STUDY ON SENSITIVITY OF MICROPHYSICS FOR THE SIMULATION OF RAINFALL FOR THE MONTH OF MAY 2015 OVER BANGLADESH USING HIGH RESOLUTION WRF-ARW MODEL

M. Sc. Thesis

BY

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ROLL NO.: 1755503

SESSION: JANUARY-2017

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

DEPARTMENT OF PHYSICS

KHULNA UNIVERSITY OF ENGINEERING & TECHNOLOGY

KHULNA – 9203, BANGLADESH

MARCH– 2019

DECLARATION

This is to certify that the thesis work entitled "***Study on Sensitivity of Microphysics for the simulation of Rainfall for the Month of May 2015 over Bangladesh using High Resolution WRF-ARW Model***" has been carried out by Md. Salman Khan 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.

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Approval

This is to certify that the thesis submitted by ***Md. Salman Khan*** entitled ***"Study on Sensitivity of Microphysics for the Simulation of Rainfall for the Month of May 2015 over Bangladesh using High Resolution WRF-ARW Model"*** has been accepted by the Board of Examiners for the partial fulfillment of the requirements for the degree of M. Sc. in the Department of Physics, Khulna University of Engineering & Technology, Khulna, Bangladesh on 28 March 2019.

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MY PARENTS

Acknowledgements

First of all I express all my admiration and devotion to the almighty Allah, the most beneficent who has enabled me to perform this research work and to submit this thesis. With my great manner to express my deepest sense of gratitude and indebtedness to my reverend supervisor Professor Dr. Md. Mahbub Alam, Head, Department of Physics, Khulna University of Engineering & Technology (KUET), Khulna, for his kind guidance and supervision and for his constant encouragement throughout the research work. His inspiration and friendly co-operation has accelerated my work.

I am indebted to Professor Dr. Shibendra Shekher Sikder for his strong support in various ways during the entire period of my study in this department. I express my heartfelt gratitude and thanks to Professor Dr. Md. Abdullah Elias Akhter and Professor Dr. Jolly Sultana Department of Physics, Khulna University of Engineering & Technology.

I gratefully acknowledge Mr. Md. Kamrul Hasan Reza, Associate Professor, and Mr. Sujit Kumar Shil, Md. Alamgir Hossain, Mr. Suman Halder and Suman Debnath, Assistant Professor of Department of Physics, Mr. Probal Roy, Md. Saifullah, Md. Idrish Ali, Lecturer of Department of Physics, KUET for their co-operation regarding writing the thesis.

I would like to give thanks from deep of my heart to my parents Md. Aliboddin Khan and Mst. Jharna Begum and my sister Khadiza Akter and Nawaz Mahmud Nahid for their comprehensive mental support and love. I have not much word to express my gratefulness to them.

I am highly indebted and thoroughly grateful to Korno Kumar Mandol, Debroto Biswas, Md. Adnan Fihir, Suman Kumar Das, KUET for providing their kind help throughout this work. My personal thankful greetings are to my good friends Md. Razu Ahammed, Mahafuz Miah and Kazi Aminul Islam for their help and co-operation. There are numerous people who could not be mentioned individually but their interesting discussions have prompted much thought on various aspects.

I am grateful to the KUET authority for approval of the project in the 47 meeting of CASR, agenda no. 05/03/18 and providing me the relevant facilities to complete this research work.

Finally, I want to express my gratitude to almighty Creator for his mercy.

Md. Salman Khan

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Nomenclature

ARW	:	Advanced Research WRF
AFWA		Air Force Weather Agency
AVHRR		Advanced Very High Resolution Radiometer
BMD	:	Bangladesh Meteorological Department
BoB	:	Bay of Bengal
CCN		Cloud Condensation Nuclei
CP	:	Cumulus Parameterization
ECMWF		European Centre for Medium–Range Weather Forecasts
EUMETSAT		European Organization for the Exploitation of Meteorological Satellites
FAA		Federal Aviation Administration
FSL		Forecast Systems Laboratory
FNL	:	Final Reanalysis
GCM		General Circulation Models
KF	:	Kain-Fritsch
LCC	:	Lambert Conformal Conic Projection
LES		large eddy simulation
LBC		lateral boundary conditions
Lin		Lin *et al*
MCS	:	Mesoscale Convective System
MP	:	Microphysics
MRF	:	Medium Range Forecast
M2-M		Morrison 2-Mom
NCEI		National Centers for Environmental Information
NCAR	:	National Center for Atmospheric Research
NCEP	:	National Centers for Environmental Prediction
NE	:	Northeastern
NOAA		National Oceanic and Atmospheric Administration
NRL		Naval Research Laboratory
NS	:	New Simplified Arakawa-Schubert
NSH	:	New SAS Hurricane Weather Research Forecast
N-NE	:	North-Northeastern
N-NW	:	North-Northwestern
NW	:	Northwestern
NWP	:	Numerical Weather Prediction
OLR	:	Outgoing Long Wave Radiation
PBL	:	Planetary Boundary Layer

