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

M. Sc. Thesis
BY

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FEBRUARY 2016

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ROLL NO: 1455555
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.

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DECLARATION

This is to certify that the thesis work entitled "***Simulation of Pre-monsoon Rainfall over Bangladesh using High Resolution WRF-ARW Model***" has been carried out by Taslima Khatun 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)	Taslima Khatun

<u>DEDICATED TO</u>
MY PARENTS

Acknowledgements

It gives me immense satisfaction to acknowledge the blessings of Allah, the Creator of the Universe who is the most gracious compassionate and beneficent to its creature, who beloved me with knowledge and potential to implement my research work.

With my great manner it is a pleasure for me to express my deepest sense of gratitude and indebtedness to my reverend supervisor Dr. Md. Mahbub Alam, Professor, Department of Physics, Khulna University of Engineering & Technology, Khulna, for his kind guidance and supervision and for his constant encouragement throughout the research work. His inspiration and friendly cooperation accelerated my works.

I am very much indebted to Professor Dr. Md. Abdullah Elias Akhter, Department of Physics, Khulna University of Engineering & Technology, Khulna for introducing the present research topic and for inspiring guidance and valuable suggestions throughout this research work. It would have not been possible for me to bring out this thesis without the help of his constant encouragement.

I express my heartful gratitude and thanks to Professor Dr. Shibendra Shekher Sikder, Department of Physics, Khulna University of Engineering and Technology. Many thanks for their inspiration and advices from the beginning of my study.

I am indebted to Professor Dr. Jolly Sultana, Head, Department of Physics, Khulna University of Engineering & Technology for her strong support in various ways during the entire period of my study in this department. I gratefully acknowledge Mr. Md. Kamrul Hasan Reza, Mr. Sujit Kumar Shil and Md. Alamgir Hossain, Assistant Professor, Department of Physics, KUET for their cooperation regarding writing the thesis.

My personal thankful greetings are to my best friends Afsar Hosain, Ashraful Alom, Mamun, Soumitra, Krishna and well wishers for their help and cooperation. There are numerous people who could not be mentioned individually but their interesting discussions have prompted much thought on various aspects, I would also like to thank them.

I would like to express my heart full obligation thanks to my parents, sisters, brothers and nearest relatives for their inspiration, encouragement and multifaceted support to carry out this thesis work.

Taslima Khatun

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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
RMSE	:	Root mean square error
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 pre-monsoon rainfall during 2010–2014 for all the meteorological station points of 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 for the public at $1°\times1^{o}$ resolution. The model is 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 pre-monsoon rainfall, WSM6-class graupel scheme coupled with Kain-Fritsch (KF) cumulus parameterization (CP) scheme has been used. Initially, the model is run 107 days for long term prediction starting with the initial condition of 0000 UTC of 17 February up to 0000 UTC of 01 June for the period 2010-2014. The model is also run for 72 hours with every day at 0000 UTC initial conditions for 94 days for the prediction of 24, 48 and 72 hours lead time rainfall in the pre-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 107 days during the studied period. We have compared this data with the observed rainfall at 33 meteorological stations of BMD and TRMM rainfall.

From this research it has been found that the 107 days predicted and TRMM rainfall is much lower than that of observed rainfall. The simulated rainfall at different stations for 24, 48 and 72 hours for the month of March, April and May are good agreement with the observed rainfall. The long term predictions of simulated rainfall are also matched with BMD observed rainfall. From the rainfall distribution the maximum rainfalls have been found in the northeastern region and also obtain in the southeastern region and the minimum rainfalls have been found in the west, northwest and southwestern regions of Bangladesh. From the rainfall distribution pattern the maximum Correlation coefficient (CC) has been shown at southern and southeastern regions and the minimum CC's has been found in the northern, northwest and southwestern regions of the country. From this study, it has been analyzed that where the rainfall is maximum there the RMSE, MAE and CC is also maximum and vice versa. Finally, it has been observed that WRF-ARW model is suitable for the prediction of pre-monsoon rainfall.

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.

There are four seasons: the pre-monsoon (March-May) has the highest temperatures and experiences the maximum intensity of cyclonic storms, especially in April; the monsoon (June-September) when the bulk of rainfall occurs; the post-monsoon (October-November) which, like the pre-monsoon season, is marked by tropical cyclones on the coast; and the cool and sunny dry season (December-February). Among these seasons pre-monsoon is one of them in Bangladesh. 10-25% rainfall occurs in this season. Significant climate variability exists in pre-monsoon seasons of South and East Asia region and occurs thunderstorms, tornado, Nor'wester or Kalbaishakhi. We are interested only to simulate the rainfall in pre-monsoon season.

Prediction of heavy rainfall is one of the many challenging problems in meteorology, but very important for issuing timely warnings for the agencies engaged in disaster preparedness and mitigation. Cumulus parameterization (CP) schemes must estimate the rate of subgrid-scale convective precipitation, release of latent heat, and the distribution of heat, moisture, and momentum in the vertical due to convection. The Advanced Research Weather Research and Forecasting model (ARW-WRF) is the new-generation model for both weather research and forecasting, and is used for regional climate research. Precipitation is recognized as one of the most difficult parameters to forecast in numerical weather prediction despite the fact that the accuracy of numerical models has increased during the past several decades. Prior studies have shown that a model's microphysical parameterization scheme can strongly influence the magnitude of predicted precipitation. Litta *et al.* (2012) illustrates that the microphysics scheme can significantly impact the accuracy of quantitative precipitation forecasts during the pre-monsoon season. 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. Most of the severe cyclonic storms form in the pre-monsoon and post-monsoon season. During the last decades the number of depressions/tropical cyclones forming in the Bay of Bengal has decreased remarkably (Alam *et al.*, 2002). Scientists believe that this is happening due to the change in climate in the East, Far East Asia and in Indian subcontinent. Alam have studied the impact of cloud microphysics and cumulus parameterization on simulation of heavy rainfall event during 7–9 October 2007 over Bangladesh using 9 and 3 km nested domain. To examine the sensitivity of the simulations of six different microphysical schemes and two different CP schemes, Kain–Fritsch and Betts–Miller–Janjic were considered.

The studies on the rainfall characteristics over Bangladesh are a few. A study on the water balance of Bangladesh has been made by Khan and Islam (1966) while the variability of annual rainfall by Shamsuddin (1974), correlation between winter temperature and monsoon rainfall over Bangladesh by Alam and Hossain (2002) and correlation between winter temperature and post-monsoon rainfall by Alam and Hossain (2004) are among the significant studies towards understanding of rainfall characteristics and distribution in Bangladesh.

Banerjee *et al.* (1978) showed that the total monsoon rainfall over India is significantly correlated with the latitudinal position of the subtropical ridge of the mean circulation of April at 500 hPa level. Upadhyay *et al.*, (1990) and Kanaujia *et al.*, (1992) determined the rainfall correlation decreases exponentially with distance. Kanamitsu and Krishnamurti (1978) and Verma (1980, 1982) have shown that the future performance of the monsoon is reflected by the upper tropospheric thermal and circulation anomalies over the Indian subcontinent for pre monsoon months. Karmakar *et al.*, (1994) tried to find the correlation between pre monsoon rainfall and monsoon rainfall over different stations of Bangladesh and observed no correlation. Mahbub (2002) tried to find the correlation between winter temperature and monsoon rainfall and found significant correlation in different stations over Bangladesh. The correlation between different meteorological parameters (maximum temperature, minimum temperature, dry bulb temperature, wet bulb temperature, pressure and rainfall) in pre monsoon season and monsoon rainfall has not been analyzed and it has to be analyzed.

Sanderson and Ahmed studied (1978) pre-monsoon rainfall and its variability in Bangladesh. Their analysis showed that the trend surface mapping technique was found to be satisfactory for mapping the pre-monsoon rainfall. A preliminary study of the water balance of Bangladesh (then East Pakistan) was made by Khan& Islam (1966) and a study of the variability of annual rainfall by Shamsuddin & Ahmed (1974). They found that the pre-monsoon rainfall, it was not satisfactory in explaining the variability of this rainfall monthly or seasonally except for the month of May. In Bangladesh the pre-monsoon rainfall is small in comparison to monsoon rainfall, which accounts for 80-90 per cent of the annual rainfall, it is nevertheless important from an agricultural point of view, contributing from 20 to 90 cm of rainfall for the benefit of crop growth. Ahmed (1989) studied the probabilistic estimates of rainfall extremes in Bangladesh during the pre-monsoon season. A total of 15 precipitation indices are computed which includes annual total rainfall amount greater than 99th and 95th percentiles, pre-monsoon total rainfall amount greater than 95th percentile, annual and pre-monsoon heavy rainfall days, number of rainy days, average rainfall intensity, consecutive annual and pre-monsoon wet and dry days and maximum one- and five days rainfall. The pre-monsoon rainfall has vital importance in Bangladesh as 70% of total food grain is grown during this period. Therefore, importance has been given to study the rainfall extremes in pre-monsoon season. The thunderstorms are the sources of pre-monsoon rainfall of Bangladesh (Sanderson and Ahmed, 1978). The activity of the thunderstorms during the pre-monsoon season depends upon the supply of moist air from the Bay of Bengal. Stronger and more continuous winds from the Bay of Bengal during pre-monsoon months due to the increase of sea surface temperature may be the cause of increased pre-monsoon rainfall of Bangladesh. Increase annual rainfall in north and northwester Bangladesh might increase flash flood in the region. Heavy pre-monsoon rainfall causes local runoff to accumulate in depressions. Therefore, increased pre-monsoon rainfall and heavy rainfall events in pre-monsoon can trigger more rain related flood in Bangladesh. An analysis to classify pre-monsoon and monsoon rainfall in and around Bangladesh using TRMM 2A25 data (Islam and Uyeda,) Characteristics of rainfall in these 3 parts of the rainy season are analyzed by using Tropical

Rainfall Measuring Mission (TRMM) PR (precipitation radar) 2A25 data. This analysis objectively reveal the distinction between rain intensity and rain type for pre-monsoon and monsoon periods in a domain of 84-94°E and 18-28°N. They found that the Pre-monsoon (monsoon) convection developed over land (land and ocean). The stratiform (convective) rainfall dominates during monsoon (pre-monsoon) period and over ocean (land). Details of the analyzed result including data for more years will be discussed during the conference. Rafiuddin *et al*. (2013) Studied that the arc and scattered types precipitation systems are dominant in the pre-monsoon and monsoon seasons, respectively. They found that the characteristics of ATPS and STPS (symmetric type precipitation system (STPS), asymmetric type precipitation system (ATPS)) help to produce gusty wind, damaging hail and tornadoes, and heavy rainfall (flash flood) in Bangladesh during the pre-monsoon and monsoon periods, respectively. There is 160 and 70 arc shaped precipitation systems found during the pre-monsoon and monsoon periods. The maximum occurrence frequency of UTPS (unclassified type precipitation system) is found in the northeast and the southwest quadrant during pre-monsoon and in the southwest quadrant during the monsoon season. Hossain *et al.* (2014) conducted research on Spatial and Temporal Variability of Rainfall over the South-West Coast of Bangladesh. The objective of this study has been achieved by analyzing time series data from eight weather stations (1947–2007) using statistical tests including the homogeneity test, Sen's slope estimation, linear regression, the Mann-Kendal test and autocorrelation. They also pointed out that the rainfall during pre-monsoon season were effected the mid-latitude regime. It is suggested that the weather in this region are also effected the mid-latitude regime during the pre-monsoon season. Of this study, the one of the reasons of the convective activity during the pre-monsoon is the strengthening of the uplift flow and southwesterly in the lower troposphere in the front of the upper trough. In future, it is needed that the upper air radio observation at multiple stations to clarify the strengthening of uplift flow. Fukushima (2012) conducted research on "Determination of the pre-monsoon period and interannual variations of the premonsoon rainfall in the Himalayan foothills" In this study, the new definition of the premonsoon period was proposed and secular variation of the premonsoon period and premonsoon precipitation were evaluated using the definition. From the result, 97% days of the premonsoon period recorded rainfall from 1979 to 2002.However, the averaged total premonsoon precipitation was below 200 mm. The daily rainfall intensity was estimated to be not strong during the premonsoon season from the results. Shamsuddin Shaid (2010) studied that the Rainfall variability and the trends of wet and dry periods in Bangladesh. In this research 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. Rahman *et al*., (1997) used trend analysis to study the changes in monsoon rainfall of Bangladesh and found no significant change. Ahmed (1989) estimated the probabilistic rainfall extremes in Bangladesh during the pre-monsoon season. Karmakar and Khatun (1995) repeated a similar study on rainfall extremes during the southwest monsoon season. However, both the studies were focused only on the maximum rainfall events for a limited period. Mallika Roy (2013) studied that Time Series, Factors and Impacts Analysis of Rainfall in North-Eastern Part in Bangladesh. This study was checked annual average rainfall of 30 years for this region. It is hoped that this research may be of help to the concerned organizations and experts working on increasing rainfall problem in Chittagong. Begum *et al.,* (2013) conducted research on classification of arc-shaped precipitation systems during pre-monsoon and monsoon in Bangladesh. Arc shaped precipitation systems are classified to know their seasonal and regional variation in Bangladesh. In this study, six-year (2000-2005) radar data are used from the Bangladesh Meteorological Department. Regional analysis of the arc shaped precipitation systems indicate that at the mature stage of their life cycle, symmetric type, and asymmetric type precipitation system and combination of symmetric and asymmetric type precipitation system is dominated in southwest (northwest), northeast (southeast) and northwest (northwest) quadrants during the pre-monsoon (monsoon) period. The maximum occurrence frequency of unclassified type precipitation is found in the northeast and the southwest quadrants during the pre-monsoon season and in the southwest quadrant during the monsoon season. Madala *et al.,* (2013) conducted research on Performance Evaluation of Convective Parameterization Schemes of WRF-ARW Model in the Simulation of Pre-monsoon Thunderstorm Events over Kharagpur using STORM Data Sets. The present paper mainly focus on the performance of various convection parameterization schemes of WRF-ARW version 3.2 in simulating thunderstorms that occurred over Kharagpur on 12 May 2009 and 5 May 2010 using STORM data sets. In this study the model simulated thermodynamical structure of the atmosphere, variation of surface meteorological variables and rainfall variations are validated with the available observations to evaluate the capability of the model for forecasting the thunderstorms. Tyagi and Satyanarayana (2013) studied that the Budget of Turbulent Kinetic Energy during Premonsoon Season over Kharagpur as Revealed by STORM Experimental Data. In this study aims to discern the variations in theatmospheric surface layer turbulence transport and the processes that contribute to the total TKE during the days of thunderstorm and non-thunderstorm (no weather activity) within the same pre-monsoon period at Kharagpur. Kumar *et al*., (2014) conducted research on Effects of dust aerosols on tropospheric chemistry during a typical pre-monsoon season dust storm in northern India. This study examines the effect of a typical pre-monsoon season dust storm on tropospheric chemistry through a case study in northern India. Kumar *et al*., (2014) conducted research on Effects of dust aerosols on tropospheric chemistry during a typical pre-monsoon season dust storm in northern India. This study examines the effect of a typical pre-monsoon season dust storm on tropospheric chemistry through a case study in northern India. Kodama *et al*., (2005) studied that Seasonal transition of predominant precipitation type and lightning activity over tropical monsoon areas derived from TRMM observations. This study used TRMM-PR and LIS observations for 1998 to 2000 to describe and compare the large-scale distribution, predominant rain types, and lightning activity of pre-monsoon rainfall and monsoon rainfall.

The WRF modeling system has been reported in a variety of areas, including storm prediction and research, air quality modeling, wildfire, hurricane, tropical storm prediction, and regional climate and weather prediction. In the present study the Weather Research and Forecast (WRF-ARW V3.5.1) model has been used to simulate the pre-monsoon (March – May) rainfall over Bangladesh. Station wise daily rainfall of pre monsoon season has been simulated for the period of 2010 – 2014. The results have been then compared and validated with the observed station rainfall of Bangladesh Meteorological Department (BMD) and also rainfall obtained from TRMM.

Chapter II

Literature Review

In this work, we have tried to simulate daily, monthly and seasonal rainfall for pre monsoon seasons using ARW model. The main objective of this work is to compare model simulated rainfall with observed and TRMM. 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. There are four seasons: the pre-monsoon (March-May) has the highest temperatures and experiences the maximum intensity of cyclonic storms, especially in April; the monsoon (June-September) when the bulk of rainfall occurs; the post-monsoon (October-November) which, like the pre-monsoon season, is marked by tropical cyclones on the coast; and the cool and sunny dry winter season (December-February). The mean annual temperature is about 25°C, with extremes of 4 and 43°C. Ground frosts can occur in the hills. Humidity ranges between 60% in the dry season and 98% during the monsoon. The discussion of each season with their characteristics and description of WRF-ARW model, used for the present study, are written in the following sections.

2.1 Pre Monsoon season

Bangladesh has a tropical monsoon climate. During the pre-monsoon season, its climate is characterized by high temperatures and the occurrence of thunderstorms. April is the hottest month. Temperatures of this month range from 27°C along the northeastern foothills to 30°C along the western border. Rainfall from the thunderstorms of this season is copious, varying from 15 cm in the west-central part of the country to more than 80 cm in the northeast. This reflects the effect of orography in the northeastern parts of the country which sets the trigger action for uplift and convectional overturning of the moist air from the Bay of Bengal. The thunderstorm season begins in the northeastern and eastern parts of the country by the first week of March. The thunderstorm activity gradually moves westward, and becomes significant in the western part of the country only before the advent of the summer monsoon in late May or early June. During the early part of the thunderstorm season, a zone of discontinuity crosses the country from southwest to northeast, separating the hot dry air from the dry interior of India, and the warm moist air from the Bay of Bengal. The activity of the thunderstorms during the pre-monsoon season depends upon the supply of moist air from the Bay of Bengal. Since this season is a transitional season between the northerly circulation of winter and southerly circulation of the summer monsoon, the winds from the Bay of Bengal are neither very strong nor continuous.

The hot season from March to May is the traditional period when the winter pattern of pressure and winds gets disturbed prior to the establishment of the summer monsoon and hence, is often referred to as 'pre-monsoon' season. The pre-monsoon hot season is characterized by high temperatures and the occurrence of thunderstorms. April is the hottest month when mean temperatures range from 27°C in the east and south to 31°C in the west-central part of the country. In the western part, summer temperature sometimes reaches up to 40°C. After the month of April, the temperature dampens due to increased cloud cover. The pre-monsoon season is the transition period when the northerly or northwesterly winds of the winter season gradually changes to the southerly or southwesterly winds of the summer monsoon or rainy season (June-September). During the early part of this season, the winds are neither strong nor persistent. However, with the progression of this season wind speed increases, and the wind direction becomes more persistent.

During the early part of the pre-monsoon season, a narrow zone of air mass discontinuity lies across the country that extends from the southwestern part to the northeastern part. This narrow zone of discontinuity lies between the hot dry airs is coming from the upper Gangetic plain and the warm moist air coming from the Bay of Bengal. As this season progresses, this discontinuity weakens and retreats toward northwest and finally disappears by the end of the season, making room for the onset of the summer monsoon. The rainy season, which coincides with the summer monsoon, is characterized by southerly or southwesterly winds, very high humidity, heavy rainfall, and long consecutive days of rainfall which are separated by short spells of dry days. Rainfall in this season is caused by the tropical depressions that enter the country from the Bay of Bengal.

Events and characteristics of pre-monsoon season are discussed in the following sub-sections.

2.1.1 Pre-monsoon rainfall

The single most dominant element of the climate of Bangladesh is the rainfall. Because of the country's location in the tropical monsoon region, the amount of rainfall is very high. However, there is a distinct seasonal pattern in the annual cycle of rainfall, which is much more pronounced than the annual cycle of temperature. The winter season is very dry, and accounts for only 2-4% of the total annual rainfall. Rainfall during this season varies from less than 2 cm in the west and south to slightly over 4 cm in the northeast. The amount is slightly enhanced in the northeastern part due to the additional uplifting of moist air provided by the Meghalaya Plateau. As the winter season progresses into the pre-monsoon hot season, rainfall increases due to intense surface heat and the influx of moisture from the Bay of Bengal. Rainfall during this season accounts for 10-25% of the total annual rainfall which is caused by the thunderstorms or nor'wester (locally called Kalbaisakhi).

The amount of rainfall in this season varies from about 20 cm in the west central part to slightly over 80 cm in the northeast. The additional uplifting by the Meghalaya Plateau of the moist air causes higher amount of rainfall in the northeast. Rainfall during the rainy season is caused by the tropical depressions that enter the country from the Bay of Bengal. These account for 70% of the annual total in the eastern part, 80% in the southwest, and slightly over 85% in the northwestern part of Bangladesh. The amount of rainfall in this season varies from 100 cm in the west central part to over 200 cm in the south and northeast. Average rainy days during the season vary from 60 in the west-central part to 95 days in the southeastern and over 100 days in the northeastern part. Geographic distribution of annual rainfall shows a variation from 150 cm in the west-central part of the country to more than 400 cm in the northeastern and southeastern parts. The maximum amount of rainfall has been recorded in the northern part of Sylhet district and in the southeastern part of the country (Cox's Bazar and Bandarban districts).

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

2.1.2 Pre-monsoon temperature

January is the coldest month in Bangladesh. However, the cold winter air that moves into the country from the northwestern part of India loses much of its intensity by the time it reaches the northwestern corner of the country. Average temperatures in January vary from about 17°C in the northwestern and northeastern parts to 20-21°C in the coastal areas. In late

December and early January, minimum temperature in the extreme northwestern and northeastern parts of the country reaches within 4 to 7 degrees of freezing point. As the winter season progresses into the pre-monsoon hot season, temperature rises, reaching the maximum in April, which is the middle of the pre-monsoon hot season. Average temperatures in April vary from about 27°C in the northeast to 30°C in the extreme west central part of the country. In some places in Rajshahi and Kushtia districts the maximum temperature in summer season rises up to 40°C or more. After April, temperature decreases slightly during the summer months, which coincides with the rainy season. Widespread cloud covers causes dampening of temperature during the later part of the pre-monsoon season. Average temperatures in July vary from about 27°C in the southeast to 29°C in the northwestern part of the country

2.1.3 Pre-monsoon wind

Western Disturbance is the term used in India, Pakistan, Bangladesh and Nepal to describe an extra tropical storm originating in the Mediterranean that brings sudden winter rain and snow to the northwestern parts of the Indian subcontinent this is a non-monsoonal on pattern driven by the westerlies. The moisture in the Indian subcontinents storms usually originates over the Mediterranean Sea and the Atlantic Ocean. Extra tropical storms are a global, rather than a localized, phenomena with moisture usually carried in the upper atmosphere (unlike tropical storms where it is carried in the lower atmosphere). In the case of the subcontinent, moisture is sometimes shed as rain when the storm system encounters the Himalayas. Western Disturbances are important to the development of the Rabi crop in the northern subcontinent, which includes the locally important staple wheat. Western Disturbance causes winter and pre monsoon season rainfall across northwest India. Winter months Rainfall has great importance in agriculture, particularly for the Rabi crops. Wheat among them is one of the most important crops, which helps to meet India’s food security. During the season, normally 4-5 western disturbances in a month can be seen over northwest India. Some of the western disturbances bring well-distributed and good rainfall, while some pass with negligible rain or sometimes no rain. The Western disturbance affects day-to-day weather of northwest India especially during winter season. It is usually associated with cloudy sky, higher night temperatures, unusual rain etc. Over the Indo-Gangetic plains, it brings cold wave conditions and occasionally dense fog and cold day conditions. These conditions remain stable until it is disturbed by another Western Disturbances.

2.1.4 Thunderstorms/ Nor'wester

The regions of high activity for thunderstorms are the northeastern areas of the subcontinent, the Himalayas, east Madhya Pradesh and adjoining areas, south Kerala, northern parts of Pakistan, immediately east of the Aracvalli and the west coast of Sri Lanka. The Andaman Islands and perhaps also the adjoining seas have a high susceptibility to thunderstorms. The smallest frequency is over northern Kashmir, Sind and southeastern Tamilanadu, the first two being also areas of very low rainfall. The narrow belt of rather few thunderstorms, about 100km towards the plains from the foot of the Siwaliks, is very interesting. The West Coast between 15^0 and 20^0 N has a relatively smaller number of thunderstorms, in spite of the heavy rainfall. Local orography controls the development of thunderstorms. Northeastern parts of the subcontinent experience severe thunder squalls from March to May called the northeasters or kalbaisakhi noted for their destructiveness. One or two of them develop into tornadoes every year. The rainfall from March to May is mostly from thundershowers but not so the monsoon rainfall.

Nor'westers is meso-scale severe thunderstorms that occur in Bangladesh during the pre-monsoon season. These are local severe storms. Sometimes tornado cells are embedded in mother thunderstorm cloud. These severe weather events cause fairly widespread destruction of properties and loss of lives throughout Bangladesh. Economic losses are also enormous due to these weather events. Two transition periods between southwest and northeast monsoons over the India-Bangladesh-Pakistan subcontinent are characterized by local severe storms. In Bangladesh, these transition periods are known as pre-monsoon and post-monsoon seasons. Of these, it is the pre-monsoon season when most of the local severe storms occur over different parts of Bangladesh with frequent intervals. These storms are popularly known as Nor'westers or Kalbaishakhi in Bangladesh, West Bengal and Assam of India and Andhi (dust storms) in North India.

2.2 Monsoon season

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.

A monsoon is a seasonal prevailing wind which lasts for several months. The term was first used in English in India, Bangladesh, Pakistan and neighbouring countries to refer to the seasonal winds blowing from the India Ocean and Arabian Sea in the south-west bringing heavy rainfall to the region. In hydrology, monsoonal rainfall is considered to be that which occurs in any region that receives the majority of its rain during a particular season, and so monsoons are referred to in relation to other regions such as in North America, Sub-Saharan Africa, Brazil and East Asia.

The Bay of Bengal Branch of South-west Monsoon flows over the Bay of Bengal heading towards North-Eastern 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 North-Eastern 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.
- Fewer than one cyclone-anticyclone alternation occurs every two years in either month in a 5^o latitude-longitude rectangle.

In India and its surroundings, monsoon period is divided into three seasons which are a) Pre-monsoon (March to May), b) Monsoon (June to September) and c) Post-monsoon (October to November).

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^oC over most part of the country except the coastal belts where the fall is by 5-6^oC (WMO/UNDP/BGD/79/013, 1986).

2.3 Post Monsoon season

This is the transitional season from summer monsoon to the winter. Southwest monsoon begins to withdraw from the country; withdrawal is complete through October. There is a general rise of pressure and the monsoon pressure structure breaks down over the country. The monsoon low over the central India weakens and shifts towards the Bay of Bengal with its trough extending over the coastal Bangladesh.

The surface wind is very light and variable. Rainfall decreases considerably in October and in November the dry period starts setting in over the country. The district of Sylhet gets 200-250 mm of rain in October and the rest of the country gets about 100-170 mm. In November the amount of rainfall over the southeastern coastal districts amount to 25-65 mm whereas the rest of the country gets only about 10-20 mm of rain. In October there are 4-10 days of rainfall over the country and only 1-3 days in the month of November.

The mean temperature falls from 28-29^oC in September to 26-27^oC in October and to 23-25^oC in November. The highest maximum temperature hardly exceeds 29^oC and the lowest minimum does not fall below 10°C throughout the country (WMO/UNDP/BGD/79/013, 1986). Tropical cyclones form o intensity.ver the Bay of Bengal in this season and moves initially towards west and then towards northwest and at times towards northeast affecting Bangladesh coast. Some of these storms in the season may attain hurricane

2.4 Winter season

Winter season is considered as the peak season when temperature is low compare to the other time of the year. During winter season temperature fluctuates between 12 and 20°C without some exception of recent years when temperature went down below 12°C. The winter season is very dry in our country. It accounts for less than 4% of the total annual rainfall. The nights are longer than the days and January is the coldest month. In Bangladesh, the lowest temperature of winter was recorded in 1905 which was only 1°C. Winter is the season of fog and mists. Everything seems to be decrepit. Dew drops fall at night. When the morning sun peeps through the mists, they look like glittering beads of pearl on grass. The sky is cloudless and blue. Sometimes, biting cold wind blows. During this season, leaves of trees wither and drop off. So, nature looks bare. Although winter is cold, its mild weather is truly enjoyable in Bangladesh.

2.5 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.

2.5.1 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.

2.5.1.1 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 (1969) 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.

2.5.1.2 Lin *et al.* Scheme

A sophisticated scheme that has ice, snow and graupel processes, suitable for real-data high-resolution simulations. Lin *et al.* 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.

2.5.1.3 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.

2.5.1.4 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.

2.5.1.5 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.

2.5.1.6 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.

2.5.1.7 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.

2.5.1.8 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).

2.6 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.

2.6.1 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.

2.6.2 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.

2.7 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.

2.7.1 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; Hu *et al*. 2010; Hong *et al*. 2006).

2.8 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.

2.8.1 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.

2.9 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 has been used to simulate the monsoon rainfall over Bangladesh. Advance Research WRF (ARW) is a dynamic solver (Skamarock *et al.*, 2005), 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 been integrated by using initial and lateral boundary conditions (LBCs) obtained 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) and Rapid Radiative Transfer Model (RRTM) schemes have been used for short wave radiation and long wave (Mlawer *et al.* 1997) radiation respectively. Kain-Fritsch (1993) has been used for cumulus parameterization (CP) scheme.

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 107 days starting from the initial conditions at 0000UTC of 14 February to ending at 0000 UTC of 01 June during 2010-2014. However, the results are presented for March-May to avoid the spin-up effects of the first 15 days. The model has also been run during the Pre-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	3^{rd} order Runge-Kutta
Spatial differencing scheme	6^{th} 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 pre-monsoon rainfall prediction in Bangladesh

3.3 Data and Methodology

Final Reanalysis (FNL) data ($1^o x1^o$) 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 March, April and May 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 27 February to 0000 UTC of 01June 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 March, April and May using 24, 48 and 72-hours lead time prediction for the year 2014 and also using 107 day prediction during 2010-2014. The RMSE and MAE have been calculated for 33 meteorological stations, because there is no observational data for other 8 additional points. The RMSE and MAE of rainfall have been calculated for 107 days prediction using Microsoft Excel and then plotted using SURFER Software during 2010-2014. The RMSE and MAE for 24, 48, 72-hours predicted rainfall have also been plotted using the same procedure for the year 2014. The CC between observed and 24, 48, 72-hour and 107 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), frequently used, is a 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.

3.2 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

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

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

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

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

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

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

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

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

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

Chapter IV

Results and Discussion

4. Pre-monsoon Rainfall 2010-2014

In the present study, the Weather Research and Forecast (WRF-ARW V3.5.1) model have been used to simulate the station wise pre-monsoon rainfall during 2010–2014 for all over Bangladesh. Initially the model has run 107 days for 107 days prediction starting with the initial condition of 0000 UTC of 17 February up to 0000 UTC of 01 June for the period 2010-2014. The model has also run 72 hours with every day 0000 UTC initial conditions for 94 days for the prediction of 24, 48 and 72 hours lead time rainfall in the pre-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 hours and 107 days during the studied period. We have compared this data with the observed rainfall at 33 meteorological stations of BMD and TRMM rainfall. The RMSE, MAE and CC for the rainfall have been calculated. All of the above is discussed in the following sub-sections. For this purpose, GrADS, Microsoft Excel and SURFER Software have been used.

4.1 Pre-monsoon Rainfall distribution 2010-2014

After downloading TRMM data, station wise TRMM rainfall have been extracted. The model simulated rainfall is compared with the monthly observed rainfall and TRMM rainfall for the above mentioned years and discuss in the following sub-sections.

4.1.1 Distribution of Observed, TRMM and Model Simulated rainfall for 2010

The distributions of observed, TRMM and 107 days model simulated rainfall for the month of March, April and May of 2010 for all over Bangladesh are discussed in the following subsection and are shown in Figure 4.1.1(a-i).

4.1.1.1 Distribution of Observed, TRMM and Model Simulated rainfall for March 2010

From the distribution of observed rainfall for March 2010 (Fig 4.1.1a), the maximum rainfall is recorded in the northeastern and southeastern part of Bangladesh. At northeastern side, the maximum rainfall is recorded at Sylhet station which is about 220 mm. Again, in the southeastern region, maximum rainfall is also recorded at Rangamati station which is 170 mm. From the central region, the rainfall is increased towards the northeastern and southeastern region. Minimum Rainfall is recorded at all regions except northeastern and southeastern part of Bangladesh. In these regions, the rainfall is almost 0 mm.

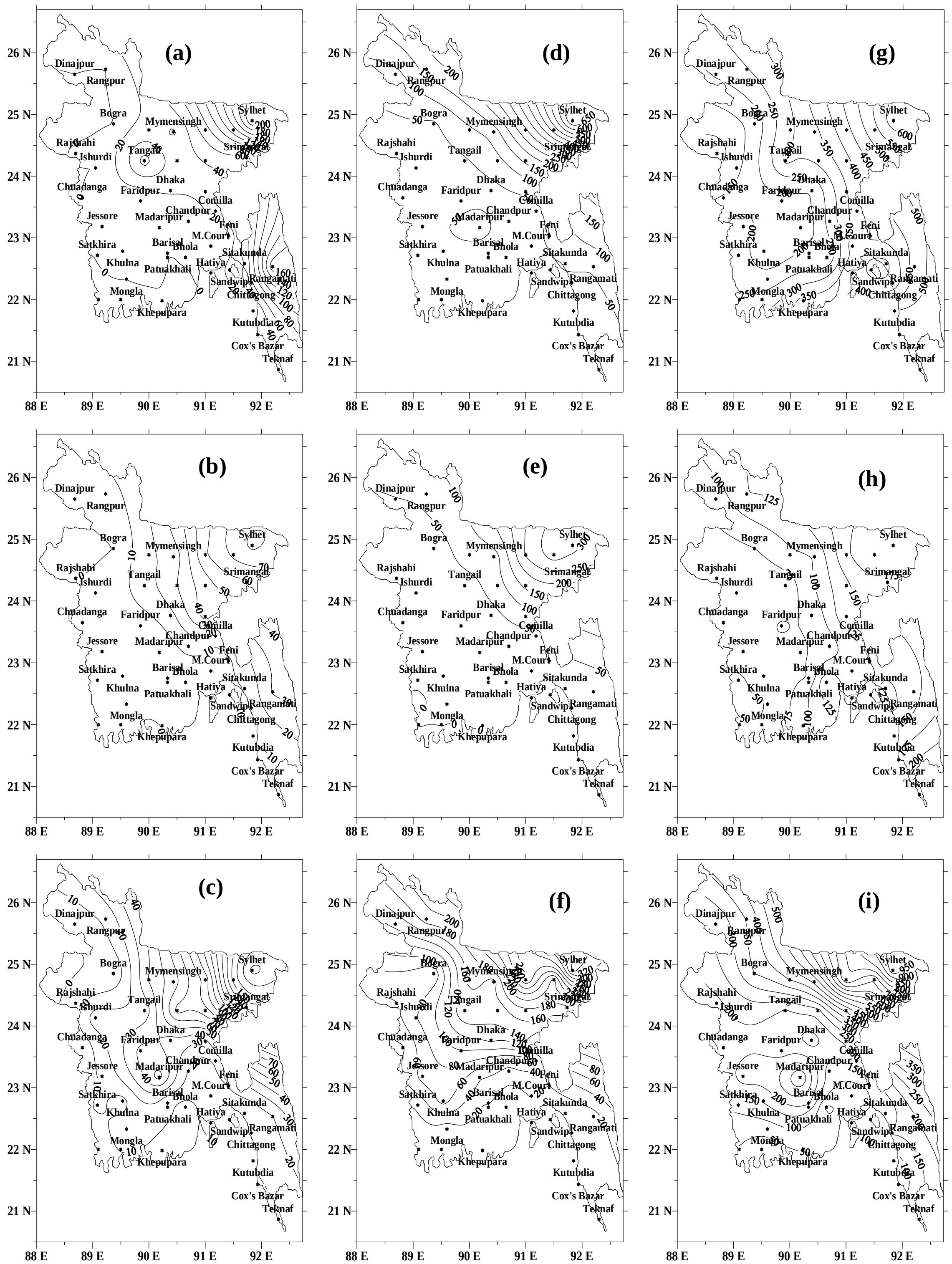

Fig. 4.1.1: Distribution of Observed, TRMM and Model simulated rainfall for the month of March (a-c), April (d-f) and May (g-i) 2010 all over Bangladesh

From the distribution of TRMM rainfall of March 2010 (Fig. 4.1.1b), the maximum rainfall is recorded in the northeastern part of Bangladesh. In this region, Sylhet station shows the maximum rainfall which is near about 80 mm and Srimangal shows about 60 mm rainfall. From the central region, the rainfall is increased towards the northeastern part. In southeastern region, Rangamati station has recorded 25 mm rainfall in this month. From the northwestern to southwestern region as a whole western region TRMM has recorded minimum rain and it is almost 0 mm.

From the 107 days prediction of rainfall of March 2010 (Fig. 4.1.1c), the maximum rainfall is simulated in the northeastern region at Sylhet and Srimangal stations are 180 and 140 mm respectively. From northeastern region the rainfall is decreased towards the western region of Bangladesh. In the 107 days 107 days prediction, minimum rainfall is simulated at Bogra, Chuadanga, Dinajpur and Rajshahi and it is about 1-5 mm. In the southwestern region at Khulna and Khepupara, the rainfall is also decreased and it is about 5mm.

From the analysis of observed, TRMM and 107 days prediction of rainfall for March 2010, it has found that the maximum rainfall has been found in northeastern region and minimum has been found in the west, southwest and northwest regions of the country. The pattern of observed and 107 days prediction rainfall is found almost similar but the value of rainfall obtained from TRMM is much lowering than that of obtained from observed and 107 days prediction. The rainfall for 107 days prediction and observed has been seen much higher value in northeastern region than those obtained from TRMM. Nevertheless, the basic features of observed and simulated rainfall distributions in all the data sets are almost similar except TRMM rainfall.

4.1.1.2 Distribution of Observed, TRMM and Model Simulated rainfall for April 2010

From the distribution of observed rainfall for April 2010 (Fig 4.1.1d), the maximum rainfall is recorded in the northeastern part at Sylhet and Srimangal stations which is more than 650 mm and 250 mm. In the northwestern, rainfall is recorded about 150 mm and almost 100 mm at Rangpur and Dinajpur stations respectively. Whole western and southern regions of Bangladesh have recorded minimum amount of rain. Less than 50 mm rain has observed in the maximum region of the country.

From the distribution of TRMM rainfall of April 2010 (Fig. 4.1.1e), the maximum rainfall is recorded at northeastern region at Sylhet station which is near about 320 mm and at Srimangal station is near about 200 mm. In the northwestern region at Dinajpur and Rangpur stations is recorded 50-60 mm rainfall. In the northeastern region, the rainfall is decreased towards the southwestern region of Bangladesh. In the southwestern region at Satkhira and Khulna stations recorded rainfall is about 1-3 mm where as in the southern region at Mongla and Khepupara stations recorded minimum rainfall is about 0 mm.

From the 107 days prediction of rainfall of April 2010 (Fig. 4.1.1f), the maximum rainfall is simulated in the northeastern part at Sylhet station which is near about 340 mm and at Srimangal station rainfall is more than 175 mm. The maximum rainfall is also simulated in the north and northwestern part. In the hellion region, the rainfall is decreased towards the oceanic region of Bangladesh. In the southeastern region at Kutubdia and Cox's Bazar stations have near about 5 mm rainfall and Chittagong and Teknaf stations have near about 2 mm rainfall. In the southern region at Khepupara and Mongla stations have near about 10-15 mm rainfall.

From the analysis of observed and TRMM rainfall for April 2010, it can be concluded that the rainfall is found maximum in northeastern region and minimum in the west, northwest, southwestern and southeastern regions of the country. The pattern of TRMM and observed rainfall are found almost similar but the value of the rainfall obtained from TRMM is much lowering than that of observed. The rainfall for 107 days prediction is simulated maximum in northeastern region and minimum in western, southern and southeastern regions. The rainfall for TRMM and 107 days prediction has been seen much lower value than observed rainfall in northeastern region.

4.1.1.3 Distribution of Observed, TRMM and Model Simulated rainfall for May 2010

From the distribution of observed rainfall for May 2010 (Fig. 4.1.1g), the maximum rainfall is recorded in the northeastern region at Sylhet station which is about more than 600 mm and at Srimangal station it is more than 500 mm. From the central region the rainfall is increased towards the northeastern and southeastern region. In the southeastern at Chittagong, Cox's Bazar, Teknaf, Kutubdia and Rangamati stations which is about 400-500 mm. From the central part to western part, rainfall is recorded minimum and at Rajshahi station it is recorded near about 80 mm. In the north-western region at Dinajpur, Rangpur, Rajshahi, Ishurdi and Chuadanga stations, rainfall is recorded minimum which is about 150-250 mm.

From the distribution of TRMM rainfall for May 2010 (Fig. 4.1.1h), the maximum rainfall is recorded in the northeastern and southeastern part of Bangladesh. In the northeastern part at Sylhet and Srimangal stations rainfall is recorded 160-180 mm. In the southeastern region at

Teknaf station rainfall is recorded more than 250 mm where as at Sandwip, Rangamati and Cox's Bazar stations rainfall is recorded 140-180 mm. In the western region, rainfall is recorded minimum. At Rajshahi, Ishurdi and Chuadanga stations rainfall is about 50-60 mm. In the southern region at Khulna, Satkhira and Mongla station, rainfall is also about 50-70 mm.

From the 107 days prediction rainfall for May 2010 (Fig. 4.1.1i) is simulated maximum in the northeastern region at Sylhet and Srimangal stations is near about 1000 and 600 mm respectively. In the north and northwestern regions, maximum rainfall is also simulated at Mymensingh, Tangail, Rangpur and Bogra station and which is about 300-500 mm. From the central region the rainfall is decreased towards the southeastern and southern region of Bangladesh. In the southern region at Bhola, rainfall is near about 40 mm and at Khepupara and Mongla it is about 50-70 mm. In the southeastern region, minimum rainfall is simulated at Cox's Bazar and Kutubdia and it is about 60-70 mm.

From the analysis of observed and TRMM rainfall for May 2010, it has been found that the rainfall is found maximum in northeastern and southern region and minimum in the central to northwest, west and southwest regions of the country. The pattern of TRMM and observed rainfall are found almost similar but the value of TRMM rainfall is much lower than the observed rainfall. The rainfall for 107 days prediction is simulated maximum in northeastern region and minimum in west, southwest and southern regions. The rainfall for observed and 107 days prediction has been found much higher value in northeastern region than that of TRMM. Simulated rainfall distributions in all the data sets are not similar with observed and TRMM rainfall.

4.1.2 Distribution of Observed, TRMM and Model Simulated rainfall for 2011

The distributions of observed, TRMM and 107 days model simulated rainfall for the month of March, April and May of 2011 for all over Bangladesh are discussed in the following subsection and are shown in Figure 4.1.2(a-i).

4.1.2.1 Distribution of Observed, TRMM and Model Simulated rainfall for March 2011

From the distribution of observed rainfall for March 2011 (Fig. 4.1.2a), the maximum rainfall is recorded at southeastern region at Sitakunda which is near about 170 mm and at Sandwip is about 140 mm and at Comilla, Feni and Hatiya is about 60-70 mm. In the northeastern region at Sylhet and Srimangal also has recorded maximum rainfall which is about 60-100 mm. The minimum rainfall is recorded in the northwestern part at Dinajpur, Rangpur, Bogra, Rajshahi

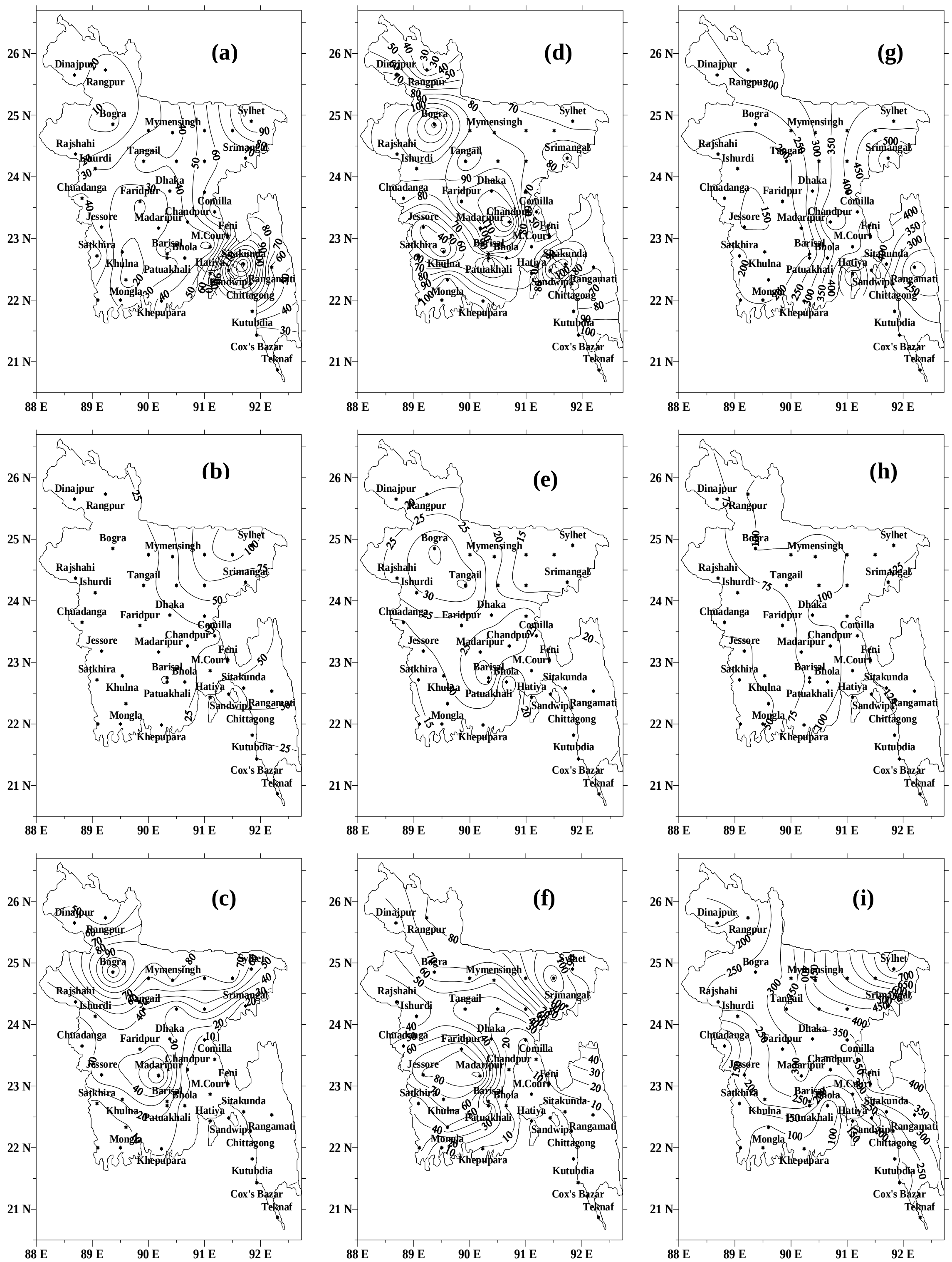

Fig. 4.1.2: Distribution of Observed, TRMM and Model simulated rainfall for the month of March (a-c), April (d-f) and May (g-i) 2011 all over Bangladesh

and Ishurdi station which is about 5-20 mm. In the southwestern region at Khulna and Mongla stations have also recorded minimum rainfall which is near about 20 mm in this month.

From the distribution of TRMM rainfall for March 2011 (Fig. 4.1.2b), the maximum rainfall is recorded in the northeastern part at Sylhet station has recorded more than 100 mm rainfall. In the southeastern region at M.court, Hatiya, Sandwip and Sitakunda stations also recorded rainfall is about 50-60 mm. From the eastern, northeastern region the rainfall is decreased towards the western region. So, the minimum rainfall is simulated at the western, northwestern, southwestern and southern region of Bangladesh and the amount of rain is low.

From the 107 days prediction rainfall for March 2011 (Fig.4.1.2c), the maximum rainfall is simulated in the northwestern region at Bogra station which is more than 120 mm. In the central region at Madaripur station, rainfall is about 70 mm. significant change of 107 days predicted rainfall has been found from Madaripur to Bhola. From central part the rainfall is decreased towards the southeastern region of Bangladesh. The minimum rainfall is simulated in the southeastern region at Bhola, Chittagong, Kutubdia and Cox's Bazzar which is near about 3-4 mm and at Rangamati, simulated rainfall is near about 1mm.

From the analysis of observed, TRMM and 107 days prediction of rainfall for March 2011, it can be concluded that the maximum value of TRMM and 107 days prediction rainfall are all most similar but the maximum rainfall region are not similar. The maximum rainfall has been found in southeastern, northeastern and northwestern regions and minimum value of rainfall has been found in the west, southwest, northwest and central regions of the country. The pattern of TRMM and observed rainfall are not similar and the value of observed rainfall is much higher value than those of 107 days and TRMM rainfall. Finally, it may be concluded that amount of rainfall obtained from TRMM is always less than that obtained from observation as well as model simulation. Again, rainfall has a spatial difference for the maximum and minimum position for all cases.

4.1.2.2 Distribution of Observed, TRMM and Model Simulated rainfall for April 2011

From the distribution of Observed rainfall for April 2011 (Fig. 4.1.2d), the maximum rainfall is recorded at different region. From the northwestern part to south and central region to southern region of Bangladesh recorded maximum rainfall. In the northwestern region at Bogra station recorded highest rainfall which is near about 150 mm, in the central region is about 100-110 mm and in the southern region is near about 120 mm. In this figure the minimum rainfall recorded at eastern part of Comilla station which is about 25 mm and minimum rainfall also recorded at different station at Rangpur, Jessore and Khulna is about 25-30 mm.

From the distribution of TRMM rainfall for April 2011 (Fig.4.1.2e), the maximum rainfall has simulated at the central region at Barisal, Madaripur, Patuakhali and Chandpur station which is about 30 mm and maximum rainfall also simulated northwestern part at Tangail and Bogra station which is near about 40 mm. From the central region towards northeastern region the rainfall is decreased i.e. Sylhet and Srimangal station simulated minimum rainfall which is about 15 mm. Significant change of TRMM rainfall has found from Patuakhali to Bhola. So the Bhola station simulated minimum rainfall which is near about 10 mm.

From the 107 days prediction rainfall for April 2011 (Fig. 4.1.2f), the maximum rainfall is simulated the northeastern and northern part i.e. Srimangal is more than 105 mm, Sylhet and Mymensingh is more than 80 mm. In the central region at Madaripur is about 95 mm and Faridpur is about 80 mm. From central region rainfall is also increased towards the southwestern part at Jessore and Khulna is about 70-80 mm. In the southeastern region is simulated the minimum rainfall at Teknaf, Rangamati, Kutubdia and Chittagong is near about 3-4 mm and Sitakunda, Cox’s Bazzar is near about 5 mm.

From the analysis of observed and TRMM rainfall for April 2011, it can be concluded that the rainfall is found maximum in north northwest, central and southern region and minimum in the northeast and western region of the country. The pattern of TRMM and observed rainfall are almost similar. The rainfall for 107 days prediction is simulated maximum in northeastern and central regions and minimum in north northwestern and southeastern regions. The rainfall for observed and 107 days prediction has been seen much higher value than that of TRMM rainfall. Nevertheless, the basic features of observed and TRMM rainfall distributions in all the data sets are almost similar but 107 days model simulated rainfall pattern is not similar.

4.1.2.3 Distribution of Observed, TRMM and Model Simulated rainfall for May 2011

From the distribution of observed rainfall for May 2011 (Fig. 4.1.2g), the maximum rainfall is recorded in the northeastern part at Sylhet station and the amount is more than 400 mm. Again, at Srimangal station records more than 600 mm. In the southeastern region also records maximum rainfall at Comilla, Feni, Hatiya, M.court and Sandwip station and its value is 350-550 mm. From the central part to western, northwestern and southwestern part records minimum rainfall. In the northwestern region at Rajshahi, Ishurdi, Jessore and Chuadanga records about 150 mm rainfall. In the southwestern region, also records about 150-200 mm rainfall.

From the distribution of TRMM rainfall for May 2011 (Fig. 4.1.2h), the maximum rainfall is recorded in the northeastern region at Sylhet and Srimangal stations and the value is 120-130 mm. In the southeastern region at Teknaf, Sandwip, Rangamati, Sitakunda, Chittagong, Feni, Hatiya and Cox's Bazzar stations records maximum rainfall and their value are 120-140 mm. From the central part to northwestern and southwestern part, minimum rainfall is recorded. In the central part, recorded is about 50-70 mm rainfall. In the western region, Rajshahi, Ishurdi and Chuadanga stations records minimum rainfall, which is about 50-60 mm and in the southern region Khulna, Satkhira and Mongla station rainfall is also about 40-60 mm.

From the 107 days prediction of rainfall for May 2011 (Fig. 4.1.2i), the maximum rainfall has been simulated in the northeastern region, at Sylhet station which more than 750 mm and at Srimangal station it is more than 400 mm. In northern part at Mymensingh station also records maximum rainfall which is more than 450 mm. From the central region the rainfall is decreased towards the southeastern and southern region. At Bhola, Khepupara and Mongla simulates the minimum rain which is near about 50-100 mm. In the northwestern part at Chuadanga station also simulates minimum rainfall which is about 50 mm.

From the analysis of observed and TRMM rainfall for May 2011, it has found that the rainfall is found maximum in northeastern and southeastern regions and minimum in the west and northwestern and southwestern regions of the country. The 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 107 days prediction is simulated maximum in northeastern region and minimum in northwestern and southwestern regions. The rainfall for observed and 107 day's prediction has been found much higher value than that of TRMM rainfall in northeastern region. Simulated rainfall distributions in all the data sets are similar with that of observed TRMM and 107 days rainfall.

4.1.3 Distribution of Observed, TRMM and Model Simulated rainfall for 2012

The distributions of observed, TRMM and 107 days model simulated rainfall for the month of March, April and May of 2012 for all over Bangladesh are discussed in the following subsection and are shown in Figure 4.1.3(a-i).

4.1.3.1 Distribution of Observed, TRMM and Model Simulated rainfall for March 2012

From the distribution of observed rainfall for March 2012 (Fig. 4.1.3a), the Maximum rainfall is recorded in the northeastern part at Sylhet station which is more than 90 mm. In the southeastern region also records maximum rainfall at Cox's Bazzar and Rangamati station which is near about 110 mm and 75 mm. From the central part towards northwest and southwest part, rainfall is recorded minimum. In the northwestern region at Dinajpur, Rangpur and Bogra and the southwestern region Satkhira, Khulna stations record minimum rainfall.

From the distribution of TRMM rainfall for March 2012 (Fig. 4.1.3b), the maximum rainfall is recorded in the southeastern region at Cox's Bazzar and Kutubdia station which is more than 16 mm and in the northeastern region at Sylhet and Srimangal stations record 10-13 mm rainfall. From the central part to northwestern part, rainfall is recorded minimum. In the central part at Barisal, Faridpur and Madaripur stations, rainfall is about 2-5 mm. Again, in the western region at Rajshahi, Ishurdi and Chuadanga stations records minimum rainfall.

From the 107 days prediction rainfall for March 2012 (Fig. 4.1.3c), the maximum rainfall has been simulated in the southern region at Khepupara station which is more than 80 mm and at Cox's Bazzar, Kutubdia, Sandwip and Sitakunda it is about 40-50 mm. In the central region at Barisal, Madaripur and Patuakhali stations simulate 30-40 mm rain. From the southeastern part to northern and northwestern regions, the rainfall is decreased. In the northwestern region at Rajshahi, Chuadanga, Ishurdi and Rangpur stations simulate minimum rainfall.

From the analysis of observed and TRMM rainfall for March 2012, it can be concluded that the rainfall is found maximum in southeastern and northeastern region and minimum in the north, west and northwest regions of the country. The pattern of TRMM and observed rainfall are almost similar but the value of TRMM observed rainfall is much lower than that of observed rainfall. The rainfall for 107 days prediction is simulated maximum in southern and southeastern regions and minimum in north northwestern region. The rainfall for observed and 107 days has been seen much higher value than that of TRMM rainfall in south southeastern regions.

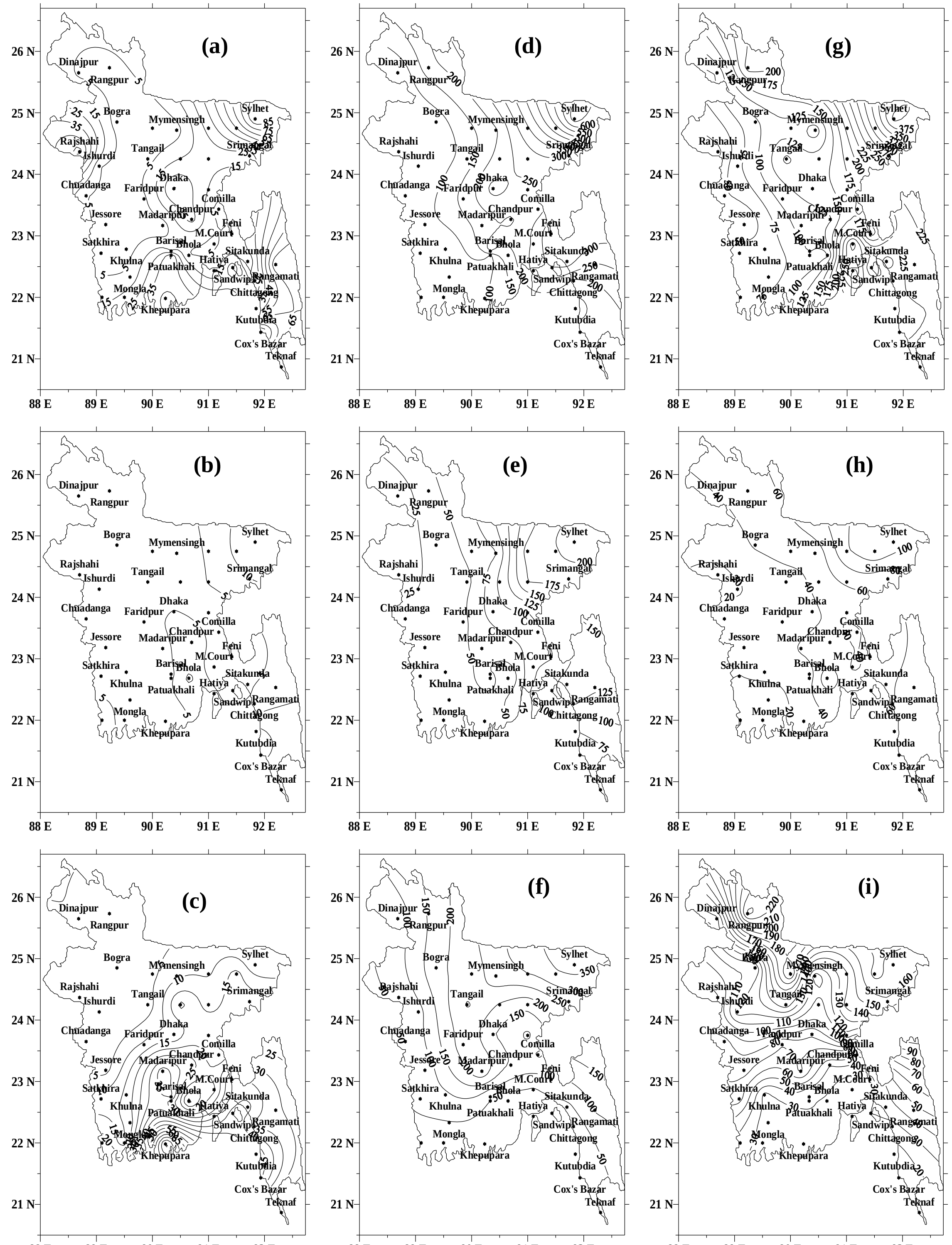

Fig. 4.1.3: Distribution of Observed, TRMM and Model simulated rainfall for the month of March (a-c), April (d-f) and May (g-i) 2012 all over Bangladesh

4.1.3.2 Distribution of Observed, TRMM and Model Simulated rainfall for April 2012

From the distribution of observed rainfall for April 2012 (Fig.4.1.3d), the maximum rainfall has been recorded in the northeastern part at Sylhet station which is more than 650 mm. The maximum rainfall is also recorded in the southeastern region at Cox's Bazzar, Feni and Sitakunda stations and it is near about 300-350 mm. From the central part to western part has recorded minimum rainfall. In the northwestern region at Dinajpur, Rajshahi, Ishurdi and Bogra station records minimum rainfall which is about 60-70 mm and the southwestern region at Satkhira and Khulna stations also records minimum rainfall.

From the distribution of TRMM rainfall for April 2012 (Fig. 4.1.3e), the maximum rainfall is recorded in the northeastern region at Sylhet and Srimangal station which is about 190-210 mm and southeastern region at Feni, Hatiya, Sandwip, Rangamati, M.court and Sitakunda stations which is about 100-140 mm. From the central part to west and northwestern part has recorded minimum rainfall. In the central part minimum rainfall is about 50-60 mm and in the western region at Rajshahi, Ishurdi and Chuadanga stations has recorded minimum rainfall which is about 10-40 mm.

From the 107 days prediction rainfall for the month of April 2012 (Fig. 4.1.3f), the maximum rainfall is simulated in the northeastern and northern region at Sylhet which is near about 375 mm and Srimangal, Tangail and Mymensingh stations it is near about 260- 270 mm. In the central region is near about 220-240 mm. In the northwestern region at Bogra and Rangpur stations, rainfall is near about 160-180 mm. From the central region the rainfall is decreased towards the southern region. The minimum rainfall is simulated in the southern and southeastern regions which is about 20-45 mm.

From the analysis of observed and TRMM rainfall for April 2012, it can be concluded that the rainfall is found maximum in northeastern and southeastern region and minimum in the west, northwest and southwestern 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 107 days prediction is simulated maximum in north northeastern region and minimum in south, southwestern and southeastern regions. The rainfall for observed has been seen much higher value than those of 107 days prediction and TRMM rainfall in northeastern and southeastern regions.

4.1.3.3 Distribution of Observed, TRMM and Model Simulated rainfall for May 2012

From the distribution of observed rainfall for May 2012 (Fig. 4.1.3g), the maximum rainfall is recorded in the northeastern part at Sylhet station which is more than 400 mm and Srimangal is about 280 mm. In the southeastern region has also recorded maximum rainfall at Cox's Bazzar, Chittagong, Feni, Hatiya and Sitakunda stations which is near about 250-300 mm rain. From the central part to western part recorded minimum rainfall. In the northwestern region at Dinajpur, Rajshahi, Ishurdi, Jessore and Chuadanga stations which is about 20-80 mm.

From the distribution of TRMM rainfall for April 2012 (Fig. 4.1.3h), the maximum rainfall is recorded in the northeastern region at Sylhet and Srimangal station which is about 60-110 mm and in the southeastern region at Bhola, Cox's Bazzar, Chittagong and Kutubdia stations which is about 60-75 mm. From the central part to west and northwestern part, the rainfall is decreased. So, the minimum rainfall is recorded in the western region at Rajshahi, Ishurdi, Jessore and Chuadanga stations which is about 10-40 mm. Again, in the south, southwestern region at Satkhira, Khulna, Mongla and Khepupara stations which is about 10-25 mm.

From the 107 days prediction rainfall for May 2013 (Fig. 4.1.3i), the maximum rainfall is simulated the northern, northwestern and northeastern part of Bangladesh. In the northwestern part at Rangpur stations has simulated highest rainfall which is more than 230 mm and at Dinajpur, Bogra and Ishurdi stations has simulated 110-125 mm and the northern region at Tangail and Mymensingh stations has about 100-140 mm. In the northeastern part Sylhet and Srimangal stations has also simulated more than 160 mm. The minimum rainfall is simulated in the southeastern region at Cox's Bazar, Feni, Hatiya, Kutubdia, Sandwip and Sitakunda which is about 10-30 mm. In the southern region minimum rainfall is also simulated at Khulna and Mongla stations which are about 25-30 mm.

From the analysis of observed and TRMM rainfall for May 2012, it can be concluded that the rainfall is found maximum in northeastern and southern regions and minimum in the west, northwest and southwestern regions of the country. The pattern of TRMM and observed rainfall are found almost similar but the value of TRMM observations is much lower than that of observed rainfall. The rainfall for 107 days prediction is simulated maximum in north northeastern and northwestern region and minimum in south, southwestern and southeastern region. In the northeastern region, the rainfall for observed has been seen much higher value than those of 107 days prediction and TRMM rainfall.

4.1.4 Distribution of Observed, TRMM and Model Simulated rainfall for 2013

The distributions of observed, TRMM and 107 days model simulated rainfall for the month of March, April and May of 2013 for all over Bangladesh are discussed in the following subsection and are shown in Figure 4.1.4(a-i).

4.1.4.1 Distribution of Observed, TRMM and Model Simulated rainfall for March 2013

From the distribution of observed rainfall for March 2013 (Fig. 4.1.4a), the maximum rainfall is recorded in the southern region at Hatiya station which is more than 300 mm. From the eastern part to western, northwestern, northeastern and eastern region has recorded minimum amount of rainfall. The maximum region of the country has observed less than 5 mm of rainfall.

From the distribution of TRMM rainfall for March 2013 (Fig. 4.1.4b), the maximum rainfall is recorded in the central region at Dhaka, Tangail, Madaripur, Patuakhali and Chandpur stations which is about 10-15 mm. From the central region to northeastern, southern and southeastern region has recorded minimum rainfall. From the southern region at Khepupara, northwestern region at Dinajpur, Rajshahi and southeastern region of Bhola, Cox’s Bazar and Kutubdia stations has recorded minimum rainfall.

From the distribution of 107 days prediction rainfall for March 2013 (Fig. 4.1.4c), the maximum rainfall has been simulated in the central region at Chandpur station which is more than 30mm. In the northeastern region at Sylhet and Mymensingh is near about 2-3 mm. From central part the rainfall is decreased towards the northwestern and southeastern region. So, the minimum rainfall is simulated at Dinajpur, Rangpur, Rajshahi, Ishurdi and Chuadanga stations which is about 0 mm. The minimum rainfall is also simulated in the southeastern region at Rangamati which is near about 0 mm and at Cox’s Bazar, Kutubdia, Teknaf and Chittagong stations; it is near about 1-1.5 mm.

From the analysis of TRMM and 107 days prediction rainfall for March 2013, it can be concluded that the rainfall is found maximum in central region and minimum in the northwestern and southeastern region of the country. The pattern of TRMM and 107 days prediction rainfall are almost similar. The rainfall for 107 days prediction is simulated maximum in south and southeastern regions, and minimum in north, northwest and western regions. The rainfall for observed has been seen much higher value than those of TRMM and 107 days prediction rainfall.

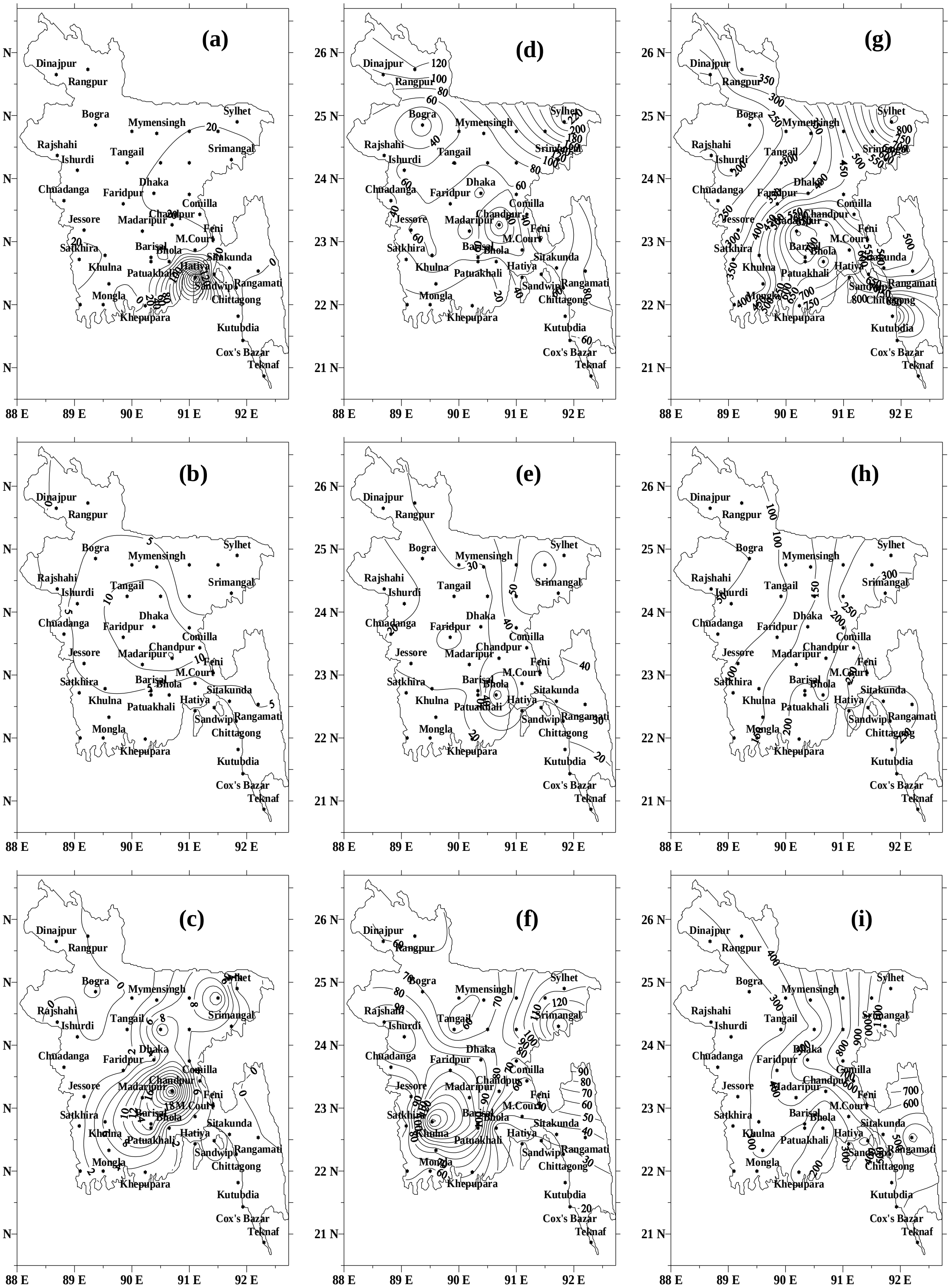

Fig. 4.1.4: Distribution of Observed, TRMM and Model simulated rainfall for the month of March (a-c), April (d-f) and May (g-i) 2013 all over Bangladesh

4.1.4.2 Distribution of Observed, TRMM and Model Simulated rainfall for April 2013

From the distribution of observed rainfall for April 2013 (Fig. 4.1.4d), the maximum rainfall is recorded at different regions. In the northeastern region at Sylhet and Srimangal stations record highest rainfall which is near about 110-230 mm, in the northwestern region at Dinajpur and Rangpur station and in the central region at Chandpur station record maximum rainfall which is near about 100-140 mm. In this figure, the minimum rainfall is recorded at whole southern region. The maximum region of the country has observed minimum rainfall.

From the distribution of TRMM rainfall for April 2013 (Fig. 4.1.4e), the maximum rainfall is recorded at the northeastern region at Sylhet and Srimangal stations which is more than 50 mm. From the southern region at Bhola station has recorded maximum rainfall which is about 70 mm. From the central region to northwestern, southwestern and southeastern regions record minimum rainfall. From the southwestern, northwestern and southeastern region has recorded minimum rainfall which is about 10-20 mm.

From the 107 days prediction rainfall for April 2013 (Fig. 4.1.4f), the maximum rainfall has been simulated in the southwestern region at Khulna station which is near about 180 mm, in the northeastern region at Sylhet, Srimangal stations which is about 105, 150 mm and in the central region also which is about 105-110 mm. From the central region, the rainfall is decreased towards the south and southeastern regions. So, in the southern region at Bhola and Hatiya and in the southeastern region at Sitakunda, Rangamati, Sandwip, Chittagong and Kutubdia stations has simulated minimum rainfall which is about 10-35 mm.

From the analysis of observed and TRMM rainfall for April 2013, it can be concluded that the rainfall is found maximum in northeastern region and minimum in the central to northwest and west and southwestern region of the country. The pattern of TRMM and observed rainfall are almost similar. The rainfall for 107 days prediction is simulated maximum in northeastern and southwestern regions, and minimum in west, northwestern and southeastern regions. In the northeastern region, the rainfall for observed and 107 day's prediction has been seen higher value than that of TRMM rainfall.

4.1.4.3 Distribution of Observed, TRMM and Model Simulated rainfall for May 2013

From the distribution of observed rainfall for May 2013 (Fig. 4.1.4g), the maximum rainfall is recorded in the southeastern region at Kutubdia which is more than 1100 mm and at Cox's Bazar, Chittagong, M. Court, Hatiya and Teknaf stations which is near about 650-750 mm. In the central part have also recorded maximum rainfall which is about 650-750 mm and in the northeastern region at Sylhet and Srimangal stations, rainfall is more than 850 and 550 mm respectively. In the northwestern region has recorded minimum rainfall at Dinajpur, Rajshahi, Ishurdi and Chuadanga stations which is about 200-250 mm.

From the distribution of TRMM rainfall for May 2013 (Fig. 4.1.4h), the maximum rainfall is recorded at the northeastern region at Sylhet and Srimangal stations which is more than 280-300 mm. From the southeastern region at Cox's Bazar, Chittagong, Rangamati and Kutubdia stations have also recorded maximum rainfall which is about 230-270 mm. From the central region to northwestern region has recorded minimum rainfall which is about 40-80 mm rainfall at Dinajpur, Bogra, Ishurdi, Chuadanga and Rajshahi stations.

From the 107 days prediction rainfall for May 2013 (Fig. 4.1.4i), the maximum rainfall has been simulated in the northeastern part at Sylhet and Srimangal stations which is near about 1200 mm. From the central region, the rainfall is decreased towards the northwestern and southwestern regions. In the northwestern region at Dinajpur, Bogra, Chuadanga and Rajshahi stations has simulated minimum rainfall which is about 200-250 mm and in the southern region at Khepupara station which is about 200 mm rainfall.

From the analysis of TRMM and 107 days prediction rainfall for May 2013, it can be concluded that the rainfall is found maximum in northeastern and southeastern regions, and minimum in the central to northwest and west and southwestern regions of the country. The pattern of TRMM and 107 days prediction rainfall are almost similar. The rainfall for observed is simulated maximum in northeastern and central to southeastern region and minimum in west and northwestern regions. The rainfall for observed and 107 days prediction has been seen much higher value and almost similar than that of TRMM rainfall and its values is very low.

4.1.5: Distribution of Observed, TRMM and Model Simulated rainfall for 2014

The distributions of rainfall for observed, TRMM, and model simulated rainfall for 24. 48, 72 hours lead time and 107 days prediction for the month of March April and May of 2014 for all over Bangladesh are discussed in the following subsection and are shown in Figure 4.1.5(a-f).

4.1.5.1: Distribution of Observed, TRMM and Model Simulated rainfall for March 2014

From the distribution of observed rainfall for March 2014 (Fig. 4.1.5a), the maximum rainfall has been seen at the northeastern region and minimum rainfall is found in southern, southeast and northwestern region of the country. Sylhet station recorded more than 75 mm and Chuadanga, Srimangal and M. Court recorded near about 50-60 mm rainfall during the month of March 2014. The minimum rainfall recorded at Rangpur, Dinajpur, Faridpur, Madaripur, Khulna, Mongla, Patuakhali, Teknaf and Cox's Bazar region which is near about 0-5 mm.

From the distribution of TRMM rainfall for March 2014 (Fig.4.1.5b), the maximum rainfall is observed at different region. But in the southeastern region, maximum rainfall is simulated at Sitakunda which is near about 12 mm. Again, in the northeastern region, maximum rainfall is also observed at Sylhet and Srimangal which is near about 8-10 mm. In the western region of Bangladesh, maximum rainfall is also observed at Chuadanga, Jessore, Faridpur and Ishurdi which is about 7-9 mm. In the northwestern part of Bangladesh Dinajpur and Rangpur station, TRMM observed minimum rainfall. In the oceanic region Kutubdia, Cox's Bazzar and Teknaf station also observed minimum rainfall which is about 0 mm.

The 24 hours predicted rainfall for March 2014 (Fig. 4.1.5c), the maximum rainfall have been simulated in the south, southwestern parts and from central parts to north northwestern and northeastern parts have been simulated minimum rainfall in this month. The maximum value has been simulated at Patuakhali and Barisal region which is more than 75 mm. Significant change of 24 hours predicted rainfall has found from Patuakhali to Bhola. 24 hours predicted rainfall is simulated minimum rain from central to northern, northeastern and northwestern region and its value is 10-20 mm.

From the distribution of 48 hour lead time predicted rainfall for March 2014 (Fig.4.1.5d), the maximum rainfall is simulated at Khulna region which is about 55 mm. About 40-50 mm rainfall is simulated in the central to western part of Bangladesh. Rainfall is decreased from Khulna region to the north and northwest part and the minimum rainfall is simulated at Dinajpur station which is near about 0 mm. It is also decreased towards the southeast part of Bangladesh and in this region the rainfall of Rangamati is about 10 mm and Kutubdia is about 5 mm and Teknaf is near about 1 mm.

From the distribution of 72 hours lead time prediction rainfall for March 2014 (Fig. 4.1.5e), the maximum rainfall is simulated at the central region at Barisal station which is more than 75 mm and at Dhaka, Ishurdi, Khulna, Madaripur and Patuakhali station, the total rainfall is near about 40-45 mm. From Barisal station towards the northern and southeastern part of Bangladesh, the rainfall is decreased.

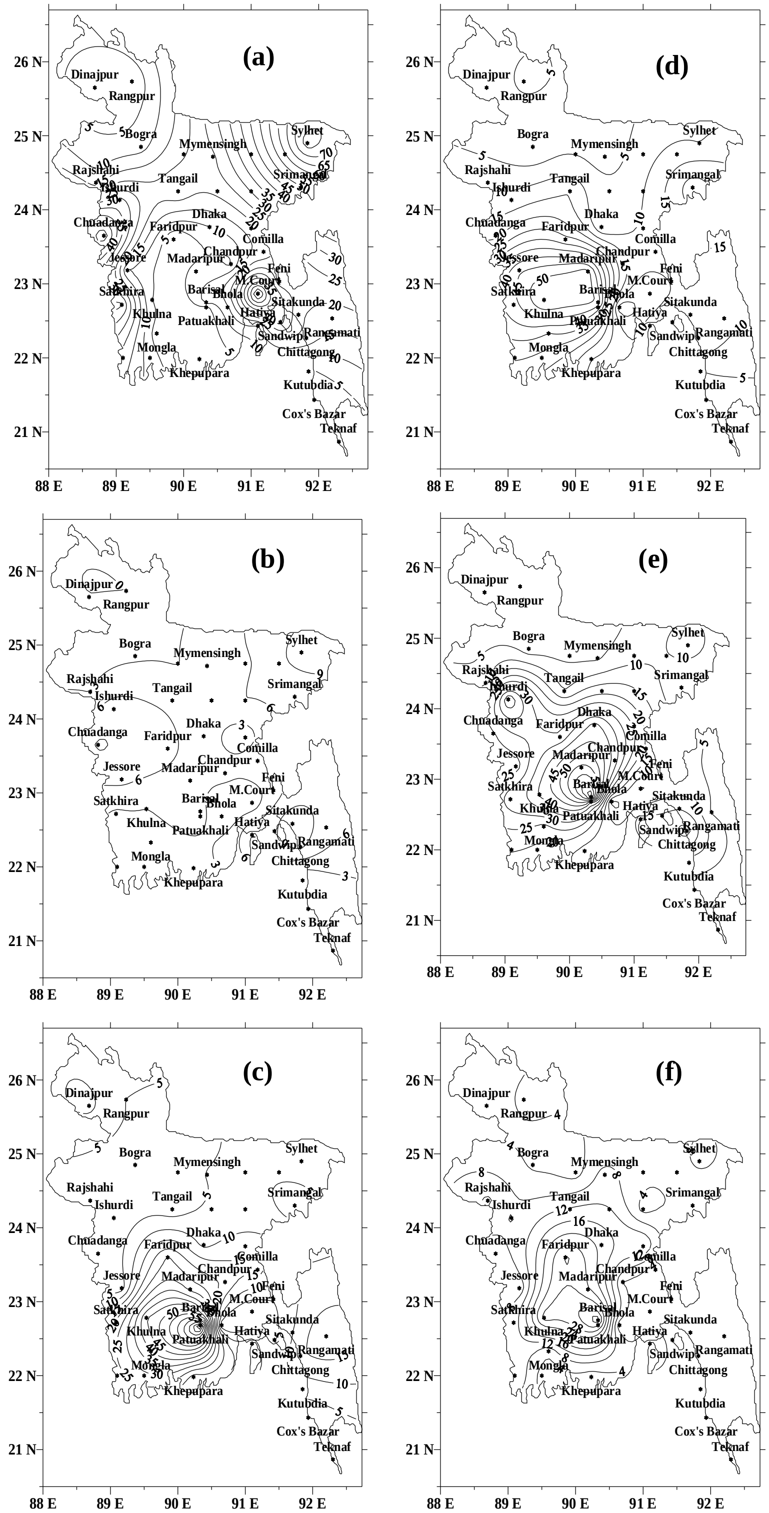

Fig. 4.1.5: Distribution of (a) Observed, (b) TRMM, (c) 24, (d) 48, (e) 72 hours and (f) 107 days model simulated rainfall for the month of March 2014 all over Bangladesh

In the northwestern part, the minimum rainfall is simulated at Rangpur, Dinajpur and Bogra station which is near about 3 mm. In the southeastern region, the minimum rainfall is simulated at Cox’s Bazar and Teknaf station which is near about 3mm.

From the 107 days prediction rainfall for March 2014 (Fig. 4.1.5f), the maximum rainfall is simulated at the central part at Barisal station which is more than 35 mm and that at Madaripur, Faridpur, Patuakhali and Khulna station is near about 25-30 mm. Rainfall is also decreased from Barisal towards the southeastern part and the minimum rainfall is simulated at southeastern part. In this part at Rangamati, simulated minimum rainfall is 0 mm, and at Bhola, Comilla and Teknaf it is near about 1 mm. The minimum rainfall is also simulated at northwestern region and at Dinajpur which is near about 0 mm.

The pattern of TRMM and observed rainfall for March 2014 are almost similar but the value of TRMM observations is much lower than that of observed rainfall and the pattern of 24, 48, 72 hours and 107 days prediction of rainfall are also almost similar to each other but their values are different among them. From the analysis of 24, 48, 72 hours and 107 days prediction of rainfall, it has found that the rainfall is minimum in the west and north northwest regions of the country. The maximum value has been simulated in central and southern regions. The rainfall for 107 days prediction has been seen much lower 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 not similar each other and the value of model simulated rainfall is much lower than observed rainfall in the southern region.

4.1.5.2 Distribution of Observed, TRMM and Model Simulated rainfall for April 2014

From the distribution of observed rainfall for April 2014 (Fig. 4.1.6a), the maximum rainfall has been recorded in the northeastern at Sylhet which is more than 110 mm and in the northern region at Mymensingh is about 70 mm. The minimum rainfall has been recorded in the western and southwestern at Satkhira, Khulna, Jessore and Chuadanga region which is near about 0 mm. The minimum rainfall has been seen at Feni is about 5 mm, Hatiya is about 2 mm, Rangamati, Cox’s Bazzar and at Teknaf is about 1-2 mm.

From the distribution of TRMM rainfall for April 2014 (Fig. 4.1.6b), the maximum rainfall is observed at northeastern part at Srimangal and Sylhet stations which are about 40 mm and 30 mm. The TRMM rainfall is decreased from the northeastern region towards the south southwestern part. In the southwestern part Satkhira, Khulna, Mongla and Khepupara station observed minimum rain which is about 0-2 mm. In the western part Jessore, Chuadanga station also observed minimum rain which is about 1-2 mm.

From the distribution of 24 hours lead time predicted rainfall for April 2014 (Fig. 4.1.6c), the maximum rainfall has been simulated in the north, northeastern and central parts. In the central part, the maximum rainfall is simulated at Barisal and Madaripur station which is near about 170-175mm and in the northeastern parts, the maximum rainfall is simulated at Srimangal and Sylhet station which is more than 170 mm. From central parts to north northwestern parts, simulated rainfall is decreased and predicted minimum amount of rainfall at Rajshahi, Rangpur, Bogra and Chuadanga station of Bangladesh which is near about 0-1mm.

From the distribution of 48 hours lead time predicted rainfall for April 2014 (Fig. 4.1.6d), the maximum rainfall has been simulated in the northeastern at Sylhet and Srimangal station which is near about 160-170mm. In the central part, the maximum rainfall have also been simulated which is near about 100-130 mm. From central parts to northwestern and southeastern parts, minimum rainfall has been simulated at Dinajpur, Rajshahi and Chuadanga is about 10-20 mm and minimum rainfall (near about 2-5 mm) is simulated at Bhola, Rangamati and Teknaf station.

From the distribution of 72 hours lead time prediction rainfall for April 2014 (Fig. 4.1.6e), the maximum rainfall have been simulated in the central and northeastern region, with value about 110 -170 mm where as highest value is obtained in the northeastern part at Srimangal station which is near about 170 mm. From Srimangal station the rainfalls is decreased towards the southeastern part and the minimum rainfall is simulated at Bhola, Chittagong, Cox's Bazaar and Teknaf stations which is near about 2-5 mm.

From the 107 days prediction rainfall for April 2014 (Fig. 4.1.6 f), the maximum rainfall is simulated at the central part at Faridpur station which is near about 50 mm and Dhaka, Tangail and Madaripur region is near about 20-30 mm. From the central part rainfall also decreased towards the northern, southeast and southern part. In the northwestern part, the minimum rainfall has been found which is near about 1-10 mm. In the southern region Khulna, Mongla and Khepupara rainfall is near about 5-10 mm. The minimum rainfall has also found in the southeastern region at Rangamati station which is about 1 mm. But at Kutubdia and Cox's Bazar station, rainfall is obtained about 10 mm where as Chittagong and Teknaf that is near about 5 mm.

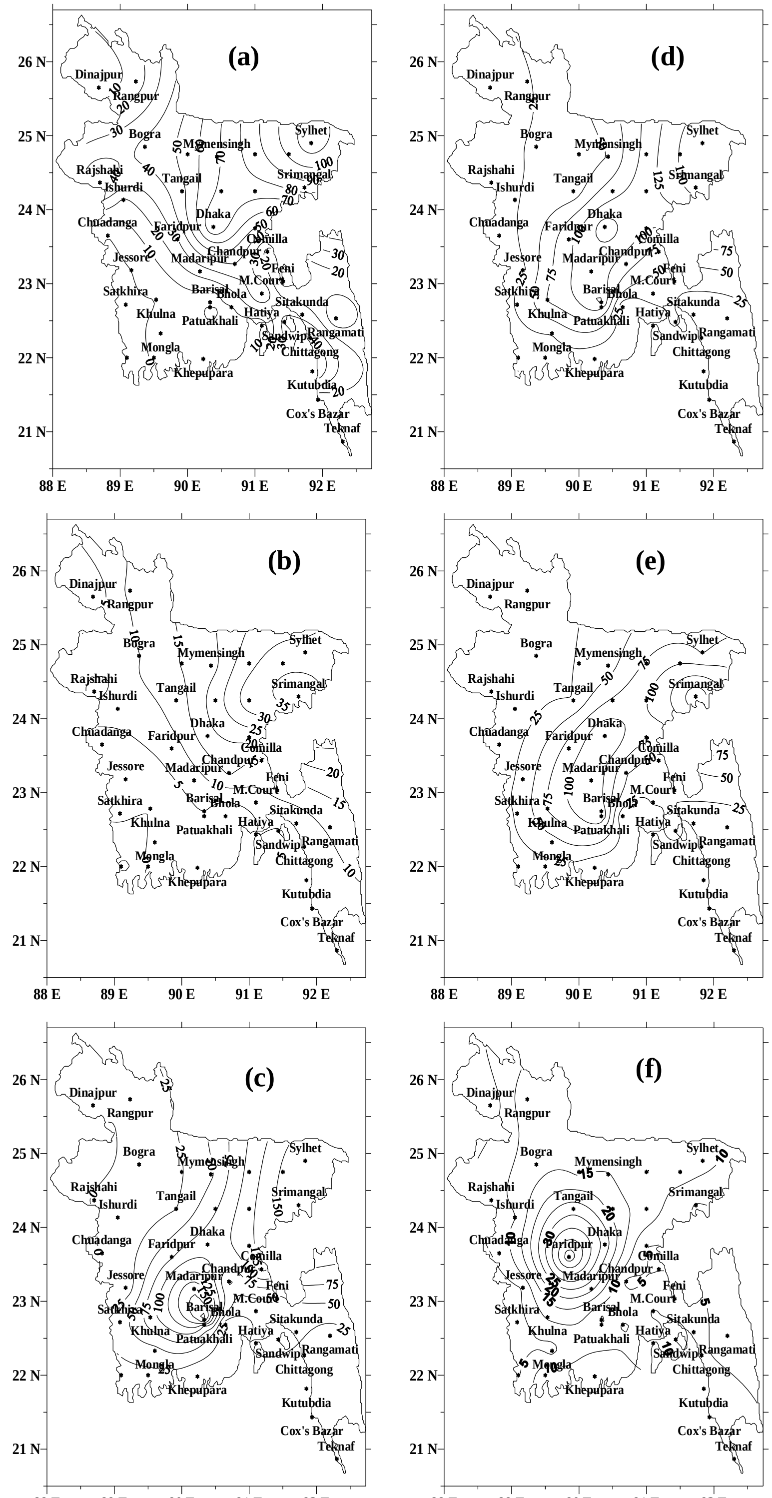

Fig. 4.1.6: Distribution of (a) Observed, (b) TRMM, (c) 24, (d) 48, (e) 72 hours and (f) 107 days model simulated rainfall for the month of April 2014 all over Bangladesh

The pattern of observed, TRMM, and 24, 48 and 72 hours prediction of rainfall are almost similar among them but the value of 107 days and TRMM observations is much lower than that of observed, 24, 48 and 72 hours rainfall. From the analysis of observed, TRMM, and 24, 48, 72 hours and 107 days prediction of rainfall for April 2014, it has been found that the rainfall is minimum in the west, northwest and southeastern regions of the country. Again, the maximum rainfall obtained from TRMM, and simulated from 24, 48, 72 hours lead time prediction has been seen in the central and northeastern regions. The maximum values of TRMM and 107 days prediction rainfall are almost similar.

4.1.5.3 Distribution of Observed, TRMM and Model Simulated rainfall for May 2014

From the distribution of observed rainfall for May 2014 (Fig. 4.1.7a), the maximum rainfall is recorded at east, northeast region at Sylhet which is more than 540 mm and southeastern part at Rangamati region has also received more than 350 mm. The maximum rainfall has also been observed at Feni, Chittagong and Mongla-Barisal-Patuakhali region and the amount are 240 mm, 300 mm and 330mm respectively. In the western region the lowest amount of rainfall is recorded at Chuadanga station which is near about 50mm. Minimum rainfall is also recorded in the southeastern region at Kutubdia is about 100mm, Cox’s Bazar is about 130mm and Teknaf is about 70mm.

From the distribution of TRMM rainfall for May 2014 (Fig. 4.1.7b), the maximum rainfall is observed at northeastern region at Sylhet which is about 170 mm and Srimangal is about 150 mm. In the southeastern region at Rangamati and Chittagong station also observed maximum rainfall which is about 130 and 100 mm. In the northwestern region observed minimum rainfall at Dinajpur, Rajshahi, Ishurdi, Chuadanga and Jessore station is about 40-60 mm. In the oceanic region Teknaf and Cox’s Bazar station also observed minimum rainfall which is about 40-50 mm. In the southern region at Bhola also observed minimum rainfall which is about 30 mm.

From the distribution of 24 hour lead time predicted rainfall for May 2014 (Fig.4.1.7c), the maximum rainfall is simulated at Sylhet region which is about 850 mm. About 350-500 mm rainfall is simulated at Hatiya, Sandwip, and Kutubdia and Teknaf stations i.e.in the southeastern part of Bangladesh. In the central part, the rainfall is equal at Barisal, Patuakhali and Madaripur stations which are near about 280 mm. From central region towards the north and northwest part it also is decreased. From this figure, the minimum rainfall is simulated at Dinajpur station which is near about 80 mm. In this region, the rainfall of Bogra and Ishurdi is about 100 mm and that of Chuadanga and Rangpur is about 120 mm.

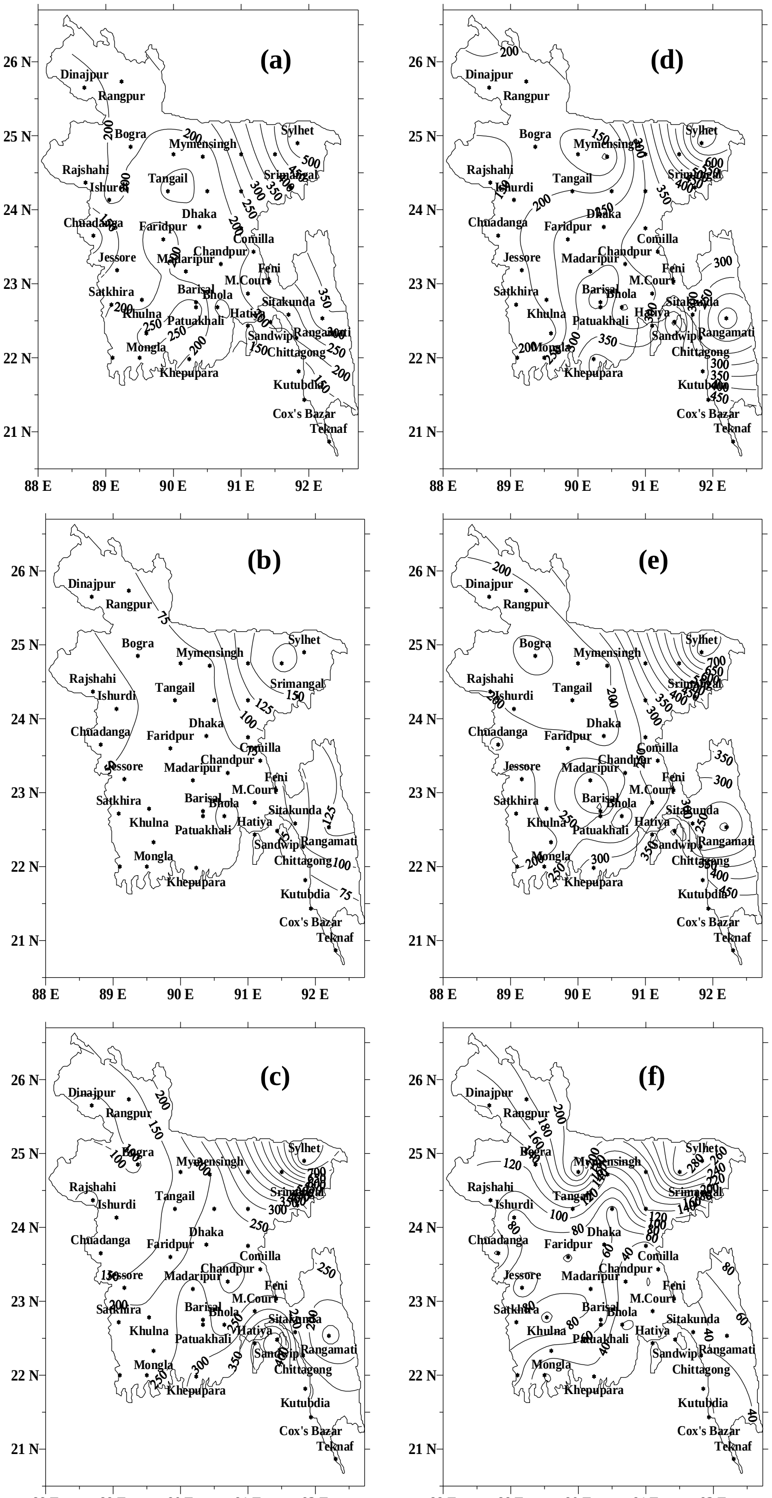

Fig. 4.1.7: Distribution of (a) Observed, (b) TRMM, (c) 24, (d) 48, (e) 72 hours and (f) 107 days model simulated rainfall for the month of May 2014 all over Bangladesh

From the distribution of 48 hour lead time predicted rainfall for March 2014 (Fig. 4.1.7 d), the maximum rainfall is simulated in the northeastern region at Sylhet station which is near about 700 mm. About 450-550 mm rainfall is also simulated in the southeastern part of Bangladesh. In the central region, the rainfall is about 280-400 mm. From the northeastern and southeastern region, it also decreased towards the north and northwest part. From this figure, the minimum rainfall is simulated at Mymensingh station which is near about 80 mm. The minimum rainfall is also shown at Rajshahi which is about 110 mm, and at Chuadanga, Bogra and Rangpur, it is about 150-180 mm.

From the distribution of 72 hour lead time predicted of rainfall for May 2014 (Fig. 4.1.7e), the maximum rainfall is simulated at northeastern region at Sylhet station which is about 780 mm. The maximum rainfall is also found at southeastern region at Sandwip, Cox's Bazar and Teknaf which is about 400-570mm. From this figure, the minimum rainfall is simulated in the northwestern region at Bogra station which is near about 130mm. It is noted that rainfall is decreased from eastern region to western region. Again, the rainfall of Ishurdi, Jessore, Rajshahi and Dinajpur is about 150-200 mm.

From the 107 days predicted of rainfall for May 2014 (Fig. 4.1.7f), the maximum rainfall is simulated at northeastern and northwestern part. But maximum rainfall is simulated in the north eastern part i.e. at Sylhet station, which is near about 280 mm. In the northwestern region at Bogra, Rangpur and Dinajpur rainfall is about 130-180 mm. From the central region, the rainfall is decreased towards the southeastern and southern region of Bangladesh. The minimum rain is simulated in the southern region of Bangladesh which is near about 20 mm is simulated at Bhola, Cox's Bazar and Kutubdia stations. It is also noted that rainfall is increased from south to north part of Bangladesh.

From the analysis of 24, 48, 72 hours lead time and 107 days prediction of rainfall for May 2014, it has been found that the rainfall is minimum in the west, northwest, southwest and central regions of the country. The maximum value of rainfall has been simulated in northeastern region and also in the southeastern 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. The rainfall for 107 days prediction has been seen much lower 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 among them but the value of model simulated rainfall is much lower than observed rainfall in northeastern, south southeastern region.

4.2 Root Mean Square Error (RMSE) of Rainfall

The WRF model simulated daily RMSE of Rainfall of the pre-monsoon season for 107 days prediction of 2010-2013 are presented in Figure 4.2.1-4.2.3 and discussed in the subsection 4.2.1-4.2.3. Again, daily RMSE of Rainfall of 2014 for 24, 48 and 72 hours lead time and 107 days prediction are presented in Figure 4.2.4-4.2.6 and discussed in the subsection 4.2.4-4.2.6.

4.2.1 RMSE of Rainfall for March 2010-2013

The RMSE of rainfall for March 2010 (Fig. 4.2.1a) is simulated minimum from central region towards west, northwest, southwest and southern regions of the country. The RMSE of rainfall has been simulated almost 0 mm in the western and southern regions of the country. The RMSE of rainfall is found maximum in the northeastern and southeastern regions. Rangamati and Sylhet stations have simulated maximum RMSE of rainfall and its value are 16 and 15 mm, respectively. The RMSE has been decreased continuously from northeastern region towards west and southwest regions. The RMSE has minimum where the rainfall is also minimum and vice versa.

The RMSE of rainfall for March 2011 (Fig. 4.2.1b) is simulated minimum from central region towards northeast, southwest and southeastern region of the country. The RMSE of rainfall has been simulated almost 0 mm in the western and southern region of the country. The RMSE of rainfall of maximum rainfall has been simulated in the southeastern, northwestern and central regions. In the southeastern at Sitakunda, Sandwip and Chittagong stations, its value is near 17 mm and in the northwestern region at Bogra has maximum RMSE and its value is 15 mm and in the central region Madaripur simulates 10 mm.

The RMSE of rainfall for March 2012 (Fig. 4.2.1c) is simulated minimum from central region towards north, northwest and western regions of the country. The RMSE of rainfall in the north and northwestern regions at Mymensingh, Dinajpur, Rangpur and Bogra region has simulated near 1 mm and in the western region at Jessore, Satkhira and Khulna station has simulated 1-2 mm. The RMSE of rainfall is found maximum in the southeastern, northeastern, southern and western regions at Cox’s Bazar, Rangamati, Sylhet, Khepupara and Rajshahi stations and their value are 10-13 mm.

The RMSE for the 107 days prediction rainfall for March 2013 (Fig. 4.2.1d) is simulated minimum from southern region towards west, northwest, northeast and southwest regions of the country. The RMSE of rainfall has been simulated almost 0-1 mm. The RMSE of rainfall is found maximum in the southeastern region at Hatiya station and its value is 22 mm and at Comilla station has simulated near 13 mm.

From the analysis of RMSE of rainfall for March 2010- 2013, the RMSE is found minimum in the west, north and northwestern regions of the country. The maximum RMSE of rainfall has been found in different region as northeast, central and south southeastern regions. The pattern of RMSE for 2010- 2013 are not similar to each other except southern region.

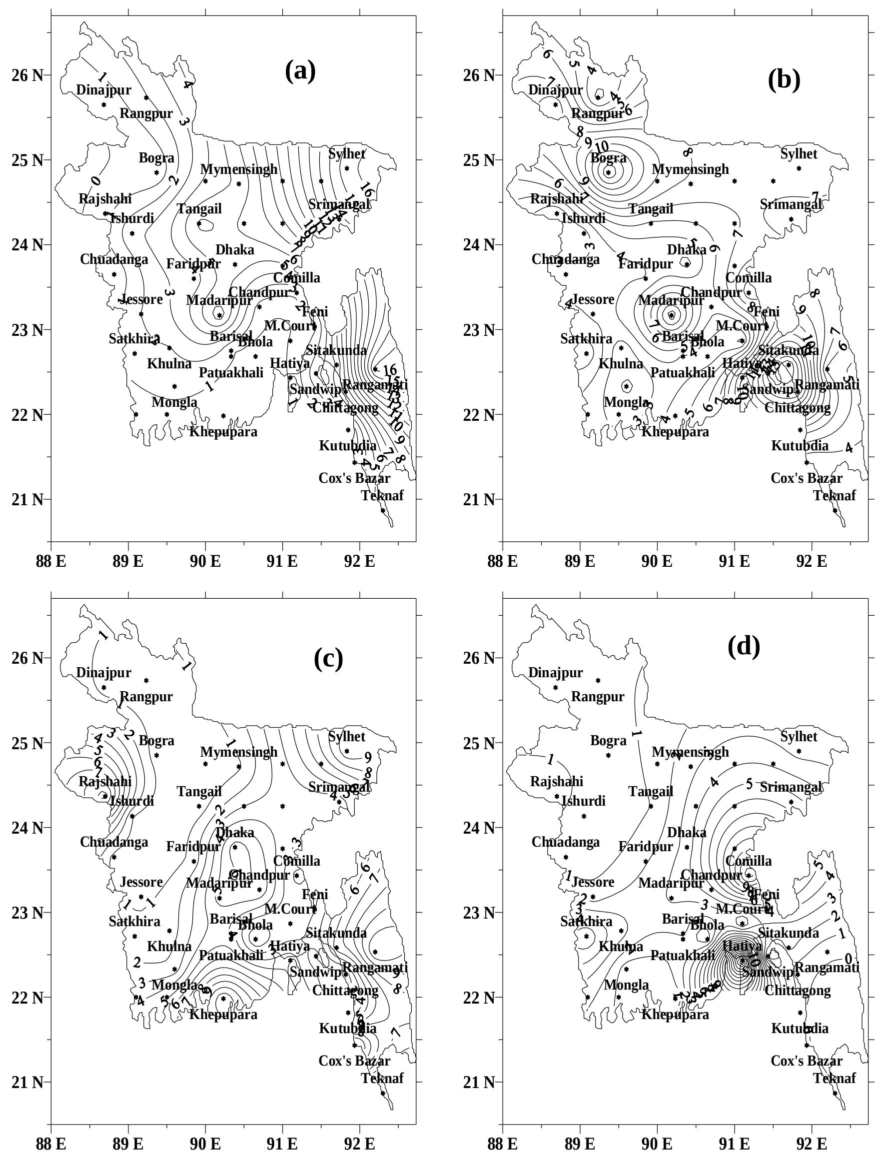

Fig. 4.2.1: Distribution of RMSE of rainfall for the month of March (a) 2010, (b) 2011, (c) 2012 and (d) 2013 all over Bangladesh

4.2.2 RMSE of Rainfall for April 2010-2013

The RMSE of Rainfall for April 2010 (Fig. 4.2.2a) is simulated minimum from northeastern region towards west, southwest, southern and southeast regions of the country. In the southeastern region at Kutubdia, Cox's Bazar and Teknaf station and their value are near 1 mm. The RMSE of rainfall is found maximum in the northeastern region at Sylhet station and its value is 40 mm. The RMSE has been decreased continuously from northeastern region towards west and southwest, southern and southeast regions of the country.

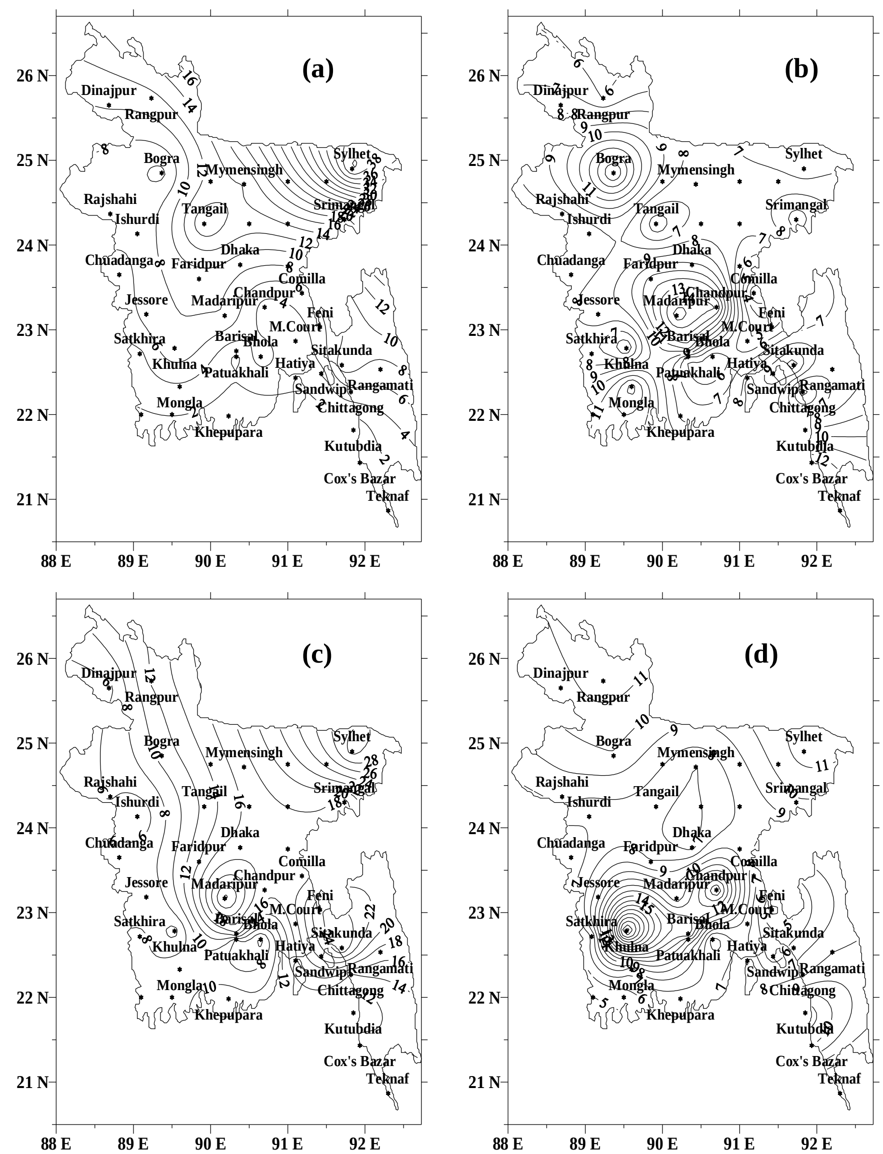

Fig. 4.2.2: Distribution of RMSE of rainfall for the month of April (a) 2010, (b) 2011, (c) 2012 and (d) 2013 all over Bangladesh

The RMSE of Rainfall for April 2011 (Fig. 4.2.2b) is simulated minimum from northeastern, east, southwest and southeast regions of the country. The RMSE of rainfall have been found maximum at different regions. In the northwestern, Central and southwestern region have simulated maximum RMSE of rainfall. In the northwestern region at Bogra has simulated 15mm and in the central region at Madaripur has simulated more than 15 mm and in the southwestern region at Mongla station has simulated 13 mm.

The RMSE of rainfall for April 2012 (Fig. 4.2.2c) is simulated minimum from central region to west, northwest and southwest regions of the country. In the west and northwestern regions the RMSE of rainfall have simulated 4-10 mm. The maximum RMSE have been simulated in the northeastern, southeastern and central regions. In the northeastern region at Sylhet station, in the southeastern region at Sitakunda and in the central region at Madaripur, the value of maximum RMSE are 30, 26 and 25 mm respectively.

The RMSE for the 107 days prediction rainfall for April 2013 (Fig. 4.2.2d) is simulated minimum at eastern and southeastern regions. At Feni and Teknaf stations, its value is 4 mm. The RMSE of rainfall is found maximum in the southwestern and central regions. The RMSE of rainfall has been found 23 and 16 mm at Khulna and Chandpur stations respectively. The RMSE has been decreased continuously from southwest region towards eastern region.

From the analysis for 107 days prediction of RMSE of rainfall for the month of April 2010-2013, the value of MAE is found minimum in the west, north, northwest and regions. The pattern of RMSE the maximum value of (2011, 2012 and 2013) rainfall has been found almost similar except 2010 for all over the country. It has seen that the value of RMSE 2011, 2012 and 2013 of rainfall has maximum in the central and southeastern region and 2010 of rainfall has maximum in the northeastern region. It has found that, the rainfall has minimum where the RMSE is also minimum and vice versa.

4.2.3 RMSE of Rainfall for May 2010-2013

The RMSE of Rainfall for May 2010 (Fig. 4.2.3a) is simulated minimum from central region towards west, northwest, and southwest region of the country. In the southwestern region at Khulna and in the western region at Rajshahi, Ishurdi and Chuadanga stations and the values of minimum RMSE are 12 and 13 mm respectively. The RMSE of rainfall is found maximum in the northeastern, southeastern and southern regions and the values are 44, 30 and 36 mm at Sylhet, Teknaf and Khepupara stations respectively. The RMSE has been decreased continuously from northeastern region towards west and southwest regions.

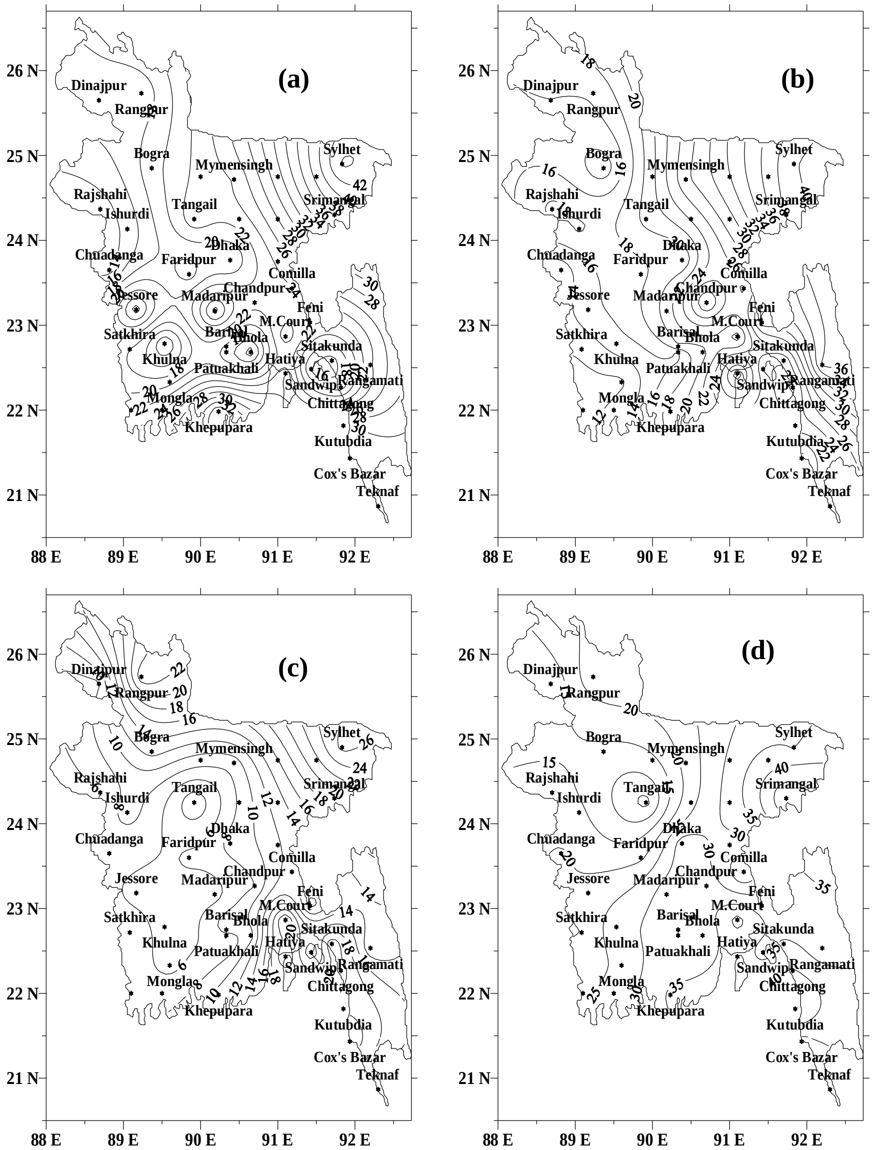

Fig. 4.2.3: Distribution of RMSE of rainfall for the month of May (a) 2010, (b) 2011, (c) 2012 and (d) 2013 all over Bangladesh

The RMSE of Rainfall for May 2011 (Fig. 4.2.3b) is simulated minimum from eastern region towards west, northwest regions. In the northwest regions at Dinajpur, Rajshahi, Ishurdi and Chuadanga and southwest regions at Khulna, Mongla and Satkhira station, its value are 12-16 mm. The RMSE of rainfall is found maximum in the northeastern, southeastern and central regions at Sylhet, Rangamati and Chandpur stations and its value are 40, 36 and 30 mm respectively. The RMSE has been decreased continuously from northeastern region towards west and southwest regions.

The RMSE of Rainfall for May 2012 (Fig. 4.2.3c) is simulated minimum from central region to north, west and southwest regions and its value are 3-6 mm. The RMSE of rainfall is simulated maximum in the northeastern region at Sylhet, northwestern region at Rangpur and southeastern region at Chittagong, Cox’s Bazar, Hatiya and M. Court stations and it value are 22-26 mm.

The RMSE for the 107 days prediction of Rainfall for May 2013 (Fig. 4.2.3d) is simulated minimum in the northern region at Tangail and it value is 3 mm, and in the northwestern region and it value are 10-16 mm. The RMSE of rainfall is simulated maximum at northeastern, southeastern and southern region of Bangladesh. In the northeastern region Srimangal has maximum RMSE which is more than 50 mm. Again, in the southeastern region Chittagong, Kutubdia and Teknaf stations, maximum RMSE value is about 35-45 mm. In the southern region Hatiya, M. Court and Khepupara has maximum RMSE about 35-40 mm.

From the analysis of RMSE of rainfall for 107 days prediction of rainfall for the month of May 2010- 2013, the value of RMSE is found minimum in the west, north northwest regions of the country and maximum in the northeastern, southern and southeastern regions of the country. The pattern of RMSE of 2010, 2011 rainfall is almost similar each other and the pattern of RMSE of 2012, 2013 rainfall is almost similar to each other for all over the country. It has been observed that the RMSE has minimum where the rainfall has minimum and vice versa.

4.2.4 Model simulated RMSE of rainfall for March 2014

The daily RMSE of 24 hour lead time predicted rainfall for March 2014 (Fig. 4.2.4a) is simulated minimum in the southeastern and northwestern region of Bangladesh. In the southeastern region at Cox’s Bazar, Kutubdia, Rangamati and Teknaf stations have minimum RMSE of rainfall in this month and its value were 0.5-2.0 mm. The maximum RMSE of rainfall has been seen in the northeastern, western and southern region at Sylhet, Chuadanga, M. Court and Patuakhali station and its value were 7-9 mm.

The daily RMSE of 48 hour lead time predicted rainfall for March 2014 (Fig. 4.2.4b) is simulated minimum from central region towards west, northwest, southeastern region and their values is almost 0 mm. The RMSE of rainfall is found maximum in the western, northeastern and southern region at Chuadanga, Sylhet and M. Court stations and its value were 6-8 mm respectively. In the central part Madaripur also simulated maximum RMSE of rainfall and its value was 6 mm. The RMSE has been decreased continuously from northeastern region to west, northwest and central region to southeastern region.

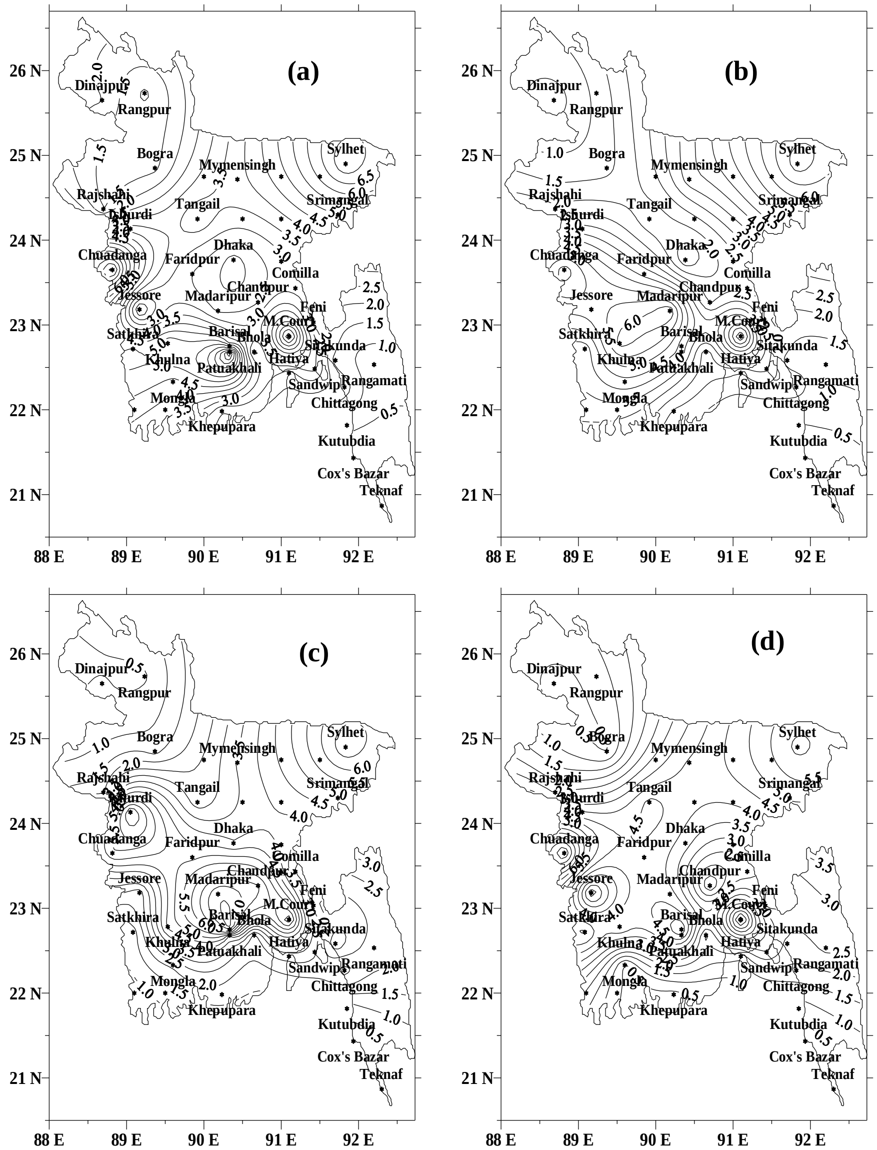

Fig. 4.2.4: Distribution of RMSE of rainfall for (a) 24, (b) 48, (c) 72 hours and (d) 107 days prediction of March 2014 all over Bangladesh

The daily RMSE of 72 hour lead time predicted rainfall for March 2014 (Fig. 4.2.4c) is simulated minimum from central region towards northwestern at Dinajpur and Rangpur and southeastern region at Cox's Bazar, Kutubdia and Teknaf station and its value were near 1 mm. The RMSE has been decreased continuously from northeastern region towards west and central region to southeastern region. The RMSE of rainfall is found maximum in the western at Ishurdi, northeastern at Sylhet and central region at Barisal and Madaripur and its value were 7-8 mm respectively..

RMSE of Rainfall for 107 days prediction for March 2014 has been shown in Fig. 4.2.4(d). The minimum RMSE of rainfall has simulated in the northwestern region at Bogra, Dinajpur, Rangpur station and southeastern and southern region at Cox's Bazar, Kutubdia, Teknaf, Mongla and Khepupara station and its value were very low. The RMSE of rainfall is found maximum in the northeastern region at Sylhet, western region at Chuadanga and southeastern region at M. Court station and its value were 7-8 mm respectively.

From the analysis of 24, 48, 72 hours and 107 days prediction of RMSE of rainfall for March 2014, the RMSE is minimum in the northwestern and southeastern regions of the country and maximum in the central to southern and northeastern region. It has been found that the RMSE has minimum where the rainfall is minimum and vice versa. The values of RMSE of rainfall in the northeastern region is almost similar for 24, 48, 72 hours lead time and 107 days prediction for all over the country.

4.2.5 RMSE of Rainfall for April 2014

The daily RMSE of 24 hour lead time predicted rainfall for April 2014 (Fig. 4.2.5a) is simulated minimum at southeastern region at Cox's Bazar, Rangamati and Teknaf stations, west region at Chuadanga station and northwestern region at Dinajpur station of Bangladesh. The maximum RMSE of rainfall has been simulated at northeastern, central and northern regions of Bangladesh. In the northeastern part at Sylhet station, RMSE of rainfall have been simulated maximum and its value is 14 mm. Again, in the central and northern region at Barisal, Dhaka, Madaripur and Mymensingh also have maximum RMSE of rainfall.

The daily RMSE of 48 hour lead time predicted rainfall for April 2014 (Fig. 4.2.5b) is simulated minimum at southeastern, northwestern and southern region of Bangladesh. In the southeastern region at Cox's Bazar, Rangamati and Teknaf station, northwestern region at Dinajpur and southern region at Bhola and Hatiya have minimum RMSE of rainfall. The maximum RMSE of rainfall has been simulated northeastern and central region of Bangladesh. In the northeastern and central region have simulated maximum RMSE of rainfall and its value is 9-14 mm.

The daily RMSE of 72 hour lead time predicted rainfall for April 2014 (Fig. 4.2.5c) is simulated minimum at southeastern, southern and western region of Bangladesh. In the southeastern region at Cox's Bazar, Teknaf, in the southern region at Bhola, Khepupara and in the western region at Chuadanga station have minimum RMSE of rainfall. The maximum

RMSE of rainfall has been simulated in the northeastern region at Srimangal and in the central region at Barisal, Dhaka, Madaripur and their values is 9-10 mm respectively.

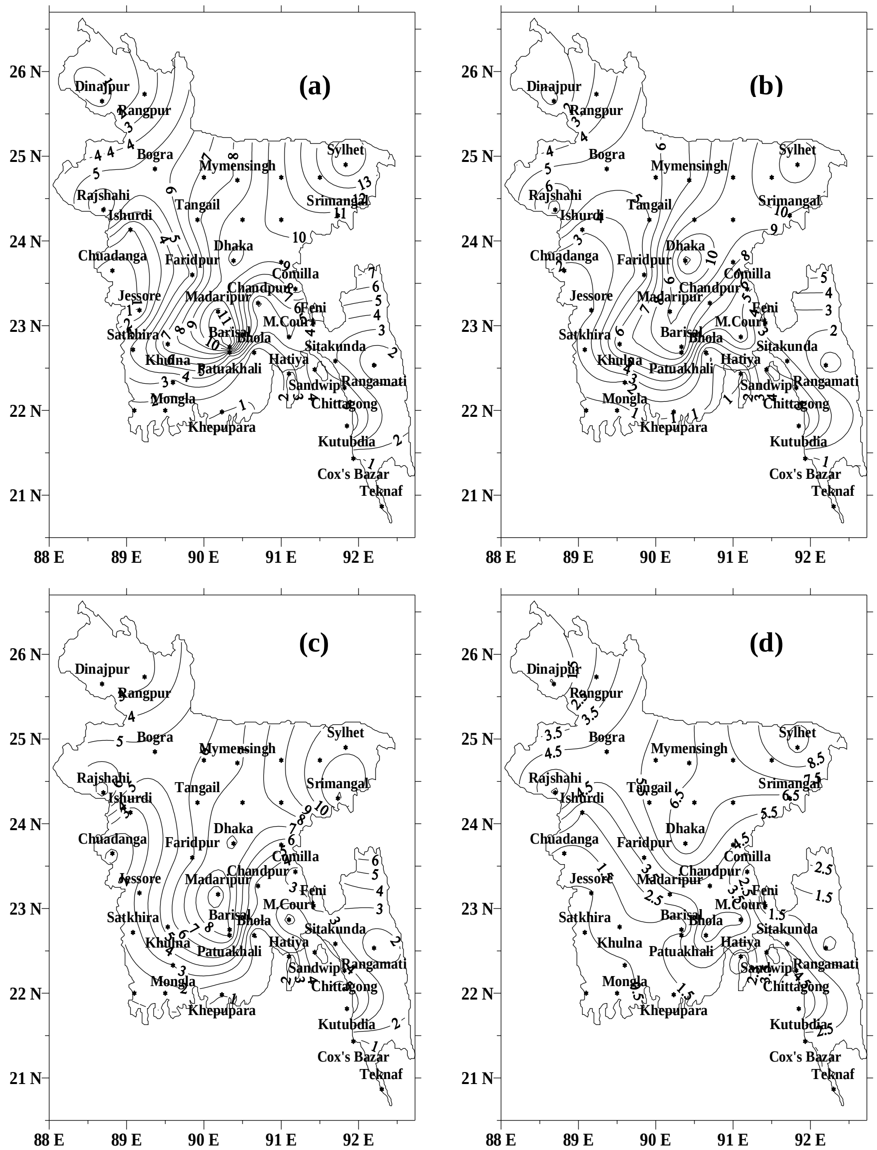

Fig. 4.2.5: Distribution of RMSE of rainfall for (a) 24, (b) 48, (c) 72 hours and (d) 107 days prediction of April 2014 all over Bangladesh

The RMSE of Rainfall for 107 days prediction for April 2014 has been shown in Fig. 4.2.5(d). The minimum RMSE of rainfall has been simulated at northwest, west, southwest and southern region at Dinajpur, Jessore, Satkhira, Mongla and Hatiya stations and their values are very low. The RMSE of rainfall is found maximum in the northeastern, western region at Sylhet, Ishurdi and Chuadanga stations and its value are 7-10 mm respectively.

From the analysis of 24, 48, 72 hours lead time and 107 days prediction of RMSE of rainfall for April 2014, the RMSE is minimum in the west, northwestern and southeastern regions of the country and maximum in the central and northeastern region. For 107 days prediction the maximum value of RMSE has been also found in the northeastern region. It has been observed that the RMSE has also minimum where the rainfall is minimum and vice versa. The RMSE of rainfall has been found almost similar for 24, 48 and 72 hours lead time prediction for all over the country. The RMSE of rainfall for 24, 48 hours prediction has been seen much higher value than those of 72 hour and 107 days prediction.

4.2.6 RMSE of Rainfall for May 2014

Figure 4.2.6(a) represents the 24 hours lead time predicted RMSE rainfall for May 2014. The minimum RMSE of rainfall has been simulated in the northern, northwestern and southern region i.e. at Mymensingh, Tangail Chuadanga, Dinajpur and Khulna and their value are 9-11 mm. The maximum RMSE of rainfall has been simulated northeastern region at Sylhet have been simulated maximum RMSE of rainfall and its value is 46 mm. Again, in the southeastern region at Chittagong and Sandwip also have been simulated maximum RMSE of rainfall.

The RMSE of rainfall of 48 hours lead time predicted for May 2014 has been shown in Fig. 4.2.6(b). The minimum RMSE of rainfall has been simulated in the northern and centre to southern regions at Mymensingh, Tangail, Chandpur and Bhola stations and their value are 11-13 mm. The maximum RMSE of rainfall have been simulated northeastern and southeastern region at Sylhet, Chittagong, Sandwip and Teknaf stations and their value is 32-36 mm respectively.

The RMSE of rainfall of 72 hours lead time predicted May 2014 has been shown in Fig. 4.2.6(c). The minimum RMSE of rainfall has been simulated in the central region, northern, northwestern and southwestern region at Dhaka, Faridpur, Mymensingh, Tangail, Dinajpur and Satkhira station and their value are 13-14 mm. The maximum RMSE of rainfall has been simulated northeastern at Sylhet station and southeastern region at Chittagong and Teknaf stations and their value are 36-38 mm respectively.

The RMSE of rainfall for 107 days prediction for May 2014 has been shown in Fig. 4.2.6(d). The minimum RMSE of rainfall has been simulated at northern region at Tangail station and its value is very low. The minimum RMSE also have been simulated in the west and northwestern region at Chuadanga and Rangpur station and their value are 10 mm. The

RMSE of rainfall is found maximum in the northeastern, northwestern and southeastern regions at Sylhet, Srimangal, Bogra, Ishurdi, Chittagong and Rangamati station and their values are 20-24 mm.

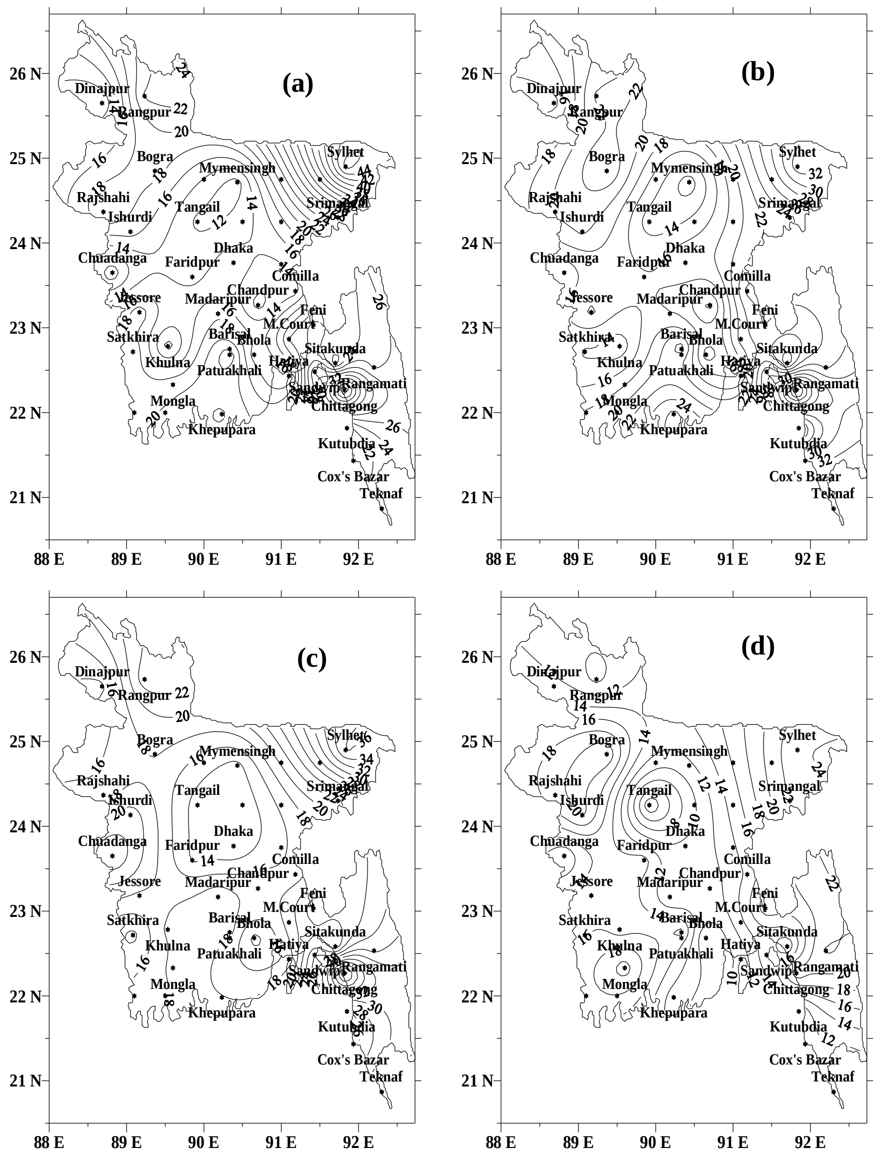

Fig. 4.2.6: Distribution of RMSE of rainfall for (a) 24, (b) 48, (c) 72 hours and (d) 107 days prediction of May 2014 all over Bangladesh

From the analysis of 24, 48, 72 hours lead time and 107 days prediction of RMSE of rainfall for May 2014, the RMSE is minimum in the west southwestern regions of the country and maximum in the north, northeastern and southeastern regions. For 107 days prediction the maximum value of RMSE has been also found in the northeastern region. It has been observed that the RMSE has minimum where the rainfall is minimum and vice versa. The RMSE of rainfall has been found almost similar for 24, 48 and 72 hours lead time prediction for all over the country. The RMSE of rainfall for 24, 48 and 72hours lead time prediction has seen much higher value than those of 107 days prediction.

4.3 Mean Absolute Error (MAE)

The WRF model simulated daily MAE of Rainfall for 107 days prediction of 2010-2013 are presented in Figure 4.3.1-4.3.3 and discussed in the subsection 4.3.1-4.3.3. Again, daily MAE of Rainfall of 2014 for 24, 48 and 72 hours lead time and 107 days prediction are presented in Figure 4.3.4-4.3.6 and discussed in the subsection 4.3.4-4.3.6.

4.3.1 MAE of Rainfall for March 2010-2013

The daily MAE of rainfall for March 2010 (Fig. 4.3.1a) is simulated minimum in the western, northwestern and southwestern regions. The lowest value of MAE of rainfall has been found at Dinajpur, Rajshahi, Chuadanga, Khulna, Mongla and Khepupara and its value is near 0 mm. The MAE of rainfall have been increased from central region towards northeast and southeast regions and decreased from central towards western region of the country. The southeastern region i.e. Rangamati and the northeastern region i.e. Sylhet has simulated the maximum value of MAE.

The daily MAE of rainfall for March 2011 (Fig. 4.3.1b) is simulated minimum in the southern region towards the western, northern and eastern region of the country. The highest value of MAE of rainfall found at Patuakhali and it is 40 mm. The daily MAE of rainfall has been decreased from Patuakhali towards western, northern and eastern regions. In the south south-eastern region of Bangladesh i.e. Mongla, Cox's Bazar, the lowest value of MAE has also been simulated.

The daily MAE of rainfall for March 2012 (Fig. 4.3.1c) is simulated minimum in the western region i.e. Ishurdi, Chuadanga, Jessore and Satkhira stations and in the northern region at Mymensingh station and its value are near 0 mm. The MAE of rainfall is found maximum in the northeastern region at Sylhet station which more than 3 mm. The maximum value of MAE of rainfall has also been found in the southeastern region i.e. Cox's Bazar and Rangamati stations and its value are almost 3 mm. The daily MAE of rainfall has been decreased from northeast towards western region of the country.

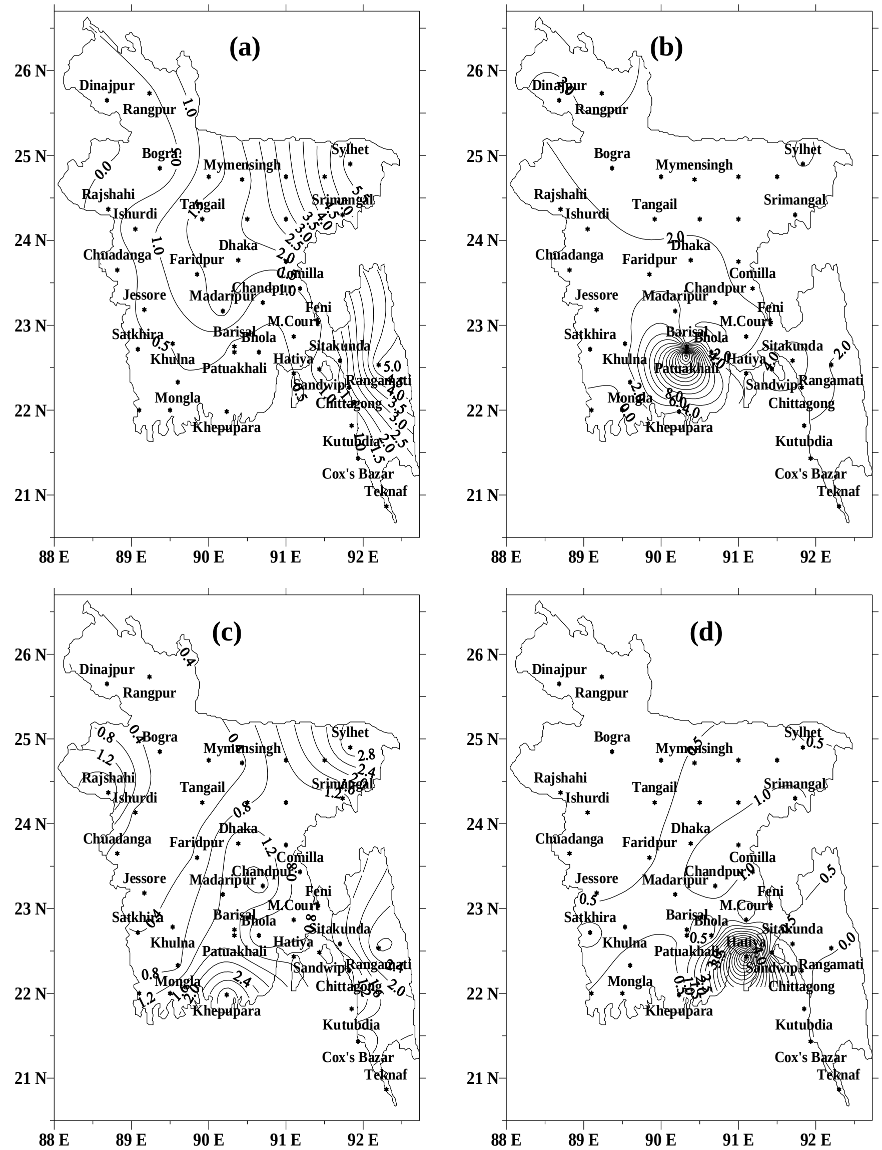

Fig. 4.3.1: Distribution of MAE of rainfall for the month of March (a) 2010, (b) 2011, (c) 2012 and (d) 2013 all over Bangladesh

The daily MAE of rainfall for March 2013 (Fig. 4.3.1d) is simulated minimum in the all regions of Bangladesh except at Hatiya station and those values are almost 0 mm. The highest value of MAE of rainfall has found in the southern part i.e. Hatiya and its value is almost 10 mm. The monthly average MAE of rainfall has increased from Bhola towards southeast region of the country.

From the analysis for 107 days prediction of MAE of rainfall for the month of March 2010-2013, the value of MAE is found minimum in the west, north and northwest regions of the country and maximum in the southern region. The pattern of MAE of (2010, 2012) rainfall has been found almost similar and (2011, 2013) rainfall has been found almost similar for all over the country. It has been observed that the value of MAE 2010, 2012 of rainfall has maximum in the northeast, southeast and southern regions and 2011, 2013 of rainfall has maximum in the southern region. It has been found that, the MAE has minimum where the rainfall is minimum and vice versa.

4.3.2 MAE of Rainfall for April 2010-2013

The daily MAE of rainfall for April 2010 (Fig. 4.3.2a) is simulated minimum in the western, southwestern and southeastern regions at Mongla, Khepupara, Kutubdia and Teknaf and their value are near 0 mm. The monthly MAE of rainfall predictions have been increased from central region towards northeastern region at Sylhet and the value is about 22mm.

The daily MAE of rainfall for April 2011 (Fig. 4.3.2b) is simulated minimum in the southern region at Comilla, Feni, M. Court, Rangamati and Chittagong stations. The central region i.e. Faridpur and Madaripur, the highest value of MAE has been simulated and their value is 6 mm. The maximum value of MAE of rainfall has also been simulated in northwestern and southwestern region.

The daily MAE of rainfall for April 2012 (Fig. 4.3.2c) is simulated minimum in the west and northwest region i.e. Dinajpur, Rajshahi, Ishurdi, Chuadanga and Jessore stations and its value are almost 3 mm. The southwestern region i.e. Khulna and Satkhira have also simulated minimum MAE of rainfall. The MAE of rainfall is found maximum in the northeastern region at Sylhet and its value is almost 22 mm. The daily MAE of rainfall has been decreased from northeast towards western and southwestern regions of the country.

The daily MAE of rainfall for April 2013 (Fig. 4.3.2b) is simulated minimum in the south and southeastern regions. At Bhola station, the value is almost 1.5 mm and at Sandwip and Teknaf stations, the value is very low. The MAE of rainfall is found maximum in the northeastern, northwestern and southwestern region. The highest value of MAE of rainfall has been found in the southwestern part i.e. Khulna and it is almost 7 mm. The daily MAE of rainfall has been increased from southern at Bhola station towards southwest, northwest regions of the country.

From the analysis for 107 days prediction of MAE of rainfall for the month of April 2010-2013, the value of MAE is found minimum in the west, north and northwest regions.

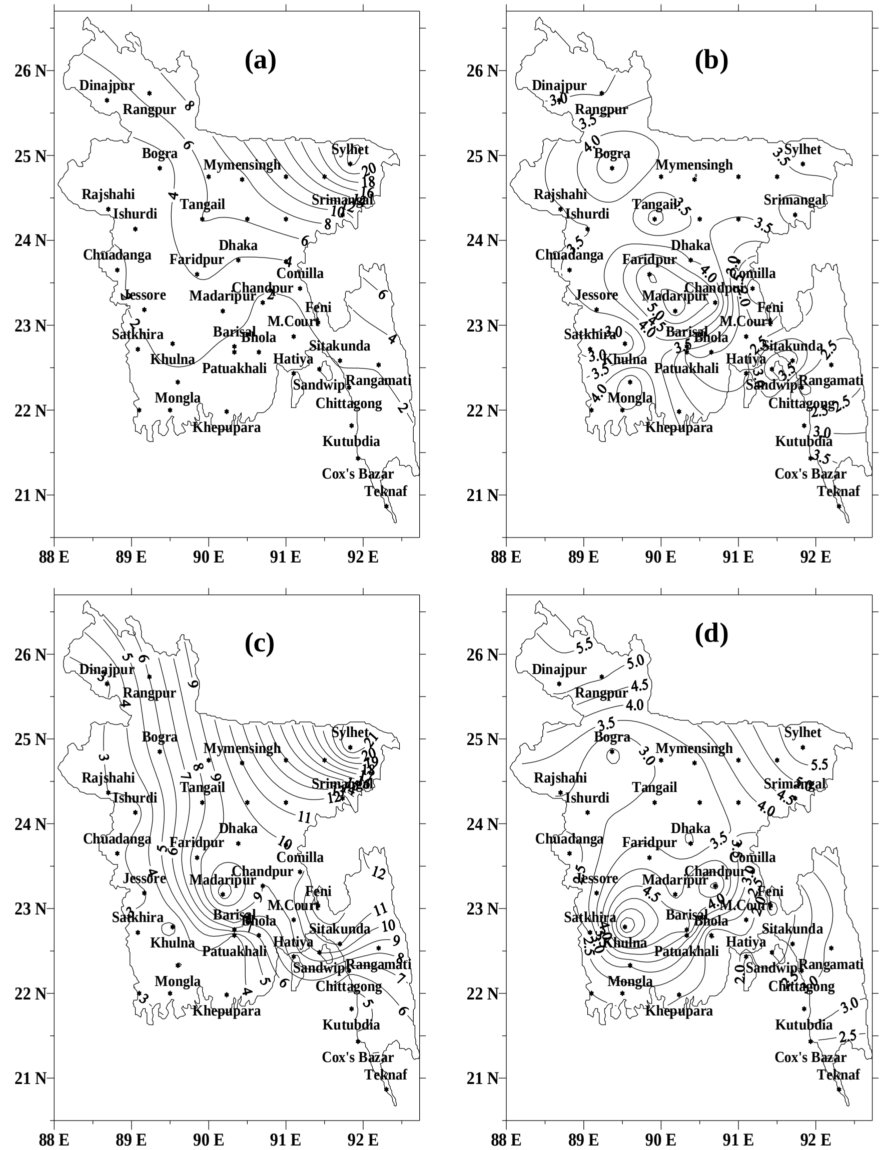

Fig. 4.3.2: Distribution of MAE of rainfall for the month of April (a) 2010, (b) 2011, (c) 2012 and (d) 2013 all over Bangladesh

The pattern of MAE along with the maximum value of rainfall between 2010 and 2012, and between 2011 and 20113 has been found almost similar for all over the country. It has been observed that the value of MAE for 2010 and 2012 of rainfall has maximum in the northeastern region, and that for 2011 and 2013 has maximum in the central to southwestern regions. It has found that, the MAE has minimum where the rainfall is minimum and vice versa.

4.3.3 MAE of Rainfall for May 2010-2013

The daily MAE of rainfall for May 2010 (Fig. 4.3.3a) is simulated minimum in the southern region at Bhola and it is 5 mm. The minimum value of MAE of rainfall has also been found in the west northwest and southwestern region at Dinajpur, Rajshahi, Chuadanga, Khulna and Mongla station. The daily MAE of rainfall for 107 days predictions have been increased from southern region towards northeastern region and decreased from central towards western region of the country.

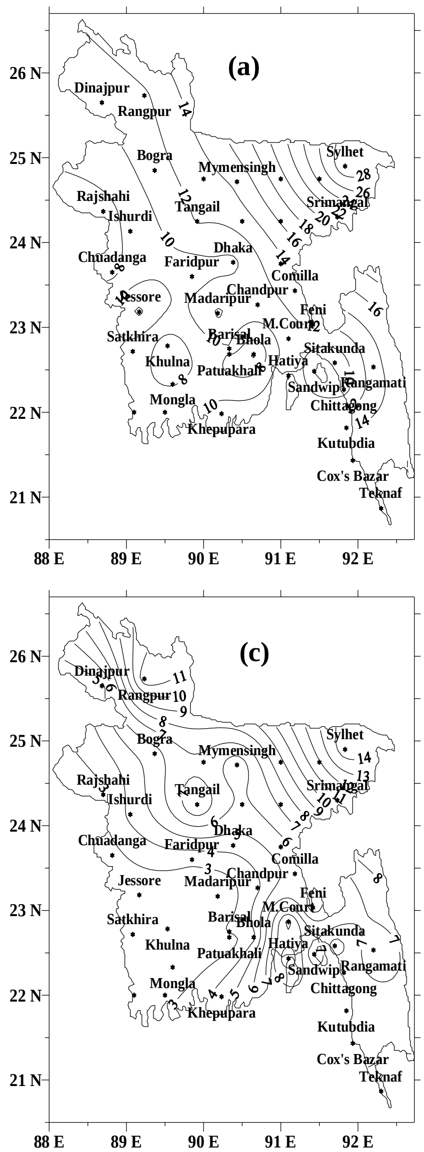

Fig. 4.3.3: Distribution of MAE of rainfall for the month of May (a) 2010, (b) 2011, (c) 2012 and (d) 2013 all over Bangladesh

The daily MAE of rainfall for May 2011 (Fig. 4.3.3b) is simulated minimum in the western region at Chuadanga station and it is 7 mm. Again, in the northwestern and southwestern region at Bogra, Rangpur, Satkhira, Khulna and Mongla stations has also simulated minimum daily MAE of rainfall. In the northeastern region i.e. Sylhet has simulated maximum MAE of rainfall and it is 28 mm. The maximum value of MAE of rainfall has also been simulated in south, southeastern region. The MAE of rainfall have been increased from west, northwest towards northeast and decreased from northeast towards western region of the country.

The daily MAE of rainfall for May 2012 (Fig. 4.3.3c) is simulated minimum in the central region to west, southwestern region and their values are very low. The daily MAE of rainfall is found maximum in the northeastern region at Sylhet and it value is15 mm and in the northwestern region at Rangpur and it value is 12 mm. The highest value of MAE of rainfall has also been found in the southeastern region i.e. M. Court and Hatiya and their value are almost 10 mm.

The daily MAE of rainfall for May 2013 (Fig. 4.3.3d) is simulated minimum in the northwestern region at Dinajpur station and it is almost 7 mm and Bogra, Ishurdi and Rajshahi stations and their value are 8-10 mm. The MAE of rainfall has been found highest value in the northeastern region at Srimangal and the value is 30 mm. The maximum of MAE of rainfall has also been found in the southeastern i.e. Hatiya, M.court, Kutubdia and Chittagong station. The MAE of rainfall for 107 days predictions have been increased from west towards northeast and southeastern and decreased from northeast towards northwestern region of the country.

From the analysis of MAE of rainfall for 107 days prediction for the month of May of 2010-2013, the value of MAE is minimum in the west and northwest regions of the country and maximum in the northeastern, southern and southeastern regions. The pattern of MAE of rainfall is almost similar for the month of May of 2010- 2013 all over the country. It has been observed that the MAE has minimum where the rainfall is minimum and vice versa.

4.3.4 MAE of Rainfall for March 2014

The daily MAE of 24 hour lead time predicted rainfall for March 2014 (Fig. 4.3.4a) is simulated minimum all over Bangladesh except in the northeastern part at Srimangal. The lowest value of daily MAE of rainfall at all region of Bangladesh is almost 0 mm where as in northeastern region of Bangladesh i.e. Srimangal this value is 45 mm. The daily MAE of rainfall using 24 hour lead time prediction has been decreased from northeastern region towards all region of Bangladesh.

The daily MAE of 48 hour lead time predicted rainfall for March 2014 (Fig. 4.3.4b) is simulated minimum all over Bangladesh except in the northeastern part at Srimangal. The lowest value of daily MAE of rainfall at all region of Bangladesh is almost 0 or 1 mm where as in northeastern region the maximum daily MAE has been calculated i.e. Srimangal this value is 50 mm. The daily MAE of rainfall using 24 hour lead time prediction has been decreased from northeastern region towards all region of Bangladesh.

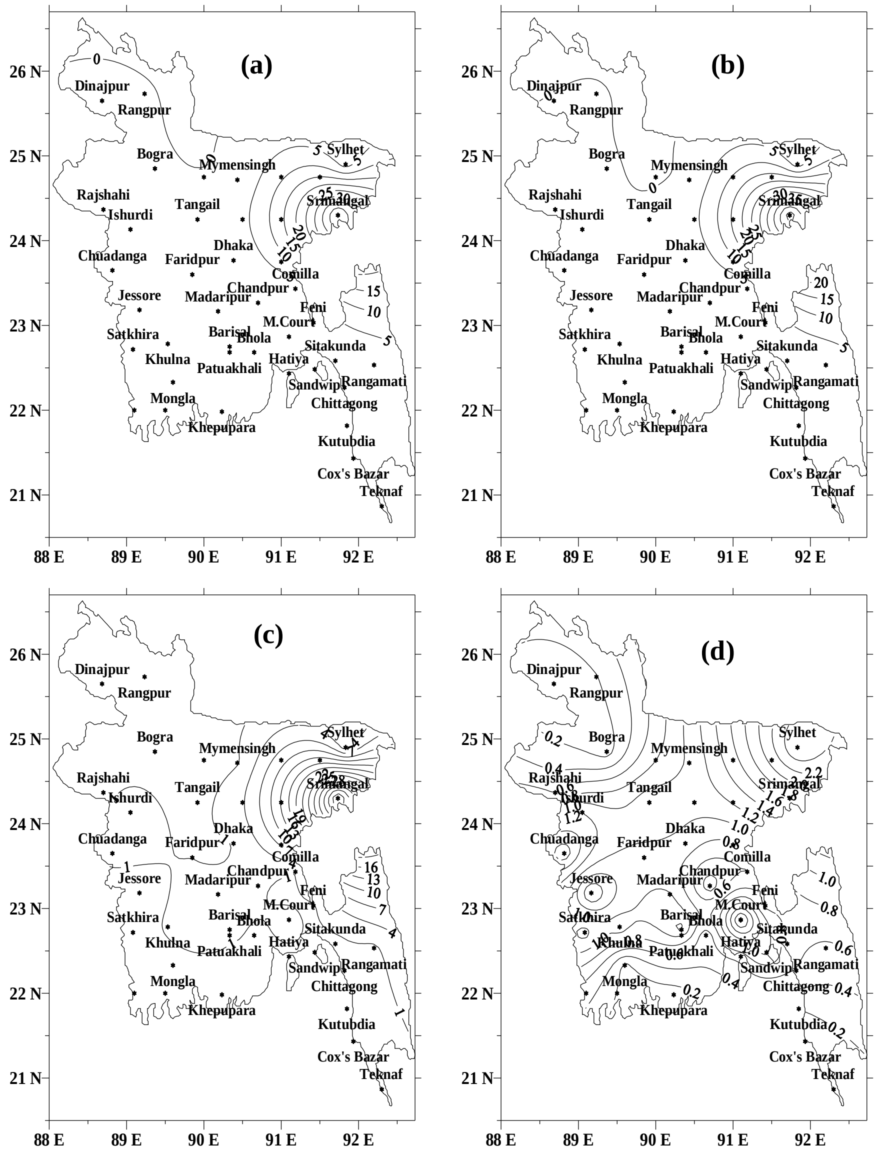

Fig. 4.3.4: Distribution of MAE of rainfall for (a) 24, (b) 48, (c) 72 hours and (d) 107 days prediction of March 2014 all over Bangladesh

The daily MAE of 72 hour lead time predicted rainfall for March 2014 (Fig. 4.3.4c) is simulated minimum all over Bangladesh except in the northeastern part of Srimangal. The lowest value of daily MAE of rainfall at all region of Bangladesh is almost 0-2 mm where as in northeastern region the maximum daily MAE has been calculated i.e. Srimangal this value is 40 mm. The daily MAE of rainfall using 24 hour lead time prediction has been decreased from northeastern region towards all region of Bangladesh.

The MAE of rainfall for 107 days prediction for March 2014 (Fig. 4.3.4d) is simulated minimum in the southeastern part i.e. Teknaf, Cox's Bazar and Kutubdia stations and its value is almost 0 mm. The minimum value of MAE of rainfall has also been found in the west and northwestern part i.e. Dinajpur, Rangpur, Bogra and Jessore. The daily MAE of rainfall is found maximum in the northeastern region at Sylhet is 2.6 mm.

From the analysis of 24, 48, 72 hours lead time and 107 days prediction of MAE of rainfall for March 2014, the MAE is minimum in the west, north, northwestern, Central and southwest regions of the country and maximum in the northeastern region. For the 107 days prediction the maximum value of MAE has also been found in the northeastern and southern regions. It has been observed that the MAE is found minimum where the rainfall is minimum and vice versa. The MAE of rainfall is almost similar for 24, 48 and 72 hours lead time prediction for all over the country for except 107 days prediction rainfall. The MAE of rainfall for 107 days prediction has been seen much lower value in northeastern region than those of 24, 48 and 72 hours lead time prediction.

4.3.5 MAE of Rainfall for April 2014

The daily MAE of 24 hour lead time predicted rainfall for April 2014 (Fig. 4.3.5a) is simulated minimum in all regions except in the central region towards east, west; north and southern region of Bangladesh and values are almost 0 mm in those regions. The daily MAE of rainfall is found maximum in the central region at Faridpur and its value is 70 mm. The daily MAE has been decreased from the central region towards the all stations of Bangladesh.

The daily MAE of 48 hour lead time predicted rainfall for March 2014 (Fig. 4.3.5b) is simulated minimum in all regions except in the central region towards east, west, north and southern region of Bangladesh and their values are 0-5 mm in those regions. 48 hour lead time predictions of daily MAE of rainfall of April is found maximum in the central region at

Faridpur and it is 75 mm. From the central region, the monthly average MAE has been decreased towards the all stations of Bangladesh.

The daily MAE of 72 hour lead time predicted rainfall for March 2014 (Fig. 4.3.5c) is simulated minimum in the south and southeastern regions at Bhola, Feni, M.court, Hatiya, Rangamati Chittagong and Teknaf stations and their value are almost 0 mm. 72 hour lead time prediction of daily MAE of rainfall has maximum value in the central region at Faridpur and it is 90 mm. The daily MAE of rainfall using 72 hour predictions have been decreased from central region towards south southeast region of the country.

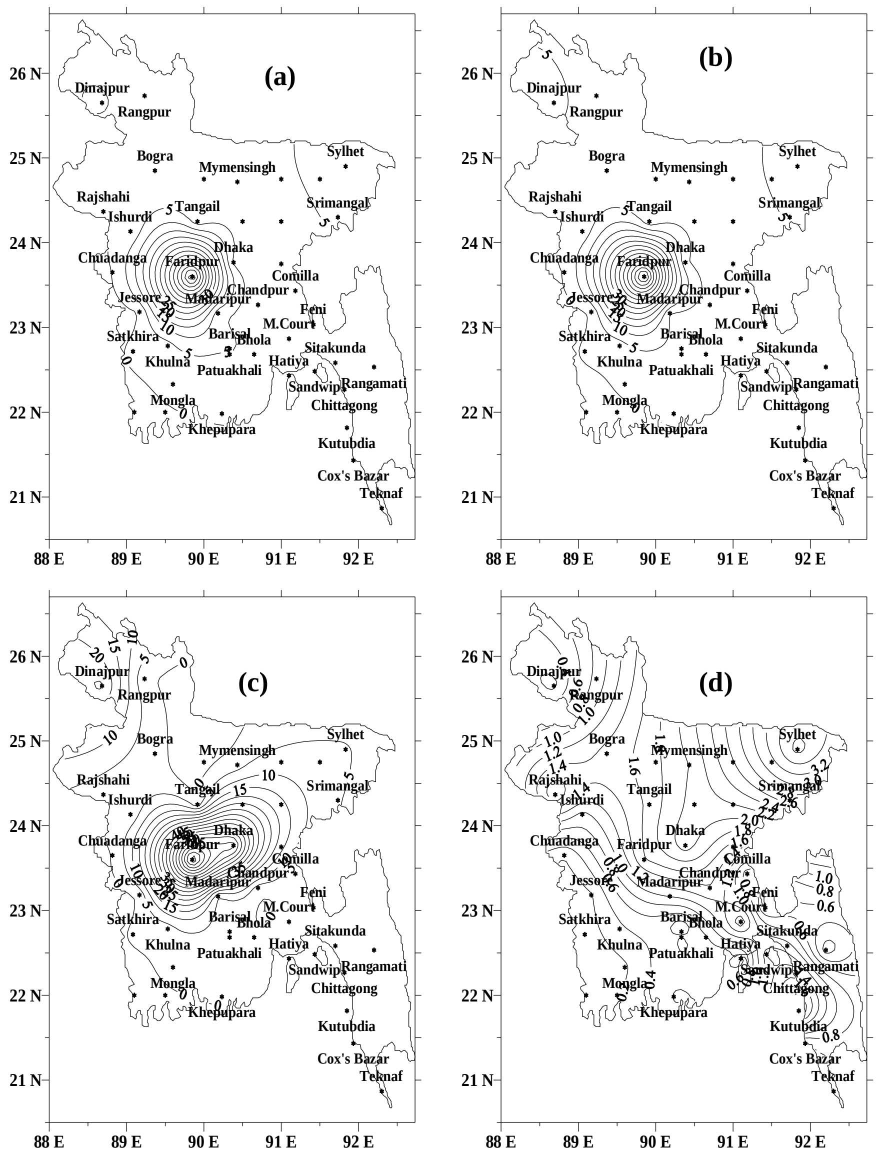

Fig. 4.3.5: Distribution of MAE of rainfall for (a) 24, (b) 48, (c) 72 hours and (d) 107 days prediction of April 2014 all over Bangladesh

The MAE of rainfall for 107 days prediction for March 2014 (Fig. 4.3.5d) is simulated minimum in the southeastern region i.e. Rangamati station and its value is very low. The minimum value of MAE of rainfall has also been found in southern region at Bhola, Feni, Hatiya stations and southwestern region at Satkhira, Khulna, Jessore and Mongla stations. The daily MAE of rainfall is found maximum in the northeastern region at Sylhet and it is 3.6 mm. Again, in the southeastern region i.e. Kutubdia its value is almost 2 mm. The daily MAE of rainfall for 107 days prediction has been decreased from northeast towards southwestern and southeastern regions of the country.

From the analysis of 24, 48, 72 hours lead time and 107 days prediction of MAE of rainfall for April 2014, it has been found that the MAE is minimum in the north, northwestern, southwest and southeastern regions of the country and maximum in the central region. For the 107 days prediction, the maximum value of MAE has also been found in the northeastern and southern regions. It has been observed that MAE is minimum where the rainfall is minimum and vice versa. The MAE of rainfall is almost similar among 24, 48 and 72 hours lead time prediction for all over the country except 107 days prediction rainfall. The MAE of rainfall for 107 days prediction has been seen much lower value in northeastern region than those of 24, 48 and 72 hours lead time prediction.

4.3.6 MAE of Rainfall for May 2014

The daily MAE of 24 hour lead time predicted rainfall for May 2014 (Fig. 4.3.6a) is simulated minimum in the north and northwestern regions at Chuadanga, Dinajpur, Rajshahi, Ishurdi, Mymensingh and Tangail stations and its value is 5 mm. The maximum value of MAE of rainfall has been simulated in northeastern region at Sylhet and its value is 28 mm. The MAE of rainfall has been decreased from central towards northwestern and western regions of the country.

The daily MAE of 48 hour lead time predicted rainfall for May 2014 (Fig. 4.3.6b) is simulated minimum in the western region at Chuadanga and its value is 5 mm. The minimum value of MAE of rainfall has also been found in north and northwestern regions The maximum value of MAE of rainfall has been found in the northeastern region at Sylhet and its value is 22 mm and also in the southeastern region i.e. Sandwip and Chittagong regions. The daily MAE of rainfall decreased from northeast towards western region.

The daily MAE of 72 hour lead time predicted rainfall for May 2014 (Fig. 4.3.6c) is simulated minimum in the southern at Bhola station and its value is 6 mm. The minimum value of MAE of rainfall has also been found in north and northwestern regions. The maximum value of MAE of rainfall has been found in the northeastern region at Sylhet and its value is 24 mm and also been simulated in southeastern region i.e. Cox's Bazar, Sandwip, Kutubdia and Rangamati stations. The daily MAE of rainfall have been increased from north-west towards northeast region of the country

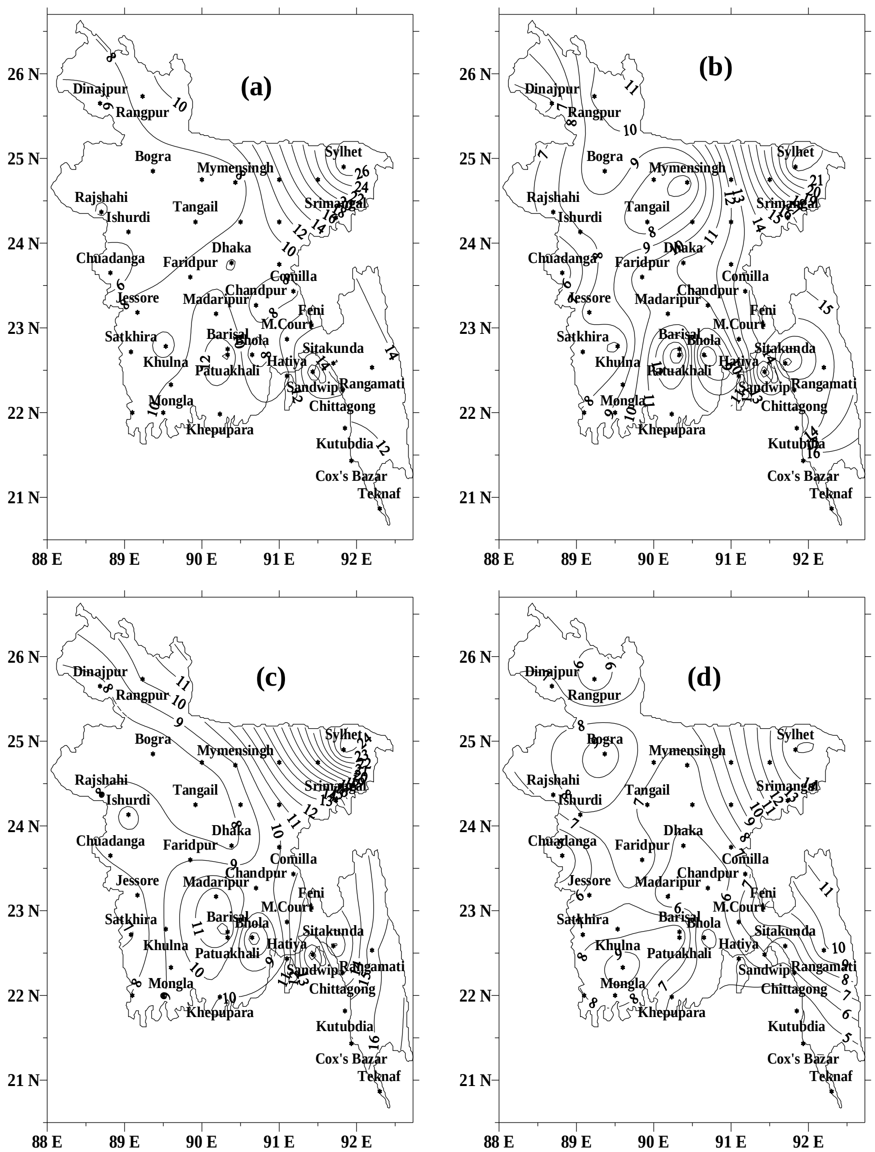

Fig. 4.3.6: Distribution of MAE of rainfall for (a) 24, (b) 48, (c) 72 hours and (d) 107 days prediction of May 2014 all over Bangladesh

The daily MAE of rainfall for 107 days prediction for May 2014 (Fig. 4.3.6d) is simulated minimum in the southeastern region i.e. Teknaf and its value is almost 3 mm and has also been simulated at Bhola, Kutubdia and Cox's Bazar stations. The MAE of rainfall is found maximum in the northeastern region at Sylhet and its value is 15 mm and has also been found in the southeastern part i.e. Rangamati, Southwestern part at Mongla stations and northwestern part at Bogra region and its value are almost 10 mm. The daily MAE of rainfall for 107 days predictions has been decreased from northeast towards southeast region of the country.

From the analysis of 24, 48, 72 hours lead time and 107 days prediction of MAE of rainfall for May 2014, it has been found that the MAE is minimum in the north, northwestern and southwest regions of the country and maximum in the northeastern and southeastern regions of the country. For 107 days prediction, the maximum value of MAE has also been found in the northeastern and southern regions, and also in the northwestern and southwestern regions. It has been observed that the MAE has minimum where the rainfall is minimum and vice versa. The MAE of rainfall is almost similar among 24, 48 and 72 hours lead time prediction for all over the country except 107 days prediction rainfall. The MAE of rainfall for 107 days prediction has been seen much lower value in northeastern region than those of 24, 48 and 72 hours lead time prediction.

4.4 Correlation coefficients (CC)

Distribution of CC between observed and 24 hour predicted rainfall for March, April and May 2014 has been presented in Fig. 4.4.1-4.4.3 and discussed in the following sub-sections.

4.4.1 Distribution of Correlation Coefficients (CC) between the simulated and observed rainfall for March 2014

Distribution of CC between observed and 24 hour predicted rainfall for March 2014 has been presented in Fig. 4.4.1(a). The CC has been obtained maximum in the southeastern, southern and western regions. At Rangamati, Cox's Bazar, Jessore, Sitakunda and Patuakhali stations, the CC have been found maximum and its value are 0.995, 0.95, 0.90, 0.8 and 0.71 respectively. The minimum CC has been calculated in the central, north, northwest and northeastern regions of the country.

Distribution of CC between observed and 48 hour predicted rainfall for March 2014 has been presented in Fig. 4.4.1(b). The CC has been obtained maximum in the north northwestern, southwestern, central and southeastern regions. At Tangail, Bogra, Jessore, Chuadanga, Khulna, Mongla, Barisal, Dhaka, Madaripur, Rangamati and Cox's Bazar regions, the CC have been found maximum and its value are 0.989, 0.975, 0.968, 0.935, 0.922, 0.925, 0.978, 0.984, 0.995 and 0.987 respectively. The minimum CC has been obtained in the northeast, west and northwest region of the country.

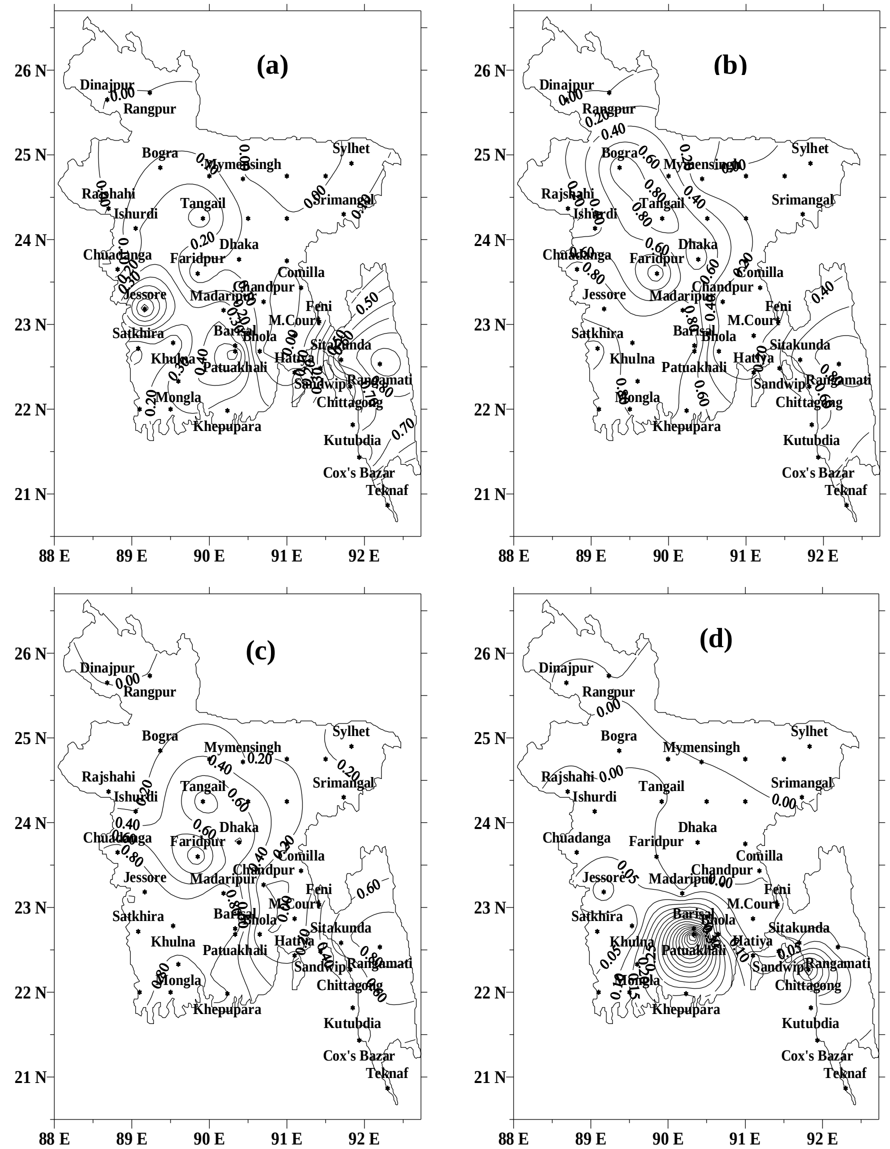

Fig. 4.4.1: Distribution of correlation coefficient of rainfall for (a) 24, (b) 48, (c) 72 hours and (d) 107 days prediction of March 2014 all over Bangladesh

Distribution of CC between observed and 72 hour lead time predicted rainfall for March 2014 has been presented in Fig. 4.4.1(c). The CC has been obtained maximum in the north, west, central, southwest and southeastern regions. At Tangail, Chuadanga, Jessore, Barisal, Madaripur, Khulna, Satkhira and Rangamati regions, the CC have been found maximum and its value are 0.956, 0.955, 0.986, 0.994, 0.987, 0.953, 0.946 and 0.987 respectively. The minimum CC has been found in the northwest, northeastern and central towards eastern regions of the country.

Distribution of CC between observed and simulated rainfall for 107 days predicted for March 2014 are shown in Fig 4.4.1(d). The CC has been obtained maximum in the southern and southeastern regions at Barisal, Patuakhali and Chittagong region and their values are 0.566, 0.998 and0.357 respectively. The minimum rainfall has been found from the central to northwest and southeastern region as a whole and those values are almost 0 mm. From the southern region, the CC has been decreased towards the north, northwest and northeastern regions of Bangladesh.

4.4.2 Distribution of Correlation coefficients between the simulated and observed rainfall for April 2014

Distribution of CC between observed and 24 hour predicted rainfall for April 2014 has been presented in Fig. 4.4.2(a). The CC has been obtained maximum in the western, eastern and southeastern regions at Ishurdi, Comilla, Cox’s Bazar and Teknaf stations and their values are 0.443, 0.496, 0.489 and 0.802 respectively. The minimum CC has been found in the northern, northwest, northeast and southwestern regions i.e. at most of the places of the country.

Distribution of CC between observed and 48 hour predicted rainfall for April 2014 has been presented in Fig. 4.4.2(b). The CC has been obtained maximum in the northern, southern and southeastern regions at Tangail, Bhola, Hatiya, Cox’s Bazar and Teknaf stations and their value are 0.783, 0.622, 0.438, 0.60 and 0.797 respectively. The minimum CC has been found in the northwest, northeast and southwestern regions of the country.

Distribution of CC between observed and 72 hour predicted rainfall for April 2014 has been presented in Fig. 4.4.2(c). The CC is simulated maximum in the central to northern and southeastern regions at Dhaka, Tangail Cox’s Bazar and Teknaf stations and their value are 0.426, 0.606, 0.666 and 0.953 respectively. The minimum CC has been obtained in the northwest, northeast and southwestern regions at most of the places of the country and their value are almost 0 mm.

Distribution of CC between observed and simulated rainfall for 107 days predicted time for March 2014 are shown in Fig 4.4.2(d). The CC has been obtained maximum in the central and northwestern regions at Faridpur, Madaripur and Rajshahi stations and their values are

0.296, 0.42 and 0.323 respectively. The minimum CC has been found in the northwest, northeast, southern, southwest and southeastern regions of the country.

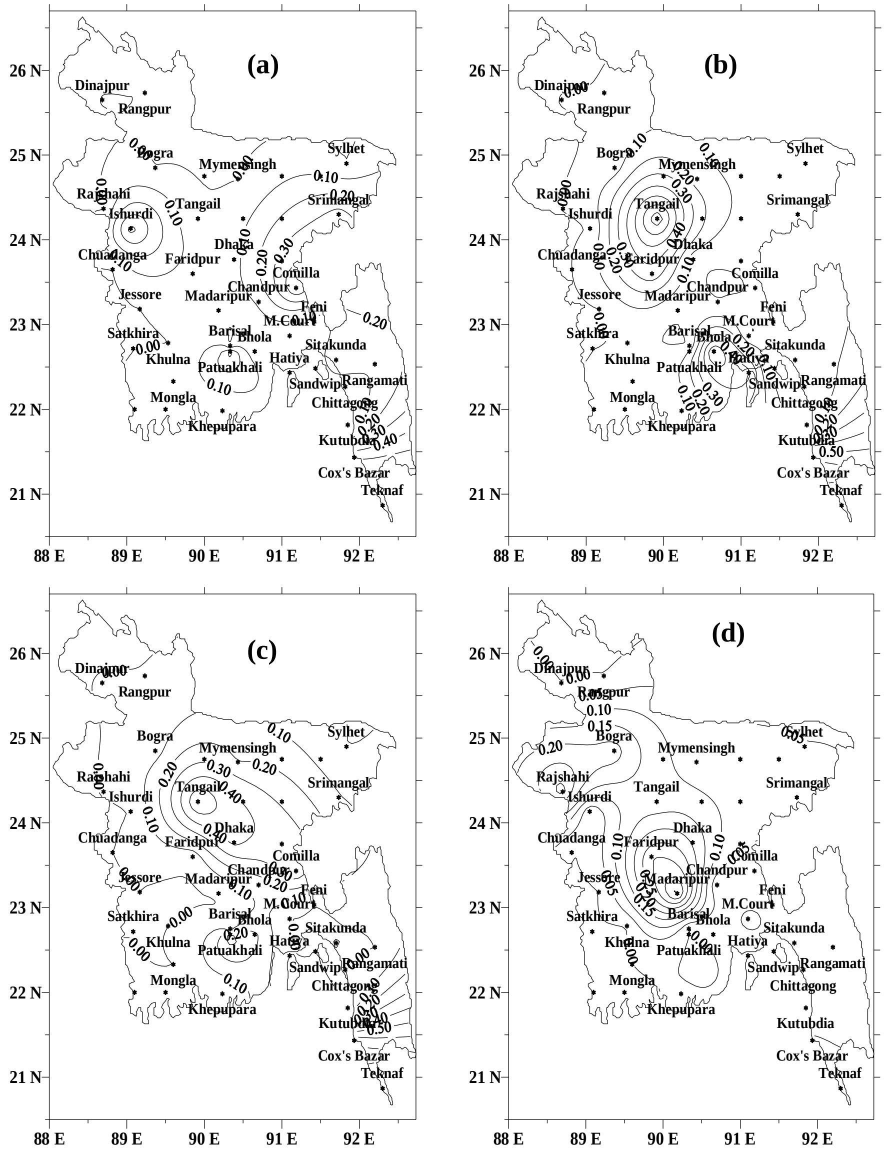

Fig. 4.4.2: Distribution of correlation coefficient of rainfall for (a) 24, (b) 48, (c) 72 hours and (d) 107 days prediction of April 2014 all over Bangladesh

4.4.3 Distribution of Correlation coefficients between the simulated and observed rainfall for May 2014

Distribution of CC between observed and 24 hour predicted rainfall for May 2014 has been presented in Fig. 4.4.3(a). The CC has been obtained maximum in the northwest, east and southern regions at Dinajpur, Comilla and Hatiya stations and their values are 0.405, 0.358

and 0.285 respectively. The minimum CC has been found in the central to northern, northeast, southwest and southeastern regions of the country.

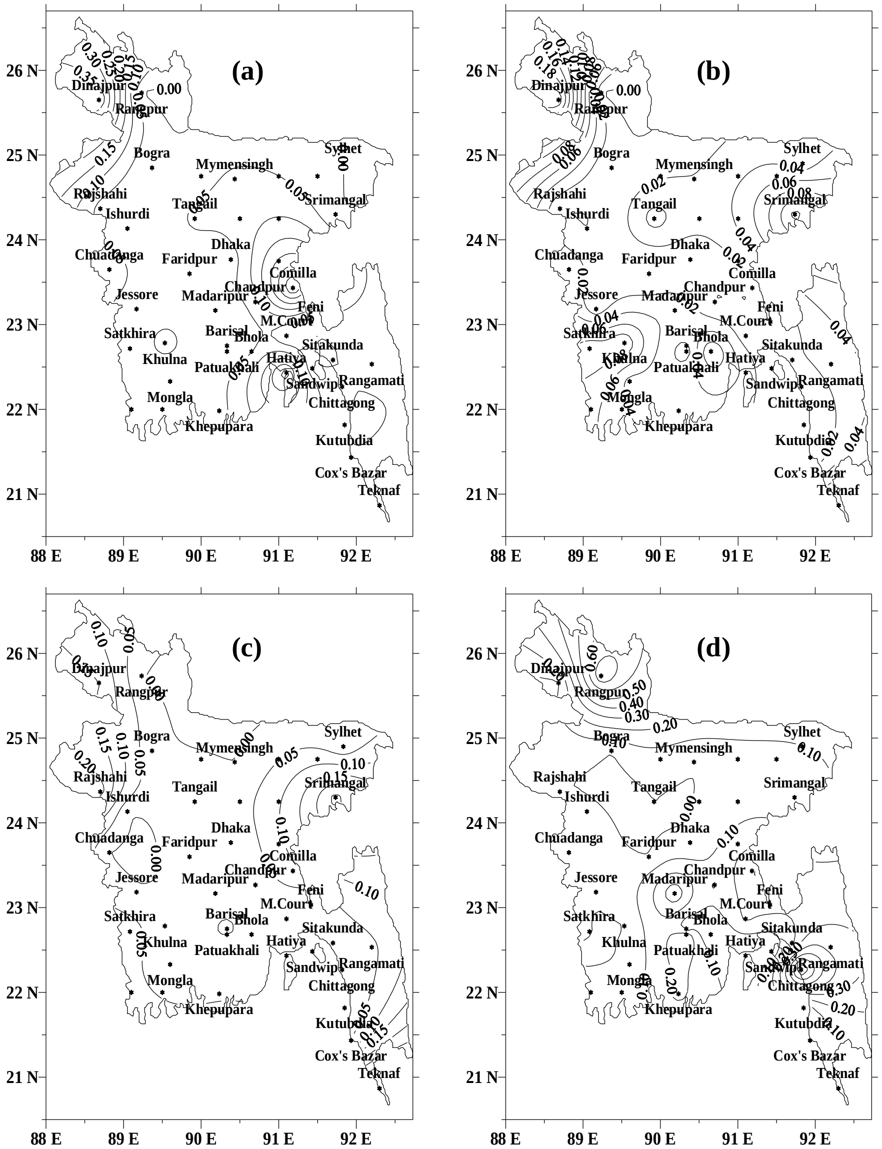

Fig. 4.4.3: Distribution of correlation coefficient of rainfall for (a) 24, (b) 48, (c) 72 hours and (d) 107 days prediction of May2014 all over Bangladesh

Distribution of CC between observed and 48 hour predicted rainfall for May 2014 has been presented in Fig. 4.4.3(b). The CC has been obtained maximum in the northwest, northeast and southwestern regions at Dinajpur, Srimangal, Khulna and Satkhira stations and their values are 0.218, 0.128, 0.099 and 0.094 respectively. The minimum CC has been found in the central to northern, western, southern and southeastern regions of Bangladesh.

Distribution of CC between observed and 72 hour predicted rainfall for May 2014 has been presented in Fig. 4.4.3(c). The CC has been obtained maximum in the northwest, northeast and southeastern regions at Dinajpur, Rajshahi, Srimangal and Teknaf stations and their values are 0.152, 0.225, 0.269 and 0.436 respectively. The minimum CC has been found in the central to northern, southwestern and southern regions of Bangladesh.

Distribution of CC between observed and obtained rainfall for 107 days predicted time for May 2014 are shown in Fig 4.4.3(d). The CC is simulated maximum in the central, northwestern and southeastern regions at Rangpur, Madaripur, and Chittagong and Rangamati stations and their values are 0.789, 0.394, 0.823 and 0.363 respectively. The minimum CC has been found in the northern, western, northeast, southern and southwest regions of the country.

Chapter V

Conclusions

In the present study, the WRF-ARW model V3.5.1 have been used to simulate the station wise monthly rainfall in the pre-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. The WSM6-class microphysics scheme coupling with Kain-Fritsch cumulus parameterization scheme have been used for the prediction of pre-monsoon rainfall. The model has been integrated by using initial and LBCs from NCEP-FNL analysis available at six hourly intervals. Surface layer is treated using Monin-Obukhov and PBL 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 is run 107 days for 107 days prediction starting with the initial condition of 0000 UTC of 14 February up to 0000 UTC of 01 June for the year of 2010-2014. The model is also run for 72 hours with every day at 0000 UTC initial conditions for 94 days starting from the initial condition at 0000 UTC of 27 February for the prediction of 24, 48 and 72 hours lead time rainfall in the month of March, April and May 2014. In this research, convective and non-convective rainfall have been extracted from the WRF model output at 3 hourly interval then made daily and monthly total rainfall data for 24, 48, 72 hours and 107 days during the studied period. We have compared this data with the observed rainfall at 33 meteorological stations of BMD and station point TRMM rainfall. BMD observed and 24, 48, 72 hours and 107 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 March, April and May during 2010-2014 are almost similar but TRMM derived rainfall have been found near one third of the observed rainfall and found minimum in the central to west-northwestern regions of the country.

The distribution patterns of model simulated 24, 48 and 72 hours lead time predicted rainfall during the month of March, April and May in 2014 are almost similar to that of observed rainfall all over the country. The distribution patterns of 24, 48 and 72 hours lead time, observed and TRMM rainfall have been found minimum in the west, northwest and southwest regions and maximum in northeastern and south-southeastern regions of the country. The 24, 48 and 72 hours predicted rainfall has comparable with the observed rainfall during pre-monsoon season in the central to southwest and northeastern regions. The 107 days predicted rainfall is found maximum in the central to northeastern and southeastern regions and minimum in the west, southwest and northwestern regions of the country. For 107 days prediction overestimated for the month of May of 2010, 2011 and 2013**.** The 107 days and 24, 48 and 72 hours lead time predicted rainfall has been comparable with the observed rainfall with little exception during pre-monsoon season of 2014.

The RMSE is found minimum in the northwest, west and southwestern region for 24, 48 and 72 hours lead time prediction rainfall and there values are very low for March, April and May. The RMSE is found maximum always for 107 days predicted rainfall. The patterns of RMSE of rainfall for 24, 48 and 72 hours lead time and 107 days prediction during the month of March, April and May are almost similar but the value of RMSE for 107 days prediction has been simulated much higher than those of 24, 48 and 72 hours and for the month of March and April 2014 rainfall and maximum value of RMSE have seen in the northeastern, central and southern regions. The minimum value of RMSE of rainfall for 24, 48 and 72 hours prediction are within 0, 0-1 and 1-5 mm respectively all over Bangladesh. It has also been observed that where the rainfall has low - medium (heavy) the RMSE has also low (high).

The minimum value of MAE of rainfall of March, April and May for 24, 48 and 72 hours lead time prediction are within 0, 0 and 0-5 mm respectively and maximum value have found in the central and northeastern region of Bangladesh. The MAE for 107 days predicted rainfall is much higher in the northeast regions. It has also been observed that where the rainfall has low - medium (heavy) the MAE have also low (high).

Maximum CC has been shown at southern and southeastern regions and the minimum CC has been found in the northern, northwest and southwestern regions of the country. On the basis of above finding it may be concluded that WRF model is suitable for the prediction of pre-monsoon rainfall.

REFERENCES

Ahmed, R., 1989: Probabilistic estimates of rainfall extremes in Bangladesh during the pre-monsoon season, Indian Geographical Journal 64, 39–53.

Ahmed, R. and Karmakar, S., 1993: Arrival and withdrawal dates of the summer monsoon in Bangladesh" .Int. J. Climatol., 13, 727-740

Alam, M. M. and Hossain, M. A., 2002: Correlation between Winter Temperature and Monsoon rainfall over Bangladesh, Biennial Symposium on Physics and Modern Development, 30-31 AEC, Dhaka, Bangladesh.

Alam, M. M. and Hossain, M. A., 2004: Correlation between Winter Temperature and Post-monsoon rainfall over Bangladesh, International Conference on Physics for Understanding and Applications 22-24 February, BUET, Dhaka, Bangladesh.

Alam, M. M., Hossain, M. A. and Shafee, S., 2002: Statistical Analysis of Cyclones and Depressions in the Bay of Bengal during 1974 – 1999, Journal of Bangladesh Academy of Sciences, 207-218.

Banerjee, A. K., Sen, P. N. and Raman, C. V. R., 1978: On four-shadowing south-west monsoon rainfall over India with mid-tropospheric circulation anomaly of April, Indian Journal of Met. Hydrology geophysics, 29, 1 & 2, 425-431.

Begum, J., Rafiuddin, M., Islam, M. N. And Uyeda, H., 2013: classification of arc-shaped precipitation systems during pre-monsoon and monsoon in Bangladesh, Bangladesh Journal of Physics: 29-39.

Chen, J. Y. and Sun, Y., 2002: Hydrolysis of lignocellulosic materials for ethanol production, a review, Bi ore source technology 83(1):1-11.

Deardorff, J. W., 1972: Parameterization of the planetary boundary layer for use in general circulation models, Mon. Wea. Rev., 100, 93–106.

Dudhia, J., 1989: Numerical study of convection observed during the winter monsoon experiment using mesoscale two-dimensional models, J. Atmos. Sci., 46, 3077-3107

Fritsch, J. M. and Chappell, C. F., 1980: Numerical Prediction of Convective Driven Mesoscale Pressure Systems, Part I: Convective Parameterization, J.Atoms.sci.37, 1722- 1733.

Fukushima, A., 2012: Determination of the premonsoon period and interannual variations of the premonsoon rainfall in the Himalayan foothills, J. Agrofor. Environ. 6 (2): 21-24.

Hong, S. Y., Dudhia J. and Chen, S. H., 2004: A Revised Approach to Ice Microphysical Processes for the Bulk Parameterization of Clouds and Precipitation, Mon. Wea. Rev., 132, 103-120.

Hong, S. Y. and Lim, J., 2006: The WRF Single-Moment 6-Class Microphysics Scheme (WSM6), J. Korean Meteor. Soc., 42, 129–151.

Hong, S. Y., Noh, Y. and Dudhia, J., 2006: A new vertical diffusion package with an explicit treatment of entrainment processes, Mon. Wea. Rev., 134, 2318-2341.

Hossain, M. S. and Roy, K. and Datta, D. K., 2014: Spatial and Temporal Variability of Rainfall over the South-West Coast of Bangladesh, Climate 2014, 2, 28-46.

Kain, J. S. and Fritsch J. M., 1990: A one-dimensional entraining/detraining plume model and its application in convective parameterization. J. Atmos Sci, 47, 2784-2802.

Kain, J. S., Fritsch, J. M., 1993: Convective parameterization for mesoscale models: the Kain-Fritsch scheme. The representation of cumulus convection in numerical models, Meteo. Monogr, No. 46 Amer. Meteor. Soc., 165 – 170.

Kanamitsu, M. A. and Krishnamurti, T. N., 1978: Northern summer tropical circulation during drought and normal rainfall months, Mon. Wea. Rev., 106, 331-347.

Kanaujia, J. N., Kaur, S. and Upadhyay, D. S., 1992: Behaviour of spatial rainfall correlation for short distance, Mausam, 43(3), 269-272.

Karmakar, S. and Khatun, A., 1995: Variability and probabilistic estimates of rainfall extremes in Bangladesh during the southwest monsoon season, Mausam 46(1): 47–56.

Khan, F. K. & Islam, M. A., 1966: Water balance of East Pakistan. Orient. Geogr. 10, 1-9.

Kodama, Y. M., Ohta, A., Katsumata, M. and Mori, S., 2005: Seasonal transition of predominant precipitation type and lightning activity over tropical monsoon areas derived from TRMM observations, Geophysical research letters, 32, 1-4.

Kumar, R., Barth, M. C., Pfister, G. G., Naja, M. and Brasseur, G. P., 2014: WRF-Chem simulations of a typical pre-monsoon dust storm in northern India: influences on aerosol optical properties and radiation budget, Atmos. Chem. Phys. 2431–2446.

Kumar, R., Barth, M. C., Madronich, Naja, M., Carmichael, G. R., Pfister, G. G., Knote, C., G. P. Brasseur, G.P., Ojha, N. and Sarangi, T., 2014: Effects of dust aerosols on tropospheric chemistry during a typical pre-monsoon season dust storm in northern India, Atmos. Chem. Phys. 6813–6834.

Lin, Y.L ., Farley, R. D. and Orville, H. D., 1983: Bulk parameterization of the snow field in a cloud model, J. Climate Appl. Meteor., 22, 1065-1092.

Litta, A. J., Mohanty, U. C. and Indicula, S. M., 2012: The diagnosis of severe thunderstorms with high-resolution WRF model, J. Earth Syst. Sci., 121, 2, 297–316.

Madala, S., Satyanarayana, A. N. V. and Tyagi, D., 2013: Performance Evaluation of Convective Parameterization Schemes of WRF-ARW Model in the Simulation of Pre-monsoon Thunderstorm Events over Kharagpur using STORM Data Sets, International Journal of Computer Applications (0975 – 8887), 71, 15, 43-50

Mlawer, E. J., Taubman, S. J., Brown, P. D., Lacono, M. J. and Clough, S. A., 1997: Radiative transfer for inhomogeneous atmosphere: RRTM, a validated correlated-k model for the longwave, J. Geophys. Res., 102(D14), 16663-16682.

Pleim, J., 2007: A combined local and non-local closure model for the atmospheric boundary layer. Part II: Application and evaluation in a mesoscale meteorological model", J. Applied Meteor. Climatology, 46, 1396–1409.

Rafiuddin, M., Uyeda, H. and Kato, M., 2013: Development of an arc-shaped precipitation system during the pre-monsoon period in Bangladesh, Meteorol Atmos Phys (2013) 120, 165–176.

Rahman, M. R., Salehin, M. and Matsumoto J., 1997: Trends of monsoon rainfall pattern in Bangladesh, Bangladesh Journal of Water Resources 14–18: 121–138.

Ramage, C. S., 1971: Monsoon Meteorology, Academic Press, New York, p.6.

Rao, Y. P., 1976: Southwest Monsoon, Meteorological Monograph: Synoptic Meteorology No. 1, 1-367.

Roy, M., 2013: Time Series, Factors and Impacts Analysis of Rainfall in North-Eastern Part in Bangladesh, International Journal of Scientific and Research Publications, Volume 3, 1-7.

Sanderson, M. and Ahmed, R., 1978: Pre-monsoon rainfall and its variability in Bangladesh: a trend surface analysis, Hydrological Sciences-Bulktin-des Sciences Hydrologiques, 24, 3, 9/79, 277-287.

Shamsuddin, S. D. and Ahmed R., 1974: Variability of annual rainfall in Bangladesh, J. of Bangladesh National Geographical Association, 13-20.

Shahid, S., 2010: Rainfall variability and the trends of wet and dry periods in Bangladesh, International journal of climatology, 30: 2299–2313.

Shin, H. H. and Hong, S. U., 2011: Intercomparison of Planetary Boundary-Layer Parametrizations in the WRF Model for a Single Day from CASES-99.

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D. M., Wang, W. and Powers, J. G., 2005: A Description of the Advanced Research WRF Version 2, NCAR Tech Note, NCAR/TN-468+STR, 88 pp. (http://box.mmm. ucar.edu /wrf/ users/docs/arw_v2.pdf).

Thompson, A. M., Chatfield R. B., Guan H. and Smit H. G. J., 2007: Mechanisms for the intraseasonal variability of ozone during the India winter monsoon, J. Geophys. Res. 112, D10303.

Tyagi, B. and Satyanarayana, A. N. V., 2013: The Budget of Turbulent Kinetic Energy during Premonsoon Season over Kharagpur as Revealed by STORM Experimental Data, Hindawi Publishing Corporation ISRN Meteorology Volume 2013, Article ID 972942, 1-11.

Upadhyay, D. S., Kaur, S., Misra, M. S. and Gupta M. K., 1990: Space correlation structure of rainfall over India, Mausam, 41(4), 523-530.

Verma, R. K., 1980: Importance of upper tropospheric anomalies for long range forecasting of Indian summer monsoon activity, Mon. Wea. Rev.108, 230-233.

Verma, R. K., 1982: Long range predictions of monsoon activity: A synoptic diagnostic study, Mausam, 33(1), 35-44.

WMO/UNDP/BGD/79/013, 1986: Bangladesh Meteorological Department Climatological data and charts (1961-80), Tech. Note No.9.