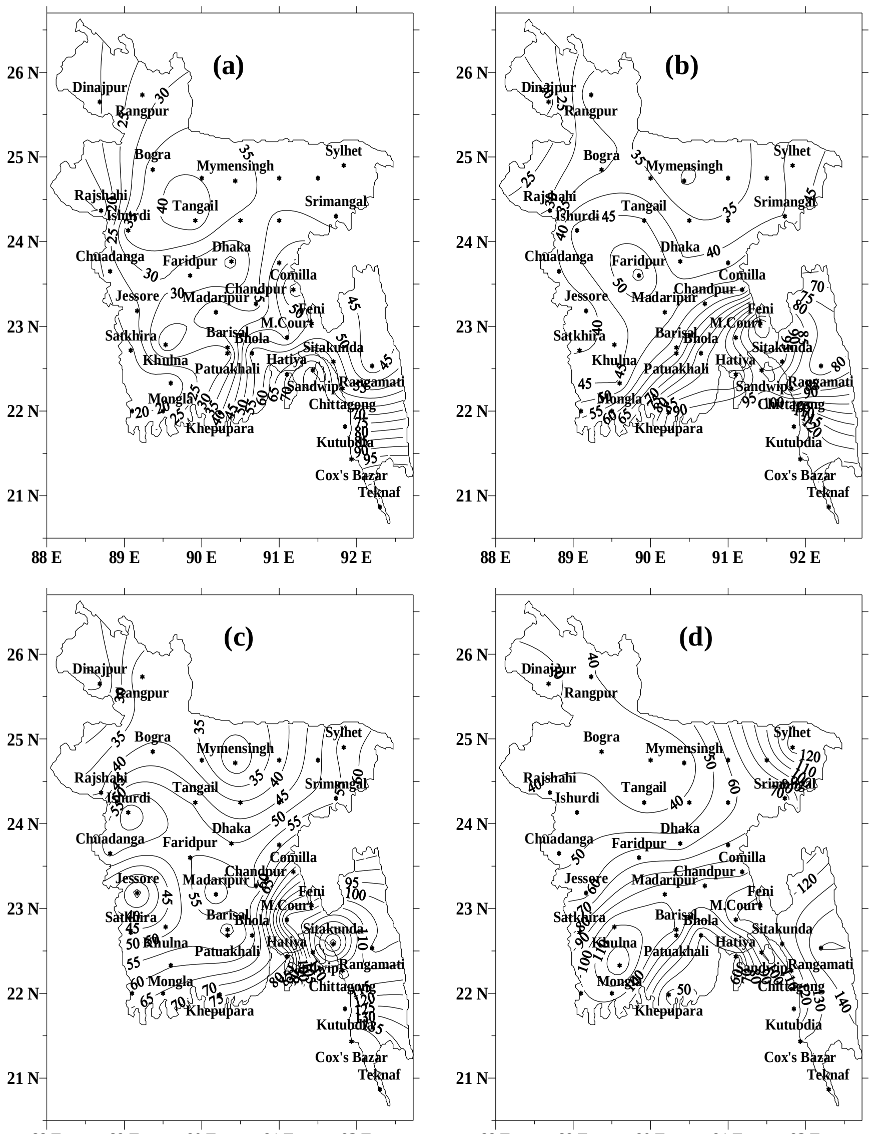

Fig. 4.2.5: Distribution of RMSE of rainfall for (a) 24, (b) 4 (c) 72 hours and (d) 137 days prediction of June 2014 all over Bangladesh

The RMSE of rainfall for 72 hour prediction of June 2014 (Fig. 4.2.5c) is found minimum in the north-northwestern region of the country. The minimum value of RMSE of Rainfall has also simulated at Mymensingh and Jessore regions. The minimum value 20-35 mm of RMSE has found at Mymensingh, Jessore, Rangpur and Dinajpur regions. The RMSE of rainfall using 72 hour predictions have increased from north-northwestern region towards south-southeastern region of Bangladesh. The RMSE of rainfall is found maximum in the south southeastern region i.e. Teknaf, Sitakunda and its value were 140 and 135 mm respectively.

The RMSE of rainfall for 137 days prediction of June 2014 (Fig. 4.2.5d) is found minimum in the west-northwestern region of the country. The minimum value 30-40 mm of RMSE has found at Mymensingh, Tangail, Bogra, Rajshahi, Rangpur and Dinajpur regions. The RMSE of rainfall for 137 days prediction have increased from west towards east and from northwestern region towards the central region. The RMSE of rainfall is found maximum in the southeastern and southwestern regions i.e. Rangamati, Mongla and Sylhet and its value were 150, 120 and 120 mm respectively.

From the analysis of 24, 48, 72 hours and 137 days prediction of RMSE of rainfall for June 2014, it has found that the RMSE was minimum in the west, north and northwestern regions of the country and maximum in the south and southeastern regions. For 137 days prediction the maximum value of RMSE has also found in the northeastern region. It has observed that the rainfall has minimum in a place the RMSE has also minimum in that place. The RMSE of rainfall has almost similar for 24, 48 and 72 hours prediction all over the country except south-southeastern region. The RMSE of rainfall for 137 days prediction has seen much higher value than those of 24, 48 and 72 hours prediction.

4.2.5.2 RMSE of Rainfall of July 2014

The RMSE of rainfall of July 2014 for 24, 48, 72 hours and 137 days prediction at different stations of Bangladesh are presented in Fig. 4.2.6(a-d) respectively. The RMSE of rainfall for 24 hour prediction (Fig. 4.2.6a) is found minimum in the western, north northwestern region and its lowest value was found 10 mm at Rangpur. The RMSE of rainfall using 24 hour prediction has increased from northwestern region towards south southeastern region of Bangladesh. The RMSE of rainfall is found maximum in the south southeastern region and its highest value was 100 mm at M. Court.

The RMSE of rainfall of July 2014 for 48 hours prediction (Fig. 4.2.6b) is found minimum in the western and central region and the lowest value simulated in north-western region i.e. Rangpur was 25 mm. The minimum value of RMSE of rainfall has also simulated at

Rangamati and Srimangal region. The RMSE of rainfall has increased from northwest towards south-southeastern region of the country. The RMSE of rainfall is found maximum in the south southeastern region i.e. Sandwip, Teknaf and its value were 80 and 85 mm respectively.

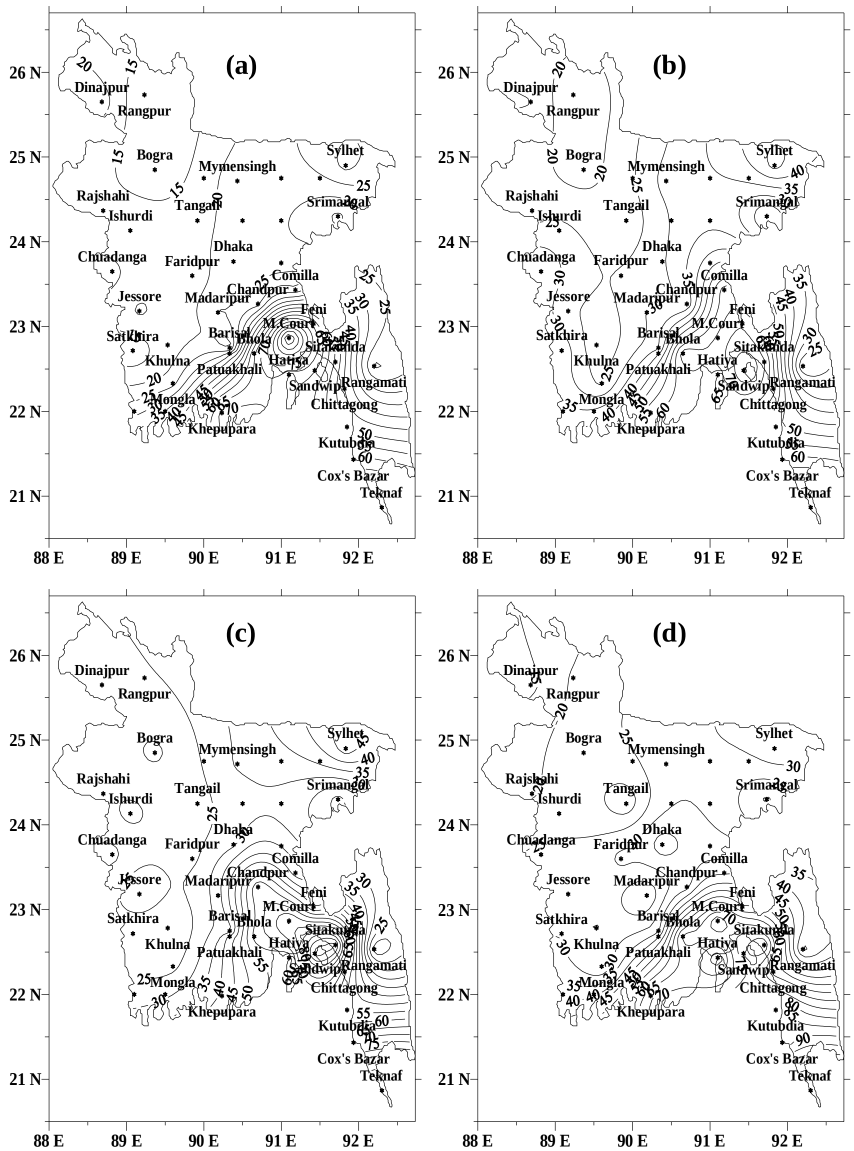

Fig. 4.2.6: Distribution of RMSE of rainfall for (a) 24, (b) 48, (c) 72 hours and (d) 137 days prediction of July 2014 all over Bangladesh

The RMSE of rainfall of July 2014 for 72 hours prediction (Fig. 4.2.6c) is found minimum in the western, northwestern and southwestern regions. The RMSE of rainfall has also simulated minimum at Rangamati and Srimangal regions. The RMSE of rainfall has increased from western towards northeastern and south southeastern regions of Bangladesh. The RMSE of rainfall is found maximum in the south southeastern regions. At Sandwip and Sitakunda regions the RMSE has found 95 mm.

The RMSE of rainfall for 137 days prediction of July 2014 (Fig. 4.2.6d) has observed minimum in the western, northeastern and northwestern regions and lowest value has simulated at Dinajpur region was 15 mm. The minimum value of RMSE has also found in Madaripur and Srimangal regions. The RMSE of rainfall has increased from southwestern region towards eastern region of the country. The RMSE of rainfall is found maximum in the south southeastern regions i.e. Teknaf and Sandwip and its value were 80 and 125 mm respectively.

From the analysis of 24, 48, 72 hours and 137 days prediction of RMSE of rainfall for July 2014 is found minimum in the west and northwestern regions and maximum in the south and southeastern regions of the country. The RMSE is found minimum in a region where the observed rainfall has also minimum. The distribution pattern RMSE of rainfall has almost similar for 24, 48, 72 hours and 137 days prediction all over the country except south-southeastern region. But the RMSE is found minimum for 24 hour prediction all over the country except south-southeastern region.

4.2.5.3 RMSE of Rainfall of August 2014

The RMSE of rainfall of August 2014 for 24, 48, 72 hours and 137 days prediction at different stations of Bangladesh are presented in Fig. 4.2.7(a-d). The RMSE of rainfall for 24 hour prediction (Fig. 4.2.7a) is found minimum in the western, southwestern Srimangal regions. The lowest value has found at Bogra and Ishurdi regions and its value has 15 mm. The RMSE of rainfall is found maximum in the northeastern region and south southeastern region i.e. Sylhet, Sandwip and Teknaf and its value has 55, 60 and 90 mm respectively. The RMSE has increased from west towards northeast and from southwest region towards east and southeastern region of the country.

The station wise value of RMSE of rainfall for 48 hour prediction of August 2014 (Fig. 4.2.7b) is found minimum in the western and southwestern regions. The lowest value has found at Jessore and Satkhira regions and its value was 20 mm. The RMSE of rainfall is found maximum in the south southeastern region and at Sandwip and Teknaf its value were 90 and 135 mm respectively. The RMSE of rainfall has increased from west towards northeastern, eastern and southeastern regions.

The RMSE of rainfall for 72 hours prediction of August 2014 (Fig. 4.2.7c) is found minimum in the western and northwestern region. The lowest value of RMSE has found at Dinajpur and its value was 20 mm. The RMSE of rainfall has increased from western towards eastern and south southeastern regions of the country. The RMSE of rainfall is found maximum in the south southeastern regions. The maximum value of RMSE has found at Sandwip and Teknaf regions were 95 and 100 mm respectively.

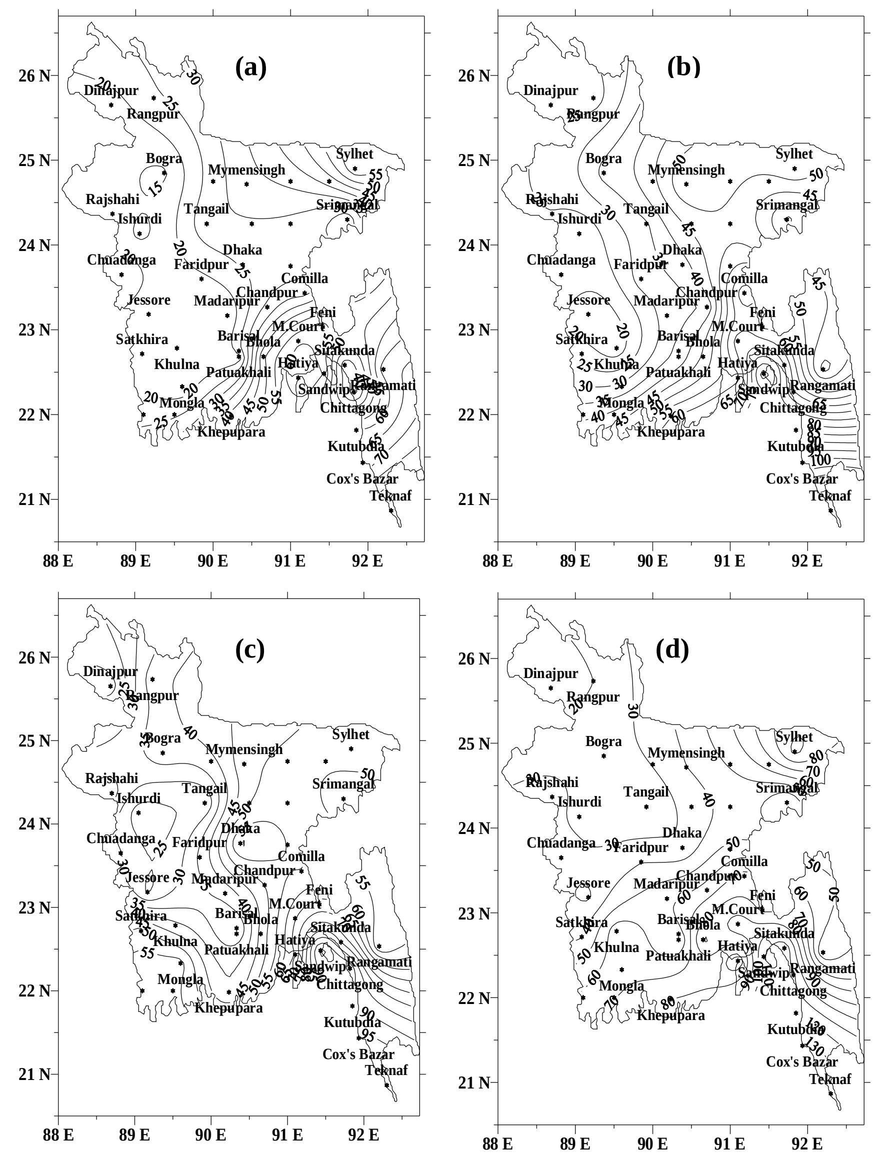

Fig. 4.2.7: Distribution of RMSE of rainfall for (a) 24, (b) 48, (c) 72 hours and (d) 137 days prediction of August 2014 all over Bangladesh

The RMSE of rainfall of August 2014 for 137 days prediction (Fig. 4.2.7d) is found minimum in the west-north-western region and the lowest value has simulated at Dinajpur and Rangpur regions and its value around 20 mm. The RMSE of rainfall has increased from northwest towards northeast and south southeastern regions of the country. The RMSE of rainfall is found maximum in the northeastern and south southeastern region. The RMSE has found 90, 105 and 135 mm at Sylhet, Sandwip and Teknaf regions respectively.

The RMSE is found minimum in the west, northwestern and southwestern regions of the country and maximum in the northeast and south-southeastern regions for 24, 48, 72 hours and 137 days prediction of RMSE of rainfall for August 2014. The RMSE of rainfall has almost similar for 48, 72 hours and 137 days prediction all over the country except south-southeastern region. The RMSE of rainfall for 24 hours prediction has seen minimum all over the country in the month of August.

4.2.5.4 RMSE of Rainfall of September 2014

The RMSE of rainfall of September 2014 for 24, 48, 72 hours and 137 days prediction at different stations of Bangladesh have presented in Fig. 4.2.8(a-d). The RMSE of rainfall for 24 hour prediction (Fig. 4.2.8a) is found minimum in the west, southwestern region and the lowest value has simulated at Ishurdi. The minimum value 10-20 mm of RMSE has found at Rajshahi, Jessore, Satkhira, Chuadanga, Faridpur, Dhaka and Rangamati regions. The value of RMSE of rainfall has increased from west towards northwest, east-northeastern and southern regions of Bangladesh. The RMSE of rainfall is found maximum in the south, northwestern and northeastern regions. The maximum value has found at Dinajpur, Rangpur, Mymensingh, Sylhet and M. Court regions and its value was 35-55 mm. The RMSE of rainfall for 48 hour prediction of September 2014 (Fig. 4.2.8b) is found minimum in the central to southwestern regions and the lowest value was in Faridpur region. The RMSE has increased all around from central regions of the country. The maximum value has found at Dinajpur, Rangpur, Sylhet and M. Court regions and its value was 40-85 mm. The minimum value 15-20 mm of RMSE has found at Jessore, Khulna, Madaripur and Dhaka regions.

The RMSE of rainfall for 72 hours prediction of September 2014 (Fig. 4.2.8c) is found minimum in the central to southwestern regions. The RMSE of rainfall has increased from central towards north, northwestern, northeastern and southern regions and are found maximum in these regions. The maximum value has found at Dinajpur, Rangpur, Mymensingh, Sylhet and M. Court regions and its value were 50-75 mm respectively. The minimum value 15-25 mm of RMSE has found at Mongla, Satkhira, Khulna, Faridpur, Madaripur and Rangamati regions. The RMSE of rainfall of September 2014 for 137 days prediction (Fig. 4.2.8d) is found minimum in western region and maximum in the northeastern, central and south-southeastern regions of the country. The maximum value has found at Ishurdi, Faridpur, Madaripur, Sylhet, Sandwip and Teknaf regions and its value was 60-100 mm. The minimum value 25-35 mm of RMSE has found at Dinajpur, Rajshahi, Jessore, Khulna and Rangamati regions.

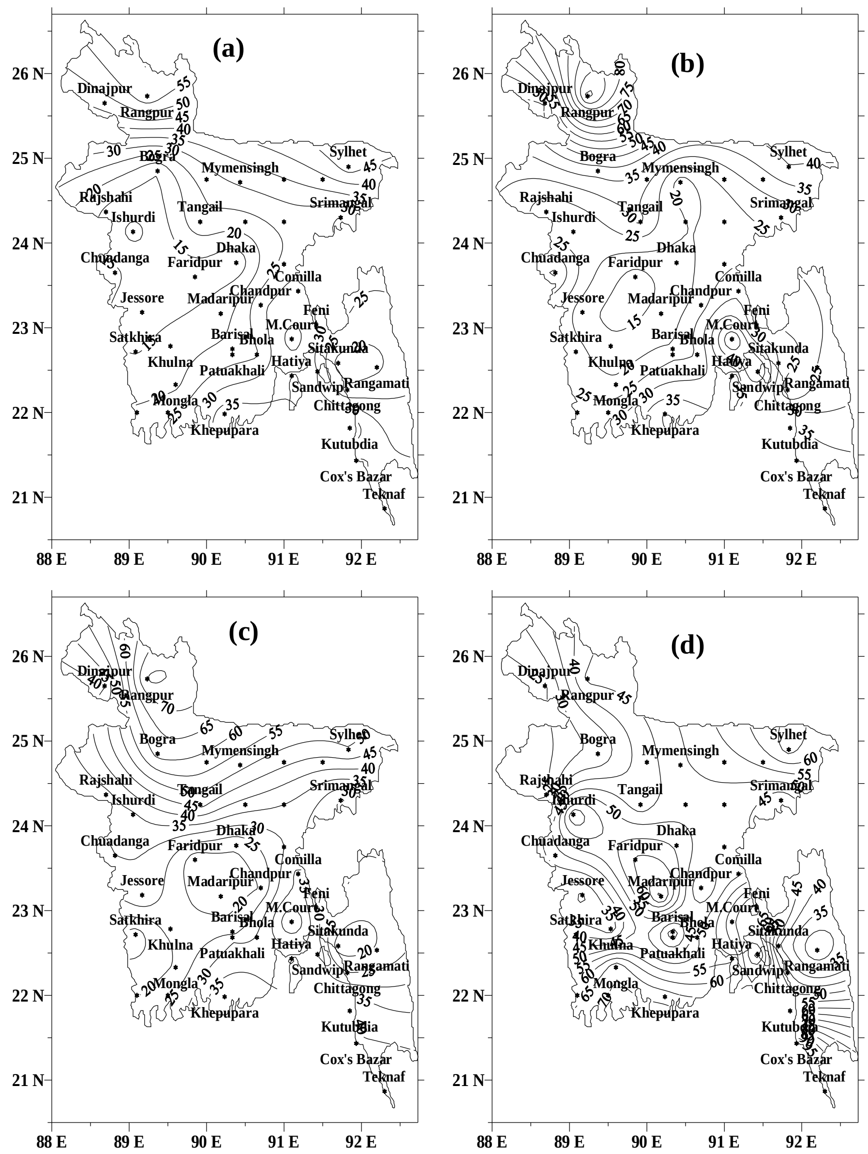

Fig. 4.2.8: Distribution of RMSE of rainfall for (a) 24, (b) 48, (c) 72 hours and (d) 137 days prediction of September 2014 all over Bangladesh

The RMSE is found minimum in September 2014 at the west, central and southwestern regions of the country and maximum in the north and northwestern regions for 24, 48 and 72 hours prediction. For 137 days prediction the maximum value of RMSE has also found in the northeastern and south southeastern region. The RMSE of rainfall has almost similar for 24, 48 and 72 hours prediction all over the country except south-southeastern region. The RMSE of rainfall for 137 days prediction has seen much higher value than those of 24, 48 and 72 hours prediction.

4.3 Mean Absolute Error (MAE) of Rainfall in Monsoon season

4.3.1 MAE of Rainfall of Monsoon 2010

The MAE of rainfall of June 2010 for 137 days prediction (Fig. 4.3.1a) is found minimum in the west, southwest and central region and the lowest value has found at Khulna region. The MAE of rainfall has increased from southwest towards northeast and southeastern regions of Bangladesh. The MAE of rainfall is found maximum in the south-southeastern and north-northeastern regions.

At Sandwip, Sylhet and Teknaf regions the values of MAE of rainfall have almost 40, 65 and 70 mm respectively. The minimum value 15-20 mm of MAE has found at Jessore, Satkhira, Khulna, Mongla, Madaripur, Faridpur, Rajshahi, Rangpur, Dinajpur and Rangamati regions. The MAE for 137 days prediction of rainfall of July 2010 (Fig. 4.3.1b) is found minimum in the central to west and southwest region and the lowest value has found at Jessore region. The MAE of rainfall has increased from southwest towards northeast and southeastern regions. The MAE of rainfall is found maximum in the southeastern region.

The MAE for 137 days predicted rainfall of August 2010 (Fig. 4.3.1c) is found minimum in the central to west, southwest and northwest regions and lowest value has found at Madaripur region. The minimum value of MAE has also found at Tangail, Faridpur, Jessore, Khulna, Chuadanga, Bogra and Ishurdi regions. The MAE of rainfall has increased from west towards northeast and south southeastern region of Bangladesh.

The MAE of rainfall for 137 days prediction of September 2010 (Fig. 4.3.1d) is found minimum in the western region and the lowest value has seen at Rajshahi region. The MAE of rainfall has increased from west towards northeast and south southeastern region of Bangladesh. The MAE of rainfall is found maximum in the south-southeastern regions. At Sandwip, Sitakunda and Teknaf regions the maximum value of MAE has obtained 38, 40 and 40 mm respectively.

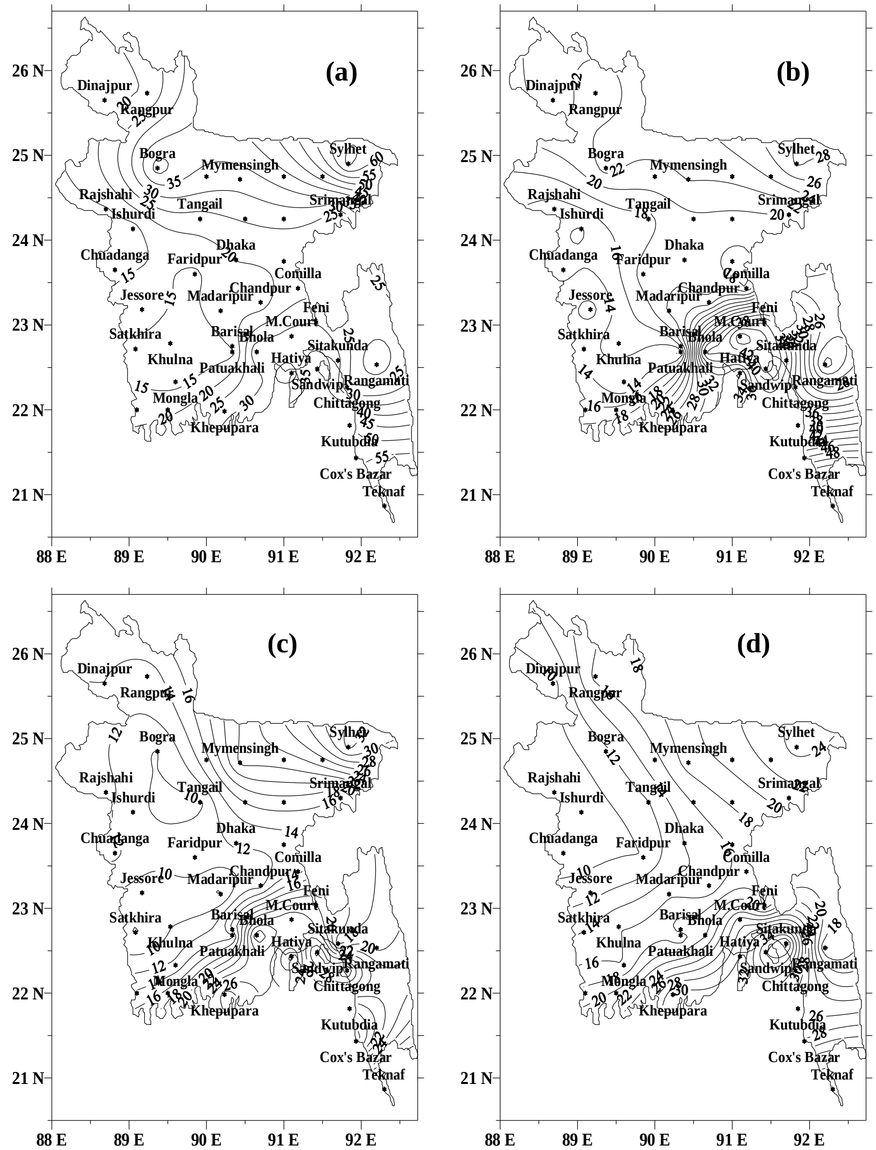

Fig. 4.3.1: Distribution of MAE of rainfall for 137 days prediction of (a) June, (b) July, (c) August and (d) September 2010 all over Bangladesh

4.3.2 MAE of Rainfall of Monsoon 2011

The MAE of rainfall of June 2011 for 137 days prediction (Fig. 4.3.2a) is found minimum in the northwestern region and the lowest value has found in Rangpur. The MAE of rainfall has increased from northwest towards south-southeastern region and found maximum in the southeastern region. The minimum value 10-20 mm of MAE has found at Tangail, Rajshahi, Bogra, Rangpur, Dinajpur, Sylhet and Srimangal regions.

The MAE of rainfall for 137 days prediction of July 2011 (Fig. 4.3.2b) is found minimum in the west, north northwest and central region and the lowest value has found at Dhaka. The

MAE of rainfall has increased from northwest towards northeast and south-southeastern regions and maximum has seen at Teknaf about 75 mm.

The MAE of rainfall of August 2011 for 137 days prediction (Fig. 4.3.2c) is found minimum in central to west, northwest and northeast regions and lowest value has seen at Rajshahi. The MAE of rainfall has increased from northwest towards south-southeastern region. The minimum value 15-20 mm of MAE has found at Faridpur, Khulna, Bogra, Ishurdi, Rangpur, Dinajpur, Sylhet and Srimangal regions.

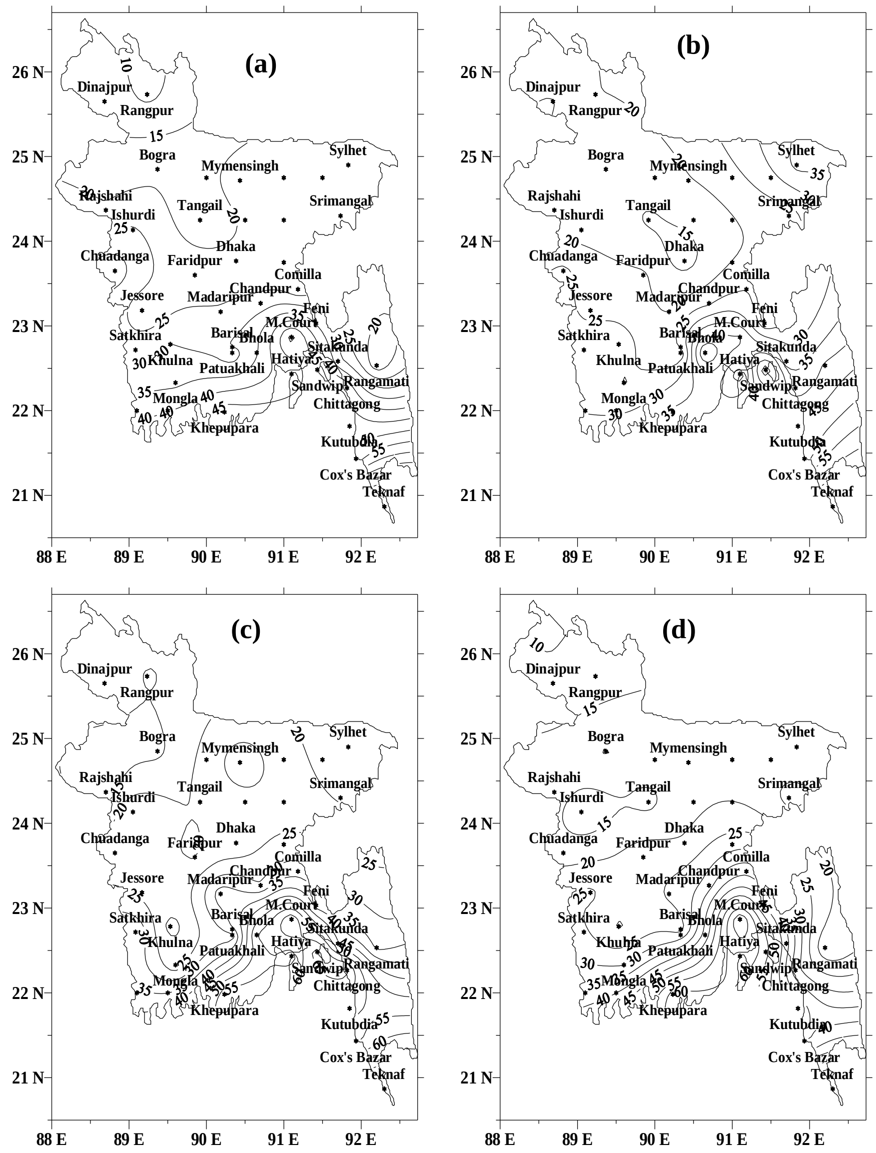

Fig. 4.3.2: Distribution of MAE of rainfall for 137 days prediction of (a) June, (b) July, (c) August and (d) September 2011 all over Bangladesh

The MAE for 137 days predicted rainfall of September 2011 (Fig. 4.3.2d) is found minimum in the west, north northwest and northeastern regions and the lowest value has found at Dinajpur region. The minimum value 10-15 mm of MAE has found at Dinajpur, Rangpur, Tangail and Ishurdi regions. The MAE of rainfall has increased from northwest towards south-southeastern region and found maximum in the southeastern region.

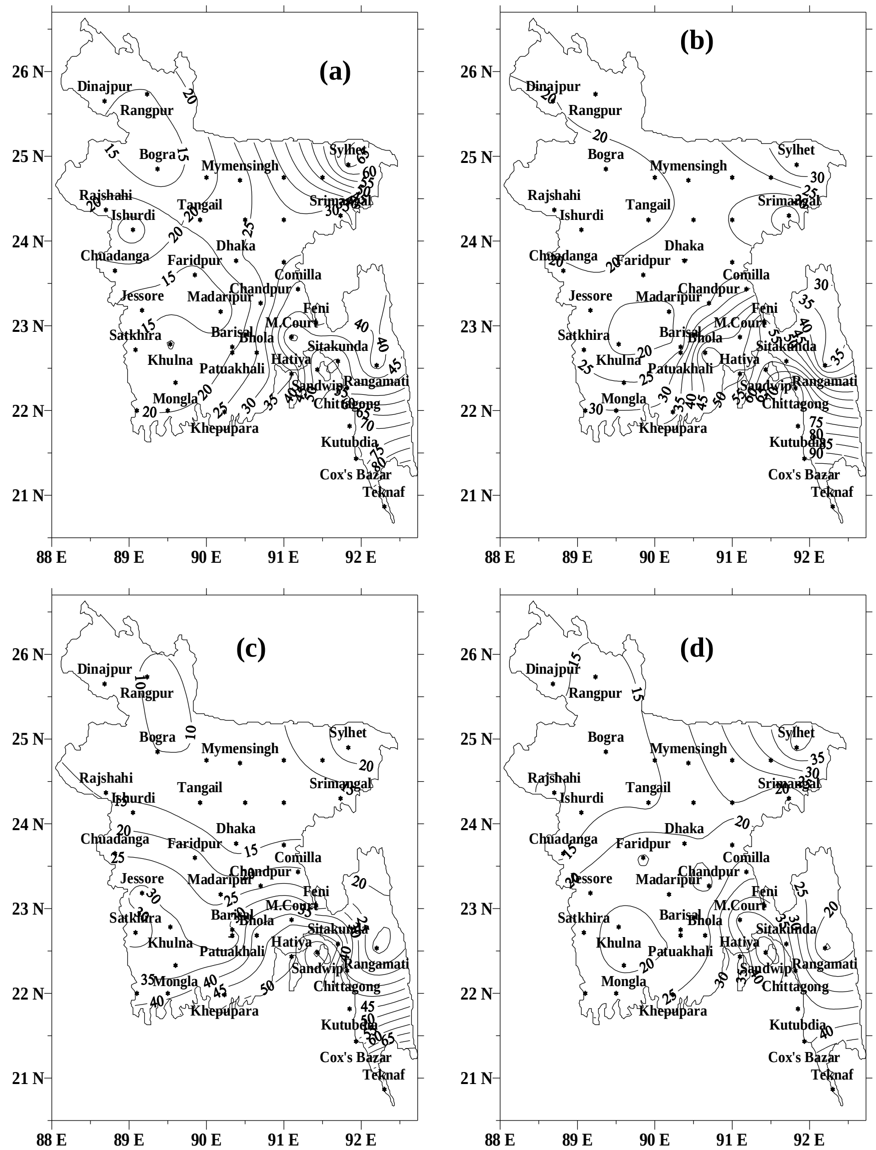

Fig. 4.3.3: Distribution of MAE of rainfall for 137 days prediction of (a) June, (b) July, (c) August and (d) September 2012 all over Bangladesh

4.3.3 MAE of Rainfall of Monsoon 2012

The MAE of rainfall of June 2012 for 137 days prediction (Fig. 4.3.3a) is found minimum in the west, northwest and southwest and the lowest value has found at Ishurdi region. The

MAE of rainfall has increased from west northwest towards northeast and southeastern region. In Sitakunda, Sylhet and Teknaf regions the values of MAE of rainfall have almost 55, 65 and 105 mm respectively. The minimum value 15-20 mm of MAE has found at Madaripur, Faridpur, Mongla, Khulna, Jessore, Rajshahi, Bogra, Rangpur and Dinajpur regions.

The MAE of rainfall for 137 days prediction of July 2012 (Fig. 4.3.3b) is found minimum in the west, southwest, north northwest and central regions and the lowest value has found at Srimangal region. The MAE of rainfall has increased from west towards south southeastern region and found maximum in the southeastern region. The minimum value of MAE has found almost 15-25 mm in the central to western regions.

The MAE of rainfall of August 2012 for 137 days prediction (Fig. 4.3.3c) is found minimum in the northwest region and lowest value has found at Rangpur region. The value of MAE of rainfall has increased from north towards south-southeastern region and found maximum in the southeastern region. The minimum value 10-15mm of MAE has found at Mymensingh, Dhaka, Rajshahi, Ishurdi, Rangpur, Dinajpur and Srimangal regions. The MAE for 137 days predicted rainfall of September 2012 (Fig. 4.3.3d) is found minimum in the central to west-northwest and southwest regions and the lowest value has found at Rangpur region. The MAE of rainfall has increased from northwest towards northeast and from southwest towards east southeast region of Bangladesh.

4.3.4 MAE of Rainfall of Monsoon 2013

The MAE of rainfall of June 2013 for 137 days prediction (Fig. 4.3.4a) is found minimum in the west, northwest and central region and the lowest value has found at Ishurdi region. The MAE of rainfall has increased from northwest towards northeast and southeastern region. The MAE of rainfall is found maximum in the northeast and southeastern region. At Sylhet, Sitakunda and Teknaf regions the value of MAE of rainfall has almost 40-60 mm. The MAE is found minimum at Tangail, Madaripur, Faridpur, Mongla, Rajshahi, Bogra, Rangpur and Dinajpur regions was 15-20 mm.

The MAE of rainfall for 137 days prediction of July 2013 (Fig. 4.3.4b) is found minimum in the central to west, southwest and northwest region and the lowest value has found at Ishurdi region. The MAE of rainfall has increased from central region towards northeast and southeastern region of Bangladesh. The MAE is found minimum at Mymensingh, Tangail, Dhaka, Madaripur, Khulna, Satkhira, Jessore and Rajshahi regions was 10-20 mm.

The MAE of rainfall of August 2013 for 137 days prediction (Fig. 4.3.4c) is found minimum in the central to west, northwestern region and lowest value has found at Bogra. The MAE of rainfall has increased from northwest towards northeast and southeastern region and is found maximum in southeastern region. The minimum value 15-20 mm of MAE has found at Dhaka, Faridpur, Madaripur, Chuadanga, Rajshahi, Ishurdi, Jessore, Rangpur, Dinajpur and Srimangal regions.

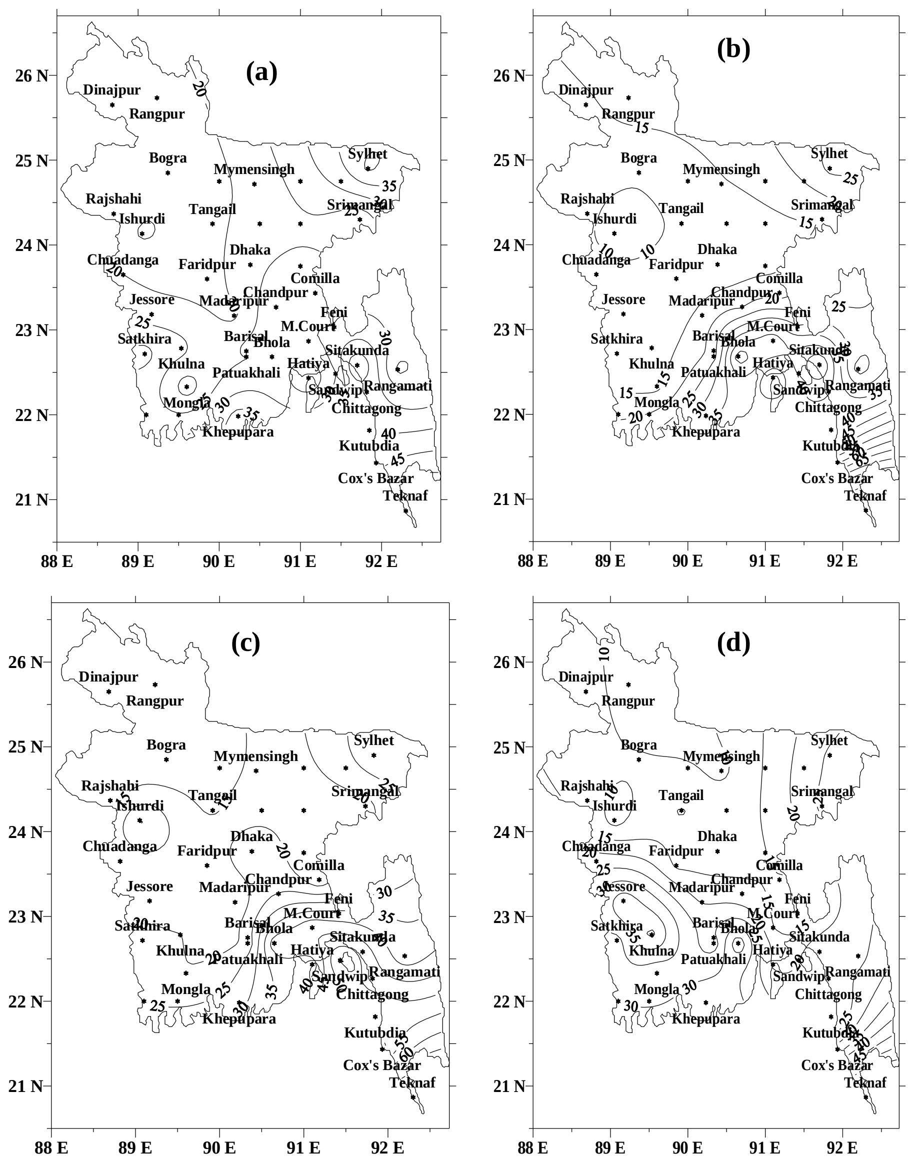

Fig. 4.3.4: Distribution of MAE of rainfall for 137 days prediction of (a) June, (b) July, (c) August and (d) September 2013 all over Bangladesh

The MAE of rainfall for 137 days prediction of September 2013 (Fig. 4.3.4d) is found minimum in the central to north northwest regions and the lowest value has found at Rangpur. The MAE of rainfall using 137 days prediction has increased from northwest towards northeast and southwestern region of Bangladesh. The MAE of rainfall is found maximum in the southwest and southeastern region.

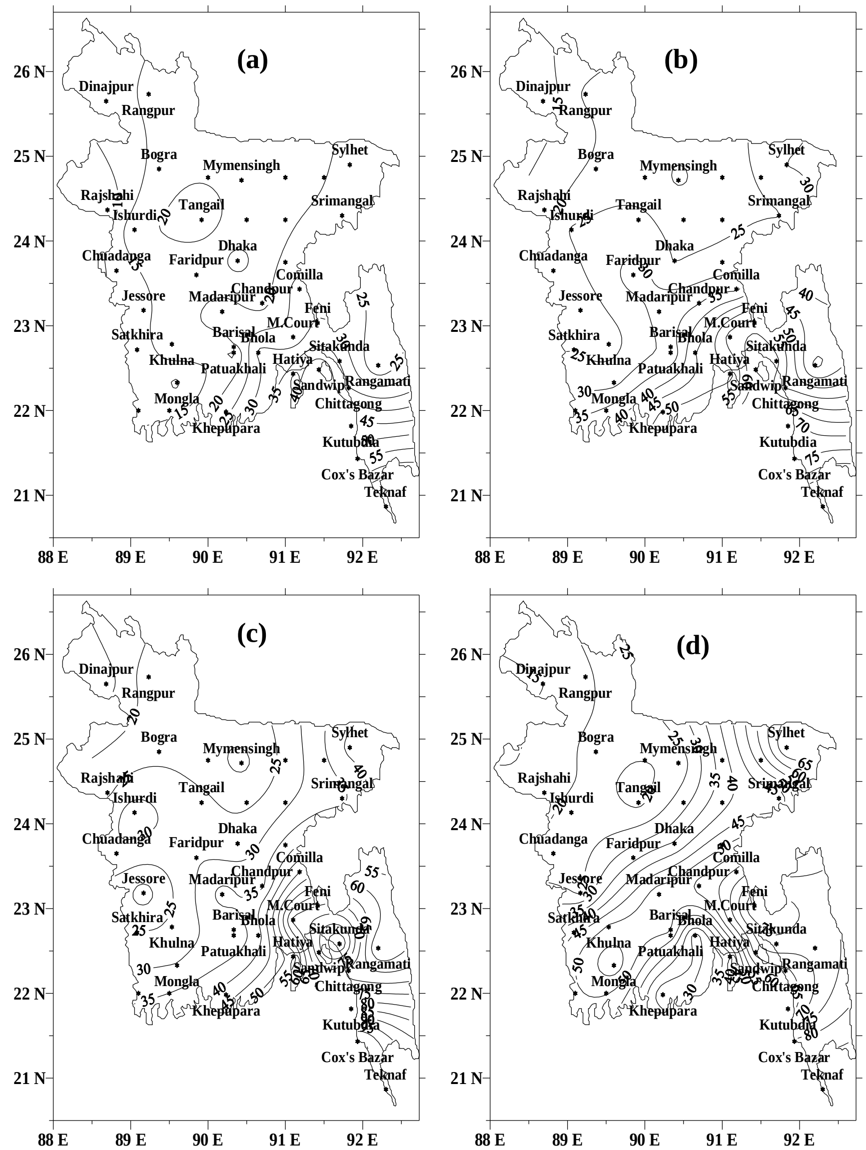

Fig. 4.3.5: Distribution of MAE of rainfall for (a) 24, (b) 48, (c) 72 hours and (d) 137 days prediction of June 2014 all over Bangladesh

4.3.5 MAE of Rainfall of June 2014

The MAE of Rainfall of June 2014 for 24, 48, 72 hours and 137 days prediction at different stations of Bangladesh are presented in Fig. 4.3.5(a-d). The MAE of rainfall for 24 hour prediction (Fig. 4.3.5a) is found minimum in the central to western, northwestern and southwestern regions. The lowest value of MAE of rainfall found at Rajshahi region. The MAE of rainfall has increased from central towards south southeast region of the country. The maximum value of MAE has found in south southeastern region i.e. Sandwip, Teknaf.

The MAE of rainfall for 48 hour prediction of June 2014 (Fig. 4.3.5b) is found minimum in the west-northwestern region of the country and lowest value has found at Dinajpur was 15 mm. The MAE of rainfall has increased from northwest towards south southeastern regions of the country. The MAE has found highest at Teknaf. The MAE of rainfall for 72 hour prediction of June (Fig.4.3.5c) is found minimum in the western-northwestern regions of Bangladesh and lowest value has found at Dinajpur region. The MAE of rainfall is found maximum in northeastern and southeastern regions and at Cox’s Bazar its value was 105 mm. The MAE of rainfall has increased from northwest towards southeast region of the country.

The MAE of rainfall for 137 days prediction of June 2014 (Fig. 4.3.5d) is found minimum in the west-northwestern regions and lowest value has found at Dinajpur region. The MAE of rainfall is found maximum in the northeastern and southeastern regions. The maximum value has found 90 and 65 mm at Teknaf and Sylhet regions. The MAE of rainfall has decreased from northeast towards west-northwestern regions of the country.

4.3.6 MAE of Rainfall of July 2014

The MAE of rainfall for 24 hour prediction of July 2014 (Fig. 4.3.6a) is found minimum all over except south-southeast regions and the lowest value has found at Rangpur and Bogra regions. The MAE of rainfall has increased from central region towards southeastern region. The minimum value 10-15 mm of MAE has found at Mymensingh, Tangail, Madaripur, Faridpur, Jessore, Satkhira, Rajshahi, Ishurdi, Dinajpur, Srimangal and Rangamati regions.

The MAE of rainfall for 48 hour prediction of July 2014 (Fig. 4.3.6b) is found minimum in the central to west, northwest, southwest regions and the lowest value has found at Rangpur region. The MAE of rainfall has increased from northwest towards northeastern and south southeastern region of Bangladesh. The MAE of rainfall is found maximum in the south southeastern region i.e. M. Court, Sandwip and Teknaf and its value were 45, 55, and 65 mm respectively. The minimum value almost 10-20 mm of MAE has found at Tangail, Faridpur, Jessore, Khulna, Rajshahi, Ishurdi, Dinajpur, Srimangal and Rangamati regions.

The MAE of rainfall of July 2014 for 72 hour prediction (Fig. 4.3.6c) is found minimum in the central to west, northwest and southwest regions. The MAE of rainfall has increased from west towards northeastern and south southeastern region. The MAE of rainfall is found maximum in the south southeastern region i.e. M. Court, Sandwip and Teknaf and its value has 50, 60, and 80 mm respectively.

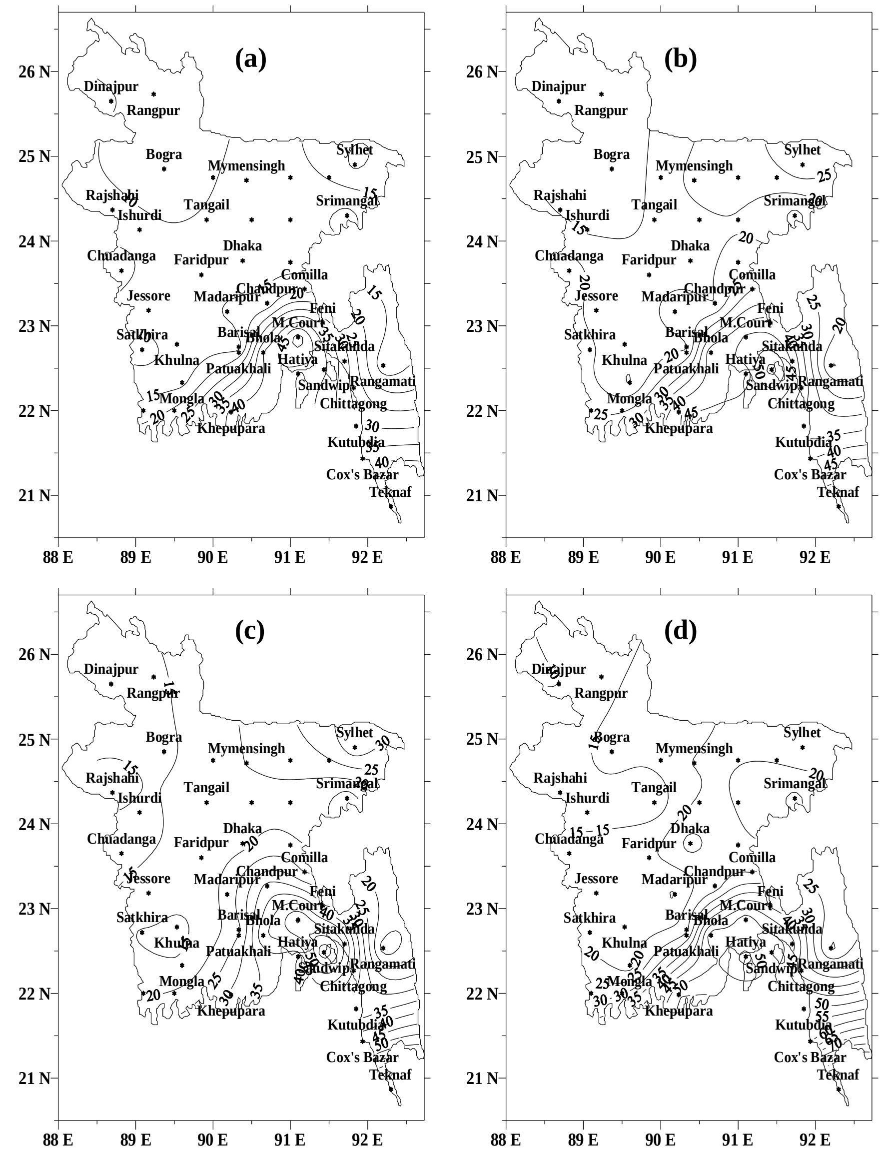

Fig. 4.3.6: Distribution of MAE of rainfall for (a) 24, (b) 48, (c) 72 hours and (d) 137 days prediction of July 2014 all over Bangladesh

The MAE of rainfall for 137 days prediction of July 2014 (Fig. 4.3.6d) is found minimum in the central to west and northwest region and the lowest value has found in Dinajpur region. The MAE of rainfall has increased from west towards south-southeastern region. The MAE of rainfall is found maximum in the south southeastern region at Teknaf its value was 100 mm. The minimum value of MAE has found at Tangail, Rajshahi, Ishurdi, Rangpur and Srimangal regions.

From the analysis of 24, 48, 72 hours and 137 days prediction of MAE of rainfall for July 2014 is found minimum in the west and northwest, central and southwestern regions and maximum has found in the south-southeastern region of the country. It has observed that where the rainfall was minimum the MAE has also minimum and vice versa. The MAE of rainfall has almost similar for 24, 48 and 72 hours prediction all over the country except southeastern region. The MAE of rainfall for 137 days prediction has seen much higher value in southeastern region than those of 24, 48 and 72 hours prediction.

4.3.7 MAE of Rainfall of August 2014

The MAE of rainfall for 24 hour prediction of August 2014 (Fig. 4.3.7a) is found minimum in the central to west, northwest and southwestern region. The lowest value has found at Ishurdi, Jessore and Satkhira regions and its value was 10 mm. The MAE of rainfall has increased from west towards northeastern and south southeastern region of Bangladesh. The MAE of rainfall is found maximum in the northeast and south southeastern region i.e. Sylhet, Sandwip and Teknaf and its value has 30, 40, and 65 mm respectively.

The MAE of rainfall for 48 hour prediction of August 2014 (Fig. 4.3.7b) is found minimum in the west, northwest and southwest and the lowest value has found at Jessore. The MAE of rainfall has increased from west northwest towards northeastern and south southeastern regions. The MAE of rainfall is found maximum in the southeastern region i.e. Sandwip and Teknaf and its value were 60 and 95 mm respectively. The minimum value almost 15-20 mm of MAE has found at Faridpur, Khulna, Rajshahi, Ishurdi, Dinajpur, Srimangal and Rangamati regions.

The MAE of rainfall of August 2014 for 72 hour prediction (Fig. 4.3.7c) is found minimum in the west and northwest regions. The MAE of rainfall has increased from west-northwest towards northeastern and southeastern region. The MAE of rainfall is found maximum in the southeastern region i.e. Sandwip and Teknaf region its value were 70 and 80 mm respectively. The minimum value 15-20 mm of MAE has found at Tangail, Jessore, Rajshahi, Ishurdi, Chuadanga, Dinajpur and Rangpur regions.

The MAE of rainfall for 137 days prediction of August 2014 (Fig. 4.3.7d) is found minimum in the west and northwestern region and the lowest value has found at Dinajpur region. The MAE of rainfall has increased from northwest towards northeast and south southeastern region of Bangladesh. The MAE of rainfall is found maximum at Sylhet, Sandwip and Teknaf and its value has 55, 80 and 120 mm respectively. The minimum RMSE has found at Tangail, Rajshahi, Ishurdi and Rangpur regions were 15-20 mm.

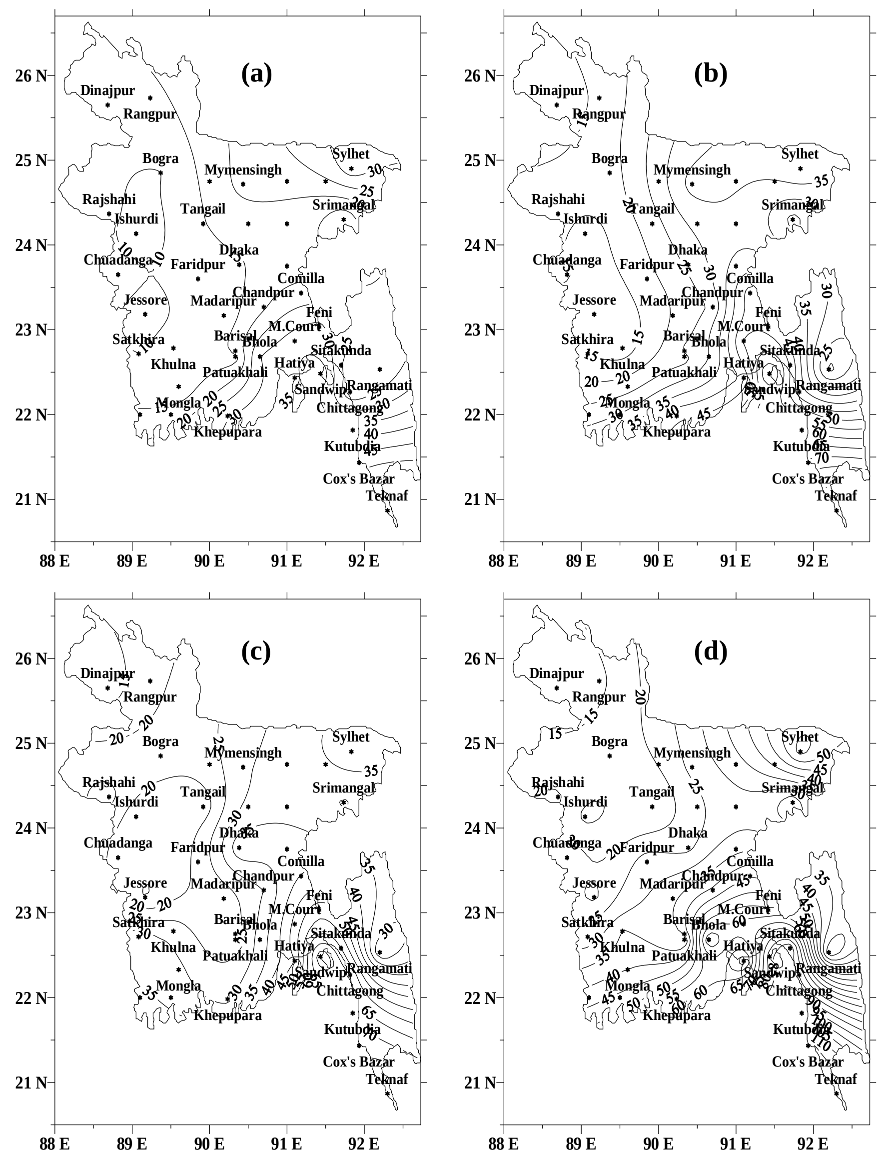

Fig. 4.3.7: Distribution of MAE of rainfall for (a) 24, (b) 48, (c) 72 hours and (d) 137 days prediction of August 2014 all over Bangladesh

The MAE was minimum in the west and northwestern regions of the country and maximum in the northeastern and south southeastern region. The MAE of rainfall has almost similar for 24, 48 and 72 hours prediction all over the country except southeastern region. The MAE of rainfall for 137 days prediction has seen much higher value in southeastern region than those of 24, 48 and 72 hours prediction.

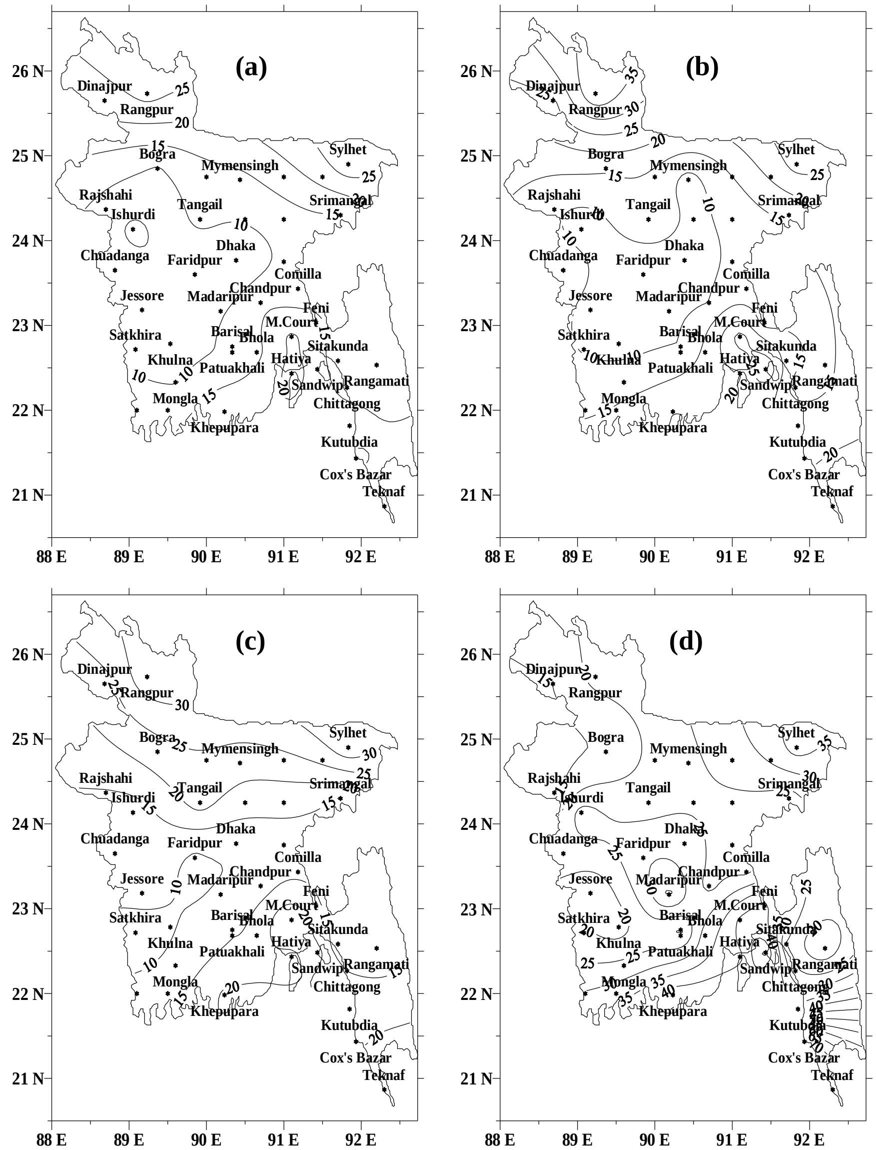

Fig. 4.3.8: Distribution of MAE of rainfall for (a) 24, (b) 48, (c) 72 hours and (d) 137 days prediction of September 2014 all over Bangladesh

4.3.8 MAE of Rainfall of September 2014

The MAE of rainfall of September 2014 for 24 hour prediction (Fig. 4.3.8a) is found minimum in the central to western, southwestern region and lowest value has found at Ishurdi region. The MAE of rainfall has increased from west towards northwest, northeast and southeastern regions. The maximum value of MAE of rainfall has also found minimum for 24 hour prediction and the maximum value at Sylhet, Rangpur, Sandwip and Teknaf was almost

20-25 mm. The MAE is found minimum at Madaripur, Faridpur, Dhaka, Khulna, Mongla, Satkhira, Rajshahi and Rangamati regions was 5-10 mm.

The MAE of rainfall for 48 hour prediction of September 2014 (Fig. 4.3.8b) is found minimum in the west, southwest and central region and the lowest value has found in Faridpur region. The MAE of rainfall has increased from central region towards northwest, northeast and south southeastern regions of Bangladesh. The MAE of rainfall is found maximum in the northwest, northeast and south southeastern region i.e. Rangpur, Sylhet, Sandwip and Teknaf and its value was 25-40 mm. The minimum value of MAE has found at Dhaka, Mymensingh, Faridpur, Madaripur, Khulna, Jessore, Satkhira, Rajshahi and Ishurdi regions.

The MAE of rainfall of September 2014 for 72 hour prediction (Fig. 4.3.8c) is found minimum in the west, southwest and central region. The MAE of rainfall has increased from southwest towards north and southeastern region of Bangladesh. The MAE of rainfall is found maximum at Rangpur, Sylhet, M. Court and Teknaf and its value was almost 25-30 mm. The MAE is found minimum at Dhaka, Faridpur, Madaripur, Chuadanga, Rajshahi, Ishurdi, Jessore, Satkhira and Rangamati regions was10-15 mm.

The MAE of rainfall for 137 days prediction of September 2014 (Fig. 4.3.8d) is found minimum in the west northwest and southwest regions and the lowest value has found at Rajshahi. The MAE of rainfall has increased from central towards southeastern region. The MAE of rainfall is found maximum 75 mm in the southeastern region. The MAE is found minimum at Jessore, Satkhira, Khulna, Bogra and Rangamati regions was 15-20 mm.

From the analysis of 24, 48, 72 hours and 137 days prediction of MAE of rainfall for September 2014, The MAE was minimum in the west, southwest and central regions of the country and maximum in the northeastern, northwestern and south southeastern region. The MAE of rainfall has almost similar for 24, 48, 72 hours and 137 days prediction all over the country. The MAE of rainfall for 137 days prediction has seen much higher value in southeastern region than those of 24, 48 and 72 hours prediction. MAE is found minimum in this month for 24, 48 and 72 hours and 137 days prediction.

4.4 Correlation Coefficients (CC) between observed and simulated rainfall

4.4.1 CC of Rainfall of June 2014

The distribution of CC between observed and found rainfall for 24, 48, 72 hours and 137 days predicted rainfall of June 2014 has presented in Fig. 4.4.1(a-d). The distribution of CC between observed and 24 hours predicted rainfall of June (Fig. 4.4.1a) is found maximum in east, south and southeastern region of the country. The highest value of CC has found 0.6 at Comilla region. The distribution of CC between observed and 48 hours predicted rainfall of June (Fig. 4.4.1b) is found maximum in west and south southeastern region of the country. The highest value of CC has found 0.45 at Chittagong region. The CC has not significant in other regions. The CC has increased from west towards east and southeastern region of Bangladesh.

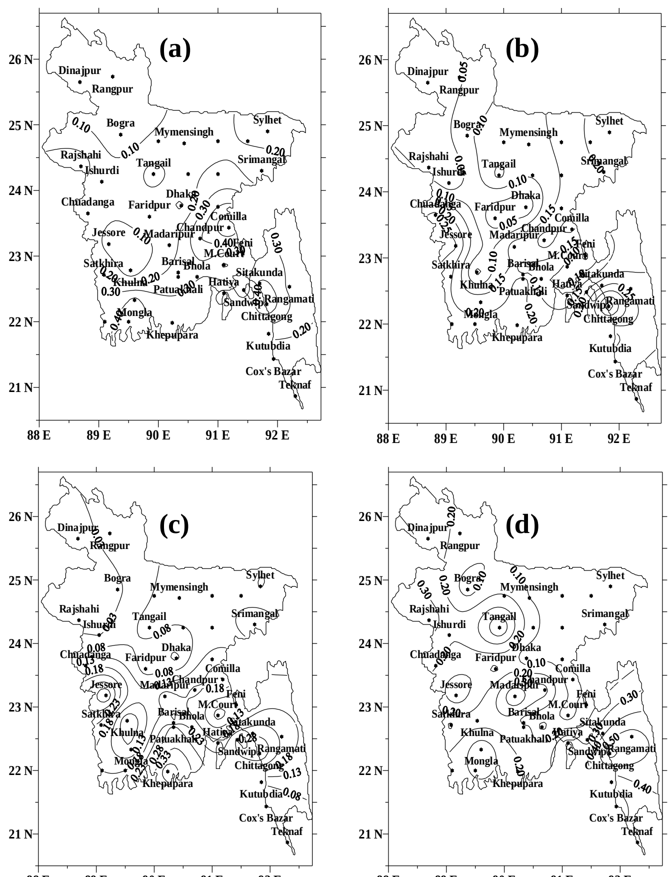

Fig. 4.4.1: Distribution of CC of rainfall of (a) 24, (b) 48, (c) 72 hour and (d) 137 days prediction of June 2014 all over Bangladesh

The distribution of CC between observed and 72 hours predicted rainfall of June (Fig. 4.4.1c) is found maximum in western, southern and southeastern region of the country. The highest value of CC has found 0.4 and 0.33 at Khepupara and Jessore regions respectively. The CC has not significant in other regions of the country. The distribution of CC between observed and 137 days predicted rainfall of June (Fig. 4.4.1d) is found maximum 0.5-0.6 at Chittagong, Rangamati, Tangail and Madaripur regions of the country. The CC has not significant in other regions of the country.

4.4.2 CC of Rainfall of July 2014

The distribution of CC between observed and 24, 48, 72 hours and 137 days predicted rainfall of July 2014 has presented in Fig. 4.4.2(a-d). The distribution of CC between observed and 24 hours predicted rainfall of July (Fig. 4.4.2a) is found maximum at Jessore and southeastern regions and its value were 0.25 and 0.45. The CC has almost nil in other regions of the country.

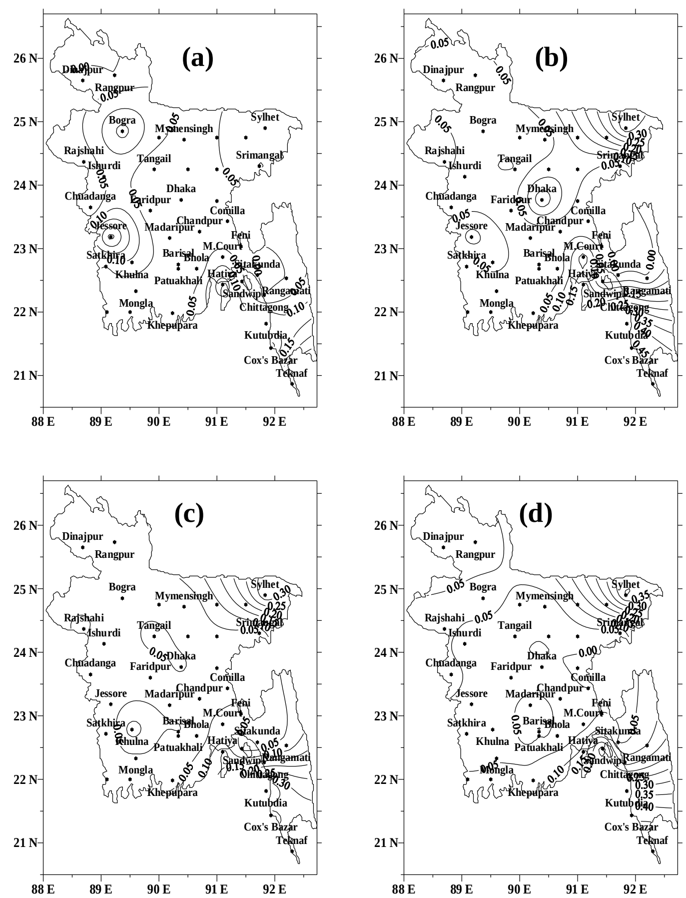

Fig. 4.4.2: Distribution of CC of rainfall of (a) 24, (b) 48, (c) 72 hour and (d) 137 days prediction of rainfall of July 2014 all over Bangladesh

The distribution of CC between observed and 48 hours predicted rainfall of July (Fig. 4.4.2b) is found maximum at Sylhet and southeastern regions. The highest value of CC has found 0.45 at Cox's Bazar and Teknaf regions and 0.35 at Sylhet. The CC has almost nil in other regions of the country.

The distribution of CC between observed and 72 hours predicted rainfall of July (Fig. 4.4.2c) is found maximum at Sylhet and southeastern regions of the country. The maximum value of CC has found 0.4 and 0.32 at Kutubdia and Sylhet regions respectively. The CC has almost nil in other regions of the country. The distribution of CC between observed and 137 days predicted rainfall of July 2014 (Fig. 4.4.2d) is found maximum at Sylhet and southeastern region of the country. The maximum value of CC has found 0.5 and 0.4 at Teknaf and Sylhet regions respectively. The CC has almost nil in other regions of the country.

4.4.3 CC of Rainfall of August 2014

The distribution of CC between observed and 24, 48, 72 hours and 137 days predicted rainfall of August 2014 has shown in (Fig. 4.4.3(a-d). The distribution of CC between observed and 24 hour predicted rainfall of August (Fig. 4.4.3a) has significant at Faridpur, Sitakunda, Feni and Srimangal regions were 0.35, 0.35, 0.45 and 0.3 respectively. The distribution of CC between observed and 48 hour prediction of rainfall of August 2014 (Fig. 4.4.3b) has found significant at Bogra and Sitakunda and its value were 0.5 and 0.35 respectively. The CC has almost nil in other regions of the country.

The distribution of CC between observed and 72 hour predicted rainfall of August 2014 (Fig. 4.4.3c) has found significant at Chandpur and Sitakunda regions. The CC is found maximum 0.4 and 0.25 at Sitakunda and Chandpur regions respectively. The CC has almost nil in other regions of the country. The distribution of CC between observed and 137 days predicted rainfall of August 2014 (Fig. 4.4.3d) is found maximum at Khepupara, Ishurdi and Rangamati regions and the CC has found in these regions are 0.9, 0.75 and 0.35 respectively. The CC has almost nil in other regions of the country.

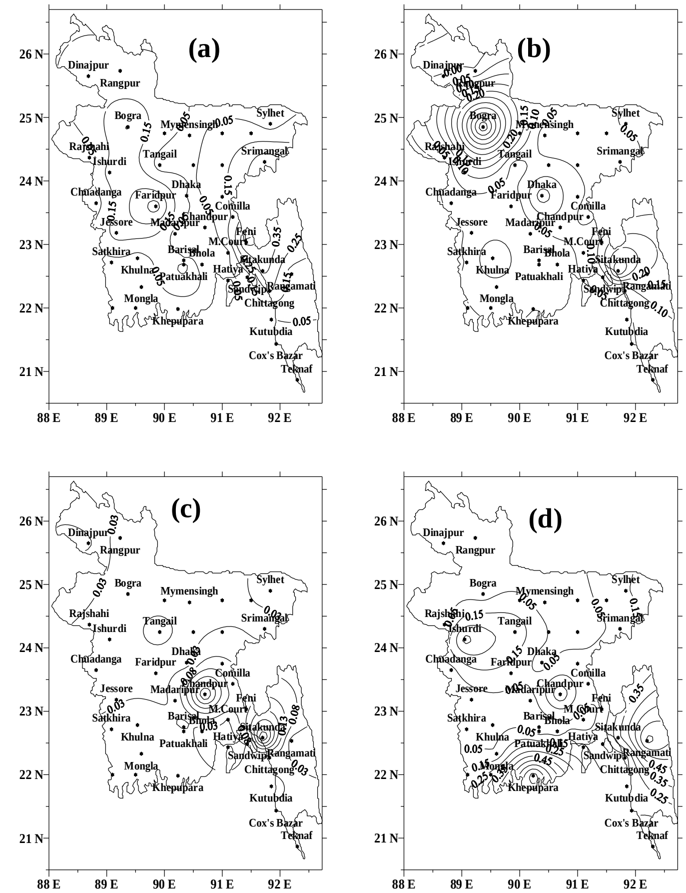

Fig. 4.4.3: Distribution of correlation coefficient of rainfall of (a) 24, (b) 48, (c) 72 hours and (d) 137 days prediction of August 2014 all over Bangladesh

4.4.4 Correlation Coefficients of Rainfall of September 2014

The distribution of CC between observed and 24, 48, 72 hours and 137 days predicted rainfall of September 2014 has shown in Fig. 4.4.4(a-d). The station wise CC between observed and 24 hour prediction of rainfall of September 2014 (Fig. 4.4.4a) is found maximum at Ishurdi, Rajshahi and Bogra regions and the values were 0.7, 0.4 and 0.38 respectively. The CC has almost nil in other regions of the country. The CC between observed and 48 hour prediction of rainfall of September 2014 (Fig. 4.4.4b) is found maximum at Mymensingh, Ishurdi, Faridpur and Feni and the CC has found in these regions were 0.7, 0.55, 0.35 and 0.4 respectively. The CC has almost nil in other regions of the country.

The CC between observed and 72 hour predicted rainfall of September 2014 (Fig. 4.4.4d) has observed maximum in central and south southeastern regions of the country. The CC is found maximum at Chandpur, Madaripur, Khepupara and Barisal regions and its value has 0.4-0.6. The CC between observed and 137 days predicted rainfall of September 2014 (Fig. 4.4.4c) is found maximum in the central to eastern region and at Chandpur, Madaripur and Barisal regions its value were 0.6, 0.4 and 0.35 respectively.

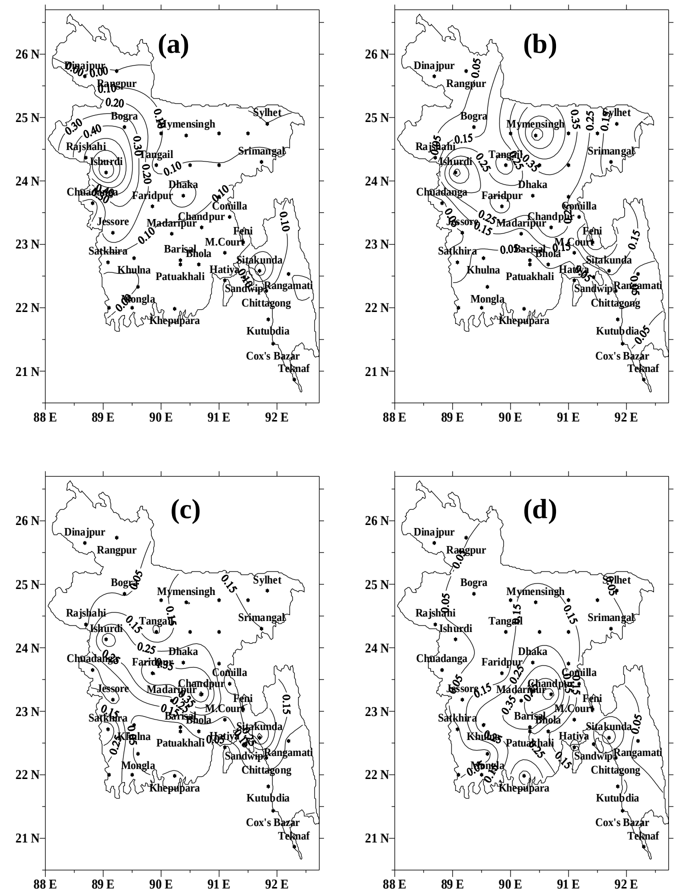

Fig. 4.4.4: Distribution of correlation coefficient of rainfall of (a) 24, (b) 48, (c) 72 hours and (d) 137 days prediction of September 2014 all over Bangladesh

Chapter V

Conclusions

In the present study the WRF-ARW model V3.5.1 have been used to simulate the rainfall in the monsoon season over Bangladesh. The model vertical coordinate is terrain following hydrostatic pressure and the horizontal grid is Arakawa C-grid staggering. The model has been configured in single domain, 6 km horizontal grid spacing with 161×183 grids in the east-west and north-south directions and 30 vertical levels. In this research the WSM6-class microphysics scheme coupling with Kain-Fritsch cumulus parameterization scheme have been used. The model has integrated by using initial and LBCs from NCEP-FNL analysis at three hourly intervals. Surface layer is treated using Monin-Obukhov and PBL used is Yonsei University scheme. Dudhia (1989) scheme has been used for short wave radiation and RRTM for long wave radiation. Time step of integration is set to 36 seconds for maintaining computational stability as the model uses third-order Runge-Kutta time integration scheme. The model was run 137 days for 137 days prediction starting with the initial condition of 0000 UTC of 17 May up to 0000 UTC of 1 October for the period 2010-2014. The model was also run 72 hours with every day 0000 UTC initial conditions for 124 days for the prediction of 24, 48 and 72 hours lead time rainfall in the month of June, July, August and September 2014. In this research convective and non-convective rainfall have been simulated at 3 hourly interval then made daily and monthly total rainfall data for 24, 48, 72 hour and 137 days during the studied period. We have compared this data with the observed rainfall at 33 meteorological stations of BMD and TRMM rainfall. BMD observed and 24, 48, 72 hours and 137 days simulated rainfalls are also used for calculating RMSE, MAE and CC of rainfall.

The distribution patterns of TRMM and BMD observed rainfall for the month of June, July, August and September during 2010-2014 are almost similar but the value of TRMM derived station rainfall is much lower than that of observed rainfall all over the country. During the study period monthly observed and TRMM rainfall of June, July, August and September are minimum in the central to west-northwestern regions of the country and TRMM derived rainfall have found one half to one third of the observed rainfall.

The distribution patterns of model simulated 24, 48 and 72 hours lead time predicted rainfall during the month of June, July, August and September was almost similar that of observed rainfall but the higher rainfall area has simulated more rainfall all over the country.

The distribution patterns of 24, 48 and 72 hours, observed and TRMM rainfall is found minimum in the west, north northwest and southwest regions and maximum in south-southeastern and northeastern regions of the country. The 24 hours predicted rainfall has comparable with the observed rainfall during monsoon season all over the country except hilly regions. With the increase of simulated time the predicted rainfall will also be increased. The 137 days predicted rainfall is found maximum in the northeastern and southeastern region and minimum in the west, southwest and central regions of the country. The 137 days predicted rainfall has simulated much higher rainfall than that of 24, 48 and 72 hours predicted rainfall.

The patterns of RMSE of rainfall for 24, 48 and 72 hours lead time and 137 days prediction during the month of June, July, August and September was almost similar but the value of RMSE for 137 days prediction has simulated much higher than those of 24, 48 and 72 hours predicted rainfall. The value of RMSE of rainfall for 24 and 48 hours prediction is within 15–30 and 20–35 mm respectively all over Bangladesh except hilly regions. The RMSE increases as the prediction time increases. The value of MAE of rainfall for 24 and 48 hours prediction is within 10–20 and 15–25 mm respectively all over Bangladesh except hilly reasons. The RMSE for 72 hours and 137 days predicted rainfall much higher in the hilly regions. It has also been observed that where the rainfall has low - medium (heavy) the RMSE and MAE have also low (high).

On the basis of above finding it may be concluded that WRF model is suitable for the prediction of rainfall up to 72 hours.

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