PERSIANN		Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks
RH		Relative Humidity
RRTM	:	Rapid Radiative Transfer Model
SD		Standard Deviation
SE	:	Southeastern
SEVIRI		Spinning Enhanced Visible and Infrared Imager
S-SE	:	South-Southeastern
S-SW	:	South-Southwestern
SPCS		State Plane Coordinate System
SW	:	Southwestern
SBU		SBU-YLin
STS		Severe Thunderstorms
TOA		Top–of–the–Atmosphere
TIROS		Television Infrared Observation Satellite
TH	:	Thomson
TRMM	:	Tropical Rainfall Measuring Mission
UTC	:	Universal Time Co-ordinate
WSM6		WRF single-moment 6-class
WDM6	:	WRF double-moment 6-class
WMO	:	World Meteorological Organization
WRF	:	Weather Research and Forecasting
YSU	:	Yonsei University Scheme

Abstract

In the present study, the Advanced Research WRF (ARW) model v3.8.1 has been used to simulate the rainfall for the month of May 2015 all over Bangladesh. The initial and boundary conditions are drawn from the global operational analysis and forecast products of National Center for Environmental Prediction (NCEP-FNL) available at $1^{\circ}\times1^{\circ}$ resolution. The model was configured in nested domain with 18 and 6 km horizontal grid spacing with 100×96 and 103×127 grids respectively in the east-west north-south directions with 30 vertical levels. Time step of integration is set to 90 and 30 seconds for maintaining computational stability as the model uses third-order Runge-Kutta time integration scheme. In this research, six different microphysics schemes such as Lin *et al.*, WSM6, Thomson, Morrison Double-Moment (M-2M), Stony Brook University (SBU), and WDM6 coupling with Kain-Fritsch (KF) cumulus parameterization scheme has been used to simulate the monthly total rainfall, monthly heavy rainfall, monthly rainy days and monthly heavy rainy days for the month of May 2015 all over Bangladesh. The outputs obtained by using different microphysics are compared with the observed outputs at 33 meteorological stations of BMD and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) output. Standard deviation of all observed, PERSIANN and model simulated parameters have been analyzed and compared.

The maximum monthly observed rain of May 2015 at Sylhet is 752 mm but WSM6, M-2M and WDM6 schemes have simulated 831, 788 and 742 mm for day 1 prediction; WSM6, WDM6 and SBU-Lin schemes have simulated 757, 916 and 981 mm for day 2 prediction and WSM6 and WDM6 schemes have simulated 741 and 925 mm for day 3 prediction, respectively and all other MPs have simulated much higher rainfall at domain (D1). The WDM6, M-2M and Lin *et al.* schemes have simulated 744, 807 and 923 mm for day 1 prediction, WSM6 and WDM6 schemes are 714 and 877 mm for day 2 predictions and WSM6, SBU-Lin and Lin *et al.* schemes are 802 and 913 and 998 mm, respectively for day 3 prediction at domain (D2). WDM6 scheme gives the better performance of rainfall and rainy days all over the country.

Chapter I
Introduction

Bangladesh is situated in the northeastern part of South Asia within 88.02–92.68^{o}E and 20.57–26.63^{o}N.The land of Bangladesh is very flat: Elevation is about 1–37 m above sea level except small portions in the southeast (elevation about 200 m) which has border with Myanmar and in the northeast (elevation about 100 m) which has border with Shilling hill of India. The major source of water available either for agriculture or for human consumption is obtained from the rain that falls on the earth's surface. Rainfall in our country varies greatly in space and time.

Pre-monsoon season is synonymous with heat and humidity with uncomfortable conditions throughout the day and night. Pre-monsoon showers are accompanied by squally winds of thunderstorms but during Monsoon, winds, especially the winds are persistently strong. Pre-monsoon season is the hottest part of the year over almost the entire South Asian region (Kothawale *et al.,* 2010). Ahmed (1989, 1995) studied the spatial distribution of pre-monsoon seasonal rainfall (PSR) and its variability over Bangladesh. PSR contributes a significant amount of the total annual rainfall, besides monsoon rainfall. This is because in the winter season (December–February) and post-monsoon season (October–November) rainfall amount is low, except for a few cyclonic storms, which lead to heavy showers over the affected region.

The mean temperature of Bangladesh during the summer months varies between 23-30^{o}C. April and May are the hottest months (Khatun *et al.,* 2016). The highest maximum temperature ranging from 36-40^{o}C is attained in the northwestern and southwestern districts. When the maximum temperature goes above 36°C heat wave situation occurs over Bangladesh. The heat wave is classified as mild heat wave (maximum temperature lies between 36-38°C), moderate heat wave (maximum temperature lies between 38-40°C), and severe heat wave (maximum temperature greater than 40°C). Due to intense heating of the land surface heat low develops over Bihar, West Bengal of India and adjoining northwestern part of Bangladesh. Occasionally, moisture incurs in the afternoon from the Bay of Bengal to that low pressure resulting in the formation of thunder cloud and development of severe thunderstorms. These severe thunderstorms are known as Nor'westers that often accompanied by destructive squalls, thunder, lightning and heavy rainfall with hails. During the pre-monsoon season, Nor'westers occur frequently at many places over Bangladesh. Due to heavy rainfall associated with severe thunderstorm in the northeastern part of Bangladesh and adjoining northeastern states of India, flash flood occurs in the northeastern part of Bangladesh. Only 19 % of the total annual rainfall occurs in this season.

Bangladesh is a country of tropical monsoon climate. During the pre-monsoon season, its climate is characterized by high temperatures and thunderstorms. April is the hottest month in this season. Average 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 (BoB).

In Bangladesh, rainy season is divided into pre-monsoon (March to May), monsoon (June-September) and post-monsoon (October to November). March to May is the pre-monsoon months and hence, any rainfall in this period can be attributed as pre-monsoon showers. Daytime heating triggers the convection process and thunderstorms occur in the post-noon period. So, ideally a day will begin with a clear sky and summer like temperature but from the afternoon, these pre monsoon showers will start occurring and strong rain cooled winds will cause decrease in the temperatures. Ahmed (1989) studied the probabilistic estimates of rainfall extremes in Bangladesh during the pre-monsoon season. The pre monsoon rainfall has vital importance in Bangladesh as 70% of total food grain is grown during this period.

The rainfall dominated climate of Bangladesh receives the heaviest rainfall in the world (Mirza *et al.*, 2008) and differs from other tropical region because of the strong influence of the Indian Ocean and the Himalayas. High temperatures, heavy rainfall and seasonal variation are the unique characteristics that distinguish the climate of Bangladesh from that of other tropical region. However, the locations of rainfall origination including the characteristics remain unclear in different rainy periods (Partal and Kahya, 2006). The pre-monsoon, monsoon and post-monsoon seasons are basically the rainy seasons (Islam, 2008). 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. The monsoon rainfall is caused by monsoon depressions in the Bay of Bengal (Rahman *et al.,* 1997). This makes Bangladesh a highly humid zone with a mean annual rainfall of 2488 mm. The pre-monsoonal rainfall and thunderstorms are dominated by the moist air from the Bay of Bengal.

The rainfall phenomena before the monsoon onset are known over Bangladesh and the northeastern part of India. Matsumoto (1997) studied the onset of rainy season by the index of precipitation over the Asian summer monsoon region, and indicated that the Assam region of India is earliest region where the onset of rainy season starts. Also in Bangladesh which is located in the northeastern region of the Indian Sub-continent, the severe local storms, sometimes associated with tornadoes, damaging hail and strong wind, occur during the pre-monsoon season (Peterson and Mehta, 1995; Goldar *et al.,* 2001; Yamane and Hayashi, 2008). Such kind of the disturbances during the pre-monsoon season cause severe damage almost each year. In last century, Bangladesh has many disasters and that damage was huge.

Most of the precipitation in South Asia falls during the monsoon season. However, studying convective systems during the pre-monsoon period is important for two reasons. First, the pre-monsoon systems bring the first rains after the dry winter season. Second, pre-monsoonal precipitation systems are more convective, owing to strong instability over land (Weston, 1972; Yamane and Hayashi, 2008). The storms are sometimes extremely deep and intense with a maximum in lightning activity, high conditional rainfall rates and severe weather (Laing and Fritsch, 1993), especially along the Indian east coast and over Bangladesh.

The inter-annual variation of monthly and seasonal country averaged rainfall during the pre-monsoon season has been studied (Karmakar, 2004). The correlations between monthly-to-monthly rainfall, monthly to seasonal rainfall during the pre-monsoon season, and between monthly winter rainfall and the monthly and seasonal rainfall during the pre-monsoon season over Dhaka, Chittagong, Khulna, Rajshahi, Sylhet and Barisal divisions and also over the country have been studied. It has been found that the monthly country averaged rainfall has inter-annual variation and it has increasing linear trends during the pre-monsoon season. The variation of monthly country averaged rainfall over Bangladesh maintains a similar pattern of variation with 11-13 year cycle. The country-averaged rainfall of March has insignificant correlation with the country-averaged rainfall of April and May. The correlation between rainfall in April and that in May is also insignificant. But the country-averaged rainfall in March has strong correlations with the country-averaged rainfall of May and March-May i.e. the seasonal rainfall upto 99% level of significance. A number of regression equations for the significant correlations are developed which will be used in the forecasting of monthly and seasonal average rainfall over different divisions as well as over Bangladesh.

The Advanced Research Weather Research and Forecasting (ARW-WRF) is the new-generation model for both weather research and forecasting (Skamarock *et al*., 2008), and is widely used for regional climate research (Leung *et al.,* 2006; Bukovsky and Karoly, 2009; Awan *et al*., 2011). Alam (2013) studied the effects of microphysics and cumulus parameterization schemes for the prediction of heavy rainfall in post-monsoon season. The study showed large variations among the different microphysical schemes. The microphysical schemes have a major impact on time and location of rainfall intensity.

Spatial distribution pattern of pre-monsoon seasonal rainfall shows a northwest–southeast gradient, indicating the importance of close proximity of the sea, the BoB, besides the land surface characteristics over the southeastern part of the study area. Cumulus parameterization (CP) schemes must estimate the rate of SBU grid-scale convective precipitation, release of latent heat, and the distribution of heat, moisture, and momentum in the vertical due to convection (Kain and Fritsch, 1993). Cumulus convection modifies the large-scale temperature and moisture fields through detrainment and cumulus-induced subsidence in the environment. The detrainment causes large-scale cooling and moistening, and the cumulus-induced subsidence causes large-scale warming and drying (Arakawa and Schubert, 1974). 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 (Wang and Seaman, 1997). Prior studies have shown that a model's microphysical parameterization scheme can strongly influence the magnitude of predicted precipitation (Otkin *et al*., 2006). Litta *et al.,* (2012) illustrates that the microphysics scheme can significantly impact the accuracy of quantitative precipitation forecasts during the pre-monsoon season. Alam (2014) 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 Kain–Fritsch (KF) and Betts–Miller–Janjic (BMJ) schemes were considered. Sanderson and Ahmed (1978) studied 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.

Nesbitt and Zipser (2002) conducted research on the diurnal cycle of rainfall intensity according to three years of tropical rainfall measuring mission (TRMM) measurements. They showed that rainfall over the oceans has a significant diurnal cycle that peaks in the early morning to predawn hours, with a minimum in the late afternoon. Over land, all feature types contribute to an afternoon maximum in precipitation but mesoscale convective system (MCS) rainfall peaks in the early morning.

Fihir (2018) has simulated the heavy rainfall events in the southeastern region of Bangladesh during May 2013 using four different MPs i.e., Lin *et al*., WSM6, Thompson and WDM6 and four different CPs i.e., KF, Tiedtke (TD), Zhang-McFarlane (ZM) and Multi-Scale KF (MSKF).The research also suggest that KF scheme has simulated similar average rainfall for all MPs and ZM and MSKF schemes coupling with WDM6 have simulated almost similar amount of rain in the heavy rainfall region. They found that WSM6 and WDM6 schemes coupling with ZM and MSKF schemes gives the better performance on the basis of Threat Score, Equivalent Threat Score and Bias Score during May 2013.

Haney (2018) has been used 12 different MPs in WRF-ARW model to simulate the heavy rainfall events in the southeastern region of Bangladesh during 23-26 June, 23-26 July and 30 August–1 September 2015. The different MPs are Kessler, Lin *et al*., WSM3, Ferrier, WSM6, Thomson graupel, MYDM, MDM, CAM V5.12-Moment 5 class, SBU, WDM6 and NSSL2. In this research, all Bangladesh stations rainfall averages suggests that MDM, SBU, WDM6, MDM and TH schemes and 5 stations in the heavy rainfall region by Lin, WDM6 and SBU schemes have simulated almost similar amount of rainfall.

Karmakar and Khatun (1995) and Ahmed (1989) studied the probabilistic estimates of rainfall extremes in Bangladesh during the pre–monsoon season. There studies were concentrated only on maximum rainfall events for a limited time period. The European Centre for Medium–Range Weather Forecasts (ECMWF) seasonal forecasting system (Anderson *et al.*, 2007) has predicted the monsoon rainfall. They found that this dynamical seasonal forecasting system displays some skill in predicting the monthly mean precipitation over India after July, but has surprisingly low skill to predict the June precipitation over India.

In the present study, WRF-ARWv3.8.1 model has been used to simulate the total rainfall, heavy rainfall, total rainy days and total heavy rainy days for the month of May 2015 all over Bangladesh. Six MPs schemes i.e. Lin *et al*., WSM6, Thomson, Morrison Double-Moment, SBU and WDM6-class and KF scheme has been considered to study the monthly rainfall and rainy days of May 2015 and try to identify the performances of different MP schemes. The primary objectives of this study are to examine which microphysics schemes,which are suitable for the prediction of monthly rain in the pre-monsoon season. The simulated results have been compared with the observed rainfall of Bangladesh Meteorological Department (BMD) and PERSIANN rainfall.

Chapter II
Review of Literatures

2.1 Pre–monsoon Season

Bangladesh has a tropical monsoon climate. 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.

Rainfall from the thunderstorms of this season is copious, varying from 20 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 (BoB). 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 BoB. The activity of the thunderstorms during the pre–monsoon season depends upon the supply of moist air from the BoB. Since this season is a transitional season between the northerly circulation of winter and southerly circulation of the summer monsoon, the winds from the BoB are neither very strong nor continuous.

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 BoB. 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 BoB.

2.1.1 Pre-monsoon Rainfall

Rain is a type of precipitation, a product of the condensation of atmospheric water vapor that is deposited on the Earth's surface. It forms when separate drops of water fall to the Earth from clouds. Not all rain reaches the surface; some evaporates while falling through dry air. When none of it reaches the ground, it is called virga, a phenomenon often seen in hot, dry desert region. Rain plays a role in the hydrologic cycle in which moisture from the oceans evaporates, condenses into drops, precipitates from the sky, and eventually returns to the ocean via rivers and streams to repeat the cycle again. The water vapor from plant respiration also contributes to the moisture in the atmosphere. A major scientific explanation of how rain forms and falls is called the Bergeron process. More recent research points to the influence of Cloud condensation nuclei released as the result of biological processes.

Rainfall is typically measured using a rain gauge. It is expressed as the depth of water that collects on a flat surface, and is routinely measured with accuracy up to 0.1 mm. Rain gauges are usually placed at a uniform height above the ground, which may vary depending on the country. Precipitation, especially rain, has a dramatic effect on agriculture. All plants need at least some water to survive; therefore rain (being the most effective means of watering) is important to agriculture. Plants need varying amounts of rainfall to survive. Agriculture of all nations at least to some extent is dependent on rain. Bangladesh’s agriculture, for example, is heavily dependent on the rainfall, especially crops like rice, oilseeds and coarse grains. 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 Bangladesh and India.

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 BoB. Rainfall during this season accounts for 10–25% of the total annual rainfall which is caused by the thunderstorms or nor'wester (locally called Kalbaishakhi). 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 (Huq, 1974). The additional uplifting by the Meghalaya Plateau of the moist air causes higher amount of rainfall in the northeast.

Classification of Rainfall

At present Bangladesh Meteorological Department (BMD) are using the classification of rainfall as described in Table 1

Table 1: Rainfall category: Operationally used in BMD (BMD, 2000)

Sl No	Amounts of rainfall recorded in 24 hours	Defined category	Class used in Bangladesh
1.	1-10 mm	Category-I (Cat-I)	Light
2.	11 - 22 mm	Category-II (Cat-II)	Moderate
3.	23 - 43 mm	Category-III (Cat-III)	Moderately heavy
4.	44 - 88 mm	Category-IV (Cat-IV)	Heavy
5.	>88 mm	Category-V (Cat-V)	Very Heavy

2.1.2 Pre–monsoon Temperature

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 (Mamun, 2016). 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. Bangladesh has a tropical monsoon climate (Sanderson and Ahmed, 1978). 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.

2.1.3 Pre–monsoon Wind

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 (Ahmed *et al*., 1997). During the early part of this season, the winds are neither strong nor 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 is narrow zone of discontinuity lies between the hot dry air 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. Pre-Monsoon showers are accompanied by squally winds leading to dust storms but during Monsoon, winds are persistently strong.

2.1.4 Thunderstorms/Nor'westers

Nor'westers are mesoscale severe thunderstorms that occur in Bangladesh during the pre–monsoon season (Chowdhury and Karmakar, 1986). 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. Local orography controls the development of thunderstorms. Northeastern parts of the subcontinent experience severe thunder squalls from March to May called the northeasters or Kalbaishakhi 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.

Bangladesh is located in the northeastern part of the Indian subcontinent and faces the Bay of Bengal in the south and the Meghalaya plateau in the northeast. Almost the entire country is less than 10 m above sea level and on a flat plane. Severe Thunderstorms (henceforth referred to simply as STS) frequently occur in Bangladesh during the pre-monsoon season from March to May, causing deaths and damage to property every year. In Bangladesh, STSs are classified depending on the magnitude of wind speed. The ones producing wind gusts above 42 m s^{-1} are defined as tornadoes, while those producing wind gusts ranging from 11 to 42 m s^{-1} are defined as nor'westers. The term nor'wester means that STS come mostly from the northwestern direction. Despite being highly arbitrary, such criteria for classifying STSs have been used in a number of climatological studies addressing STSs in Bangladesh (Yamane *et al.* 2008).

2.1.5 Relative Humidity

Relative humidity is the ratio of the partial pressure of water vapor in the air–water mixture to the saturated vapor pressure of water at those conditions (Wolkoff *et al*., 2007). The relative humidity of air depends not only on temperature but also on pressure of the system of interest. So it is defined as the ratio of the observed vapor pressure to that required for saturation at the same temperature. Designating it as if, we have

$$f = \frac{\omega}{\omega_s} \times 100 = \frac{\rho_w}{\rho_{ws}} \times 100 = \frac{q}{q_s} \times 100 = \frac{e}{e_s} \times 100$$

The multiplication by 100 being for the purpose of expressing it as a percentage

The relative humidity is a measure of the amount of water vapor in the air (at a specific temperature) compared to the maximum amount of water vapor air could hold at that temperature, and is given as a percentage value. Relative humidity depends on the temperature of the air, as warm air can hold more moisture than cold air. A relative humidity of 100 percent indicates that the air is holding all the water it can at the current temperature and any additional moisture at that point will result in condensation. As the temperature decreases, the amount of moisture in the air doesn't change, but the relative humidity goes up (since the maximum amount of moisture that cooler air can hold is smaller).

2.2 Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN)

PERSIANN is a satellite-based precipitation retrieval algorithm that provides near real-time rainfall information (Hsu *et al.,* 1997). The algorithm uses infrared (IR) satellite data from global geosynchronous satellites as the primary source of precipitation information. Precipitation from IR images is based on statistical relationship between cloud top temperature and precipitation rates. The IR-based precipitation estimates are then calibrated using satellite microwave data available from low Earth orbit satellites. The calibration technique relies on an adaptive training algorithm that updates the retrieval parameters when microwave observations become available (approximately at 3 hours intervals). The PERSIANN algorithm has been evolving since 2000 (ASCE Task Committee, 2000), and has generated near real-time rainfall estimates continuously for global water and energy studies. Over the past 2 decades, a wide range of studies have incorporated PERSIANN products. Currently, PERSIANN offers several precipitation products based on different algorithms available at various spatial and temporal scales, namely PERSIANN, PERSIANN-CCS (Hong *et al.,* 2004; Hsu *et al.,* 2013), and PERSIANN-CDR (Agha Kouchak and Nakhjiri, 2012).

The PERSIANN—Climate Data Record (PERSIANN-CDR) is a relatively new product (released in 2013) but that contains data since 1983, thus enabling long-term rainfall analysis. The PERSIANN-CDR provides daily rainfall estimates at a spatial resolution of 0.25 degrees in the latitude band 60S - 60N from 1983 to the near-present. The precipitation estimate is produced using the PERSIANN algorithm on GridSat-B1 infrared satellite data, and the training of the artificial neural network is done using the National Centers for Environmental Prediction (NCEP) stage IV hourly precipitation data. The PERSIANN-CDR is adjusted using the Global Precipitation Climatology Project (GPCP) monthly product version 2.2 (GPCPv2.2), so that the PERSIANN-CDR monthly means degraded to 2.5 degree resolution match GPCPv2.2 (Huffman and Bolvin, 2013). PERSIANN CDR is a Climate Data Record, which the National Research Council (NRC) defines as a time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change. The PERSIANN satellite precipitation data sets have been validated with ground-based observations and other satellite data products. The PERSIANN data has been used in a wide variety of studies including hydrologic modeling, drought monitoring, soil moisture analysis, and flood forecasting. The PERSIANN-CDR was developed by researchers at CHRS and NOAA's National Centers for Environmental Information (NCEI), with support from Olivier Part from the Cooperative Institute for Climate and Satellites–North Carolina. It is now one of NCEI's operational CDRs.

Satellite-derived estimates of precipitation are essential to compensate for missing rainfall measurements in region where the homogeneous and continuous monitoring of rainfall remains challenging due to low density rain gauge networks. Surface-based precipitation measurements with high accuracy on different spatial-temporal scales have a crucial importance in different land-use planning sectors, especially in arid and semi-arid region, such as Iran. Because the density of spatial distribution of rain-gauges is not uniform throughout the country, satellite sensor technology is considered useful for precipitation monitoring over the study area. In general, PERSIANN underestimates high rainfall rates by 5.5 mm/day in winter but overestimates the low rainfalls in annual and seasonal scales by 0.9 mm/day in summer.

Due to the challenging imbalance in precipitation data, a Kullback-Leibler divergence is incorporated in the objective function to preserve the distribution of it. PERSIANN-SDAE is compared with a shallow neural network with hand designed features and an operational satellite-based precipitation estimation product. The experimental results demonstrate the effectiveness of PERSIANN-SDAE in estimating precipitation accurately while preserving its distribution. It outperforms both the shallow neural network and the operational product.

The PERSIANN data sets are developed by the University of California's (UCI) Hydrometeorology and Remote Sensing group. Rainfall estimates are derived using a neural network and satellite infrared/visible imagery to produce a high resolution global (60°S to 60°N) gridded dataset, and is potentially available at (1, 3, 6) hourly, daily, monthly and annual frequency. A system PERSIANN is under development at The University of Arizona. The current core of this system is an adaptive Artificial Neural Network (ANN) model that estimates rainfall rates using infrared satellite imagery and ground-surface information. The model was initially calibrated over the Japanese Islands using remotely sensed infrared data collected by the Geostationary Meteorological Satellite (GMS) and ground-based data collected by the Automated Meteorological Data Acquisition System (AMDAS). The model can also be successfully updated using only spatially and/or temporally limited observation data such as ground-based rainfall measurements. Another important feature is a procedure that provides insights into the functional relationships between the input variables and output rainfall rate.

2.3 Weather Research & Forecasting Model

The Weather Research and Forecasting (WRF) Model is a next–generation mesoscale numerical weather prediction (NWP) 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 (NOAA) represented by the National Centers for Environmental Prediction (NCEP), the Forecast Systems Laboratory (FSL), the Air Force Weather Agency (AFWA), the Naval Research Laboratory (NRL), the University of Oklahoma, and the Federal Aviation Administration (FAA). 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 Micro scale 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. In WRF model there are different physics options. Some of the physics options are discussed in the following SBU-section.

2.3.1 Microphysics schemes in WRF-ARW Model

Microphysics includes explicitly resolved water vapor, cloud and precipitation processes. The model is general enough to accommodate any number of mass mixing-ratio variables, and other quantities such as number concentrations (Thompson *et a*l., 2006). 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 adjustment 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 SBU-steps and this is done by saving the microphysical heating as an approximation for the next time-step as described. There are many microphysics options in WRF-ARW model. Some of the microphysics is described in the following SBU-sections.

2.3.1.1 Lin *et al.* Scheme

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

2.3.1.2 WRF Single-moment 6-class (WSM6) microphysics scheme

The 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. The characteristics of the cold rain process in the WSM6 scheme follow the revised ice microphysics process (Hong *et al.*, 2004), whereas the warm rain processes are primarily based on the works of Lin *et al.* (1983) and the auto conversion process from Tropoli and Cotton (1980). The daily forecasts at NCAR have shown that the WSM6 scheme works successfully in predicting mesoscale convective systems, but it sometimes overestimates the peak intensity and underestimates the areas of anvil clouds. We attempt to improve such existing deficiencies in the WSM6 scheme by incorporating the prediction of number concentrations for warm rain species. This new method uses a large eddy simulation (LES)-based approach (Khairoutdinov and Kogan, 2000) to determine the auto conversion rates and allow for a more sophisticated coupling between cloud field and number concentrations of warm species. Double-moment prediction for the warm species in WSM6 scheme will allow more flexibility of the size distribution enabling the mean diameter to evolve in contrast to the one-moment scheme.

WSM6 scheme includes vapor, rain, snow, cloud ice, cloud water and graupel in six different arrays. 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· A new method for representing mixed-phase particle fall speeds for the snow and a scheme with ice, snow and graupel processes suitable for high-resolution simulations. The WSM6 scheme has been developed by adding additional process related to graupel to the WSM5 scheme (Hong and Lim, 2006).

2.3.1.3 Thompson Scheme

A bulk microphysical parameterization scheme developed for use with WRF or other mesoscale models. The snow size distribution depends on both ice water content and temperature and is represented as a sum of exponential and gamma distributions. Furthermore, snow assumes a non-spherical shape with a bulk density that varies inversely with diameter as found in observations. A new scheme with ice, snow and graupel processes suitable for high-resolution simulations. This adds rain number concentration and updates the scheme from the one in Version 3.0 New Thompson *et al.* scheme in v3.1. Replacement of Thompson *et al.,* (2007) scheme that was option 8 in v3.0 6-class microphysics with graupel, ice and rain number concentrations also predicted.

2.3.1.4 Morrison Double-Moment Scheme

The Morrison scheme is similar to the Thompson scheme but has a more sophisticated treatment for frozen precipitation species. Like Thompson, the Morrison scheme predicts the mass concentration of cloud water, cloud ice, rain, snow and graupel. The physics are based on the full double-moment version described in Morrison *et al*. (2009), but the rendition implemented in WRF-ARW v.3.4.1 does not include a number concentration variable for cloud water. Morrison scheme transition cloud ice to snow through auto conversion processes. The auto conversion process from cloud ice to snow is triggered when cloud ice mass exceeds a specified threshold related to the maximum permitted size of cloud ice crystals, but it does not require a corresponding minimum size for the snow category. Truncation at larger particle sizes would lead to a greater reduction as additional counts of small particles are eliminated. Morrison scheme prediction of provided a good fit to aircraft estimates with a mean profile and range that is within the bulk of aircraft estimates below 4 km and also represented the general decrease from cloud top to cloud base associated with continued aggregation.

2.3.1.5 Stony Brook University (SBU) Microphysics

Stony Brook University scheme is a 5-class scheme with riming intensity predicted to account for the mixed-phase processes. A new approach for representing the ice microphysics is presented, which considers both temperature and riming effects on ice properties. The SBU-YLIN scheme includes five prognostic mixing ratios: water vapor, cloud ice, precipitating ice (PI), cloud liquid water, and rain. Dry snow, rimed snow, and graupel are included in the PI category through the introduction of a varying riming intensity parameter. The new scheme (SBU-YLIN) allows for physically based representation of the ice particles with temperature- and riming intensity–dependent properties, such as the mass, cross-sectional area, and fall velocity relationships. Riming intensity is diagnosed from LWC, PI mass, and temperature. One advantage of the new approach is the simplification of the scheme and the reduction of the computation time. Also, it is more physically based than many existing schemes, since it considers partially rimed particles (Lin and Colle, 2011).

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

The 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 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).

2.3.2 Cumulus Parameterization

These schemes are responsible for the SBU-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., > 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 SBU-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

One of the main options which could potentially affect precipitation severely is the cumulus parameterization. The feedback from these parameterizations to the larger–scale equations of the model is the profile of latent heat release and moistening caused by convection. Two different schemes were used. Even though the efficiency of a given parameterization depends on the concrete event, other cumulus parameterizations have been proved to have less accuracy, e.g. the Anthes–Kuo (Ferretti *et al*., 2000) or Betts–Miller schemes (Cohen, 2002). The Kain–Fritsch scheme has demonstrated good performance on several situations and region (Wang and Seaman, 1997; Kotroni and Lagouvardos, 2001; Cohen, 2002). In the study by Ferretti *et al*. (2000) in Alpine region, the Grell scheme was better than the Kain–Fritsch scheme for some concrete events.

2.3.2.1 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). Kain-Fritsch (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 SBU-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 relative humidity (RH) and depth of downdraft leftover condensate accumulates at surface as precipitation

2.3.3 Planetary Boundary Layer (PBL) Parameterizations

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 SBU–grid–scale mixing which takes place in the lower levels due to these processes.

2.3.3.1 Yonsei University (YSU) scheme

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

2.3.4 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.

2.3.4.1 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 linesloxo dromes, 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.

2.3.4.2 Lambert Projection

A Lambert conformal conic (LCC) projection is a conic map projection used for aeronautical charts, portions of the State Plane Coordinate System (SPCS), and many national and regional mapping systems. It is one of seven projections introduced by Lambert (1772). This projection is one of the best for middle latitudes. It is similar to the Albers conic equal area projection except that Lambert conformal conic portrays shape more accurately than area. The SPCS uses this projection for all zones that have a greater east–west extent. Conceptually, the projection seats a cone over the sphere of the Earth and projects the surface conformally onto the cone. The cone is unrolled, and the parallel that was touching the sphere is assigned unit scale. That parallel is called the reference parallel or standard parallel. By scaling the resulting map, two parallels can be assigned unit scale, with scale decreasing between the two parallels and increasing outside them. This gives the map two standard parallels. In this way, deviation from unit scale can be minimized within a region of interest that lies largely between the two standard parallels. Unlike other conic projections, no true secant form of the projection exists because using a secant cone does not yield the same scale along both standard parallels.

Pilots use aeronautical charts based on LCC because a straight line drawn on a Lambert conformal conic projection approximates a great–circle route between endpoints for typical flight distances. The US systems of VFR (visual flight rules) sectional charts and terminal area charts are drafted on the LCC with standard parallels at 33°N and 45°N.

2.3.5 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.

2.3.6 Atmospheric Radiation

The radiation schemes provide atmospheric heating due to radiative flux divergence and surface downward longwave and shortwave radiation for the ground heat budget. Longwave radiation includes infrared or thermal radiation absorbed and emitted by gases and surfaces (Bohren and Clothiaux, 2006). Upward Longwave radiative flux from the ground is determined by the surface emissivity that in turn depends upon land–use type, as well as the ground (skin) temperature. Shortwave radiation includes visible and surrounding wavelengths that make up the solar spectrum. Hence, the only source is the sun, but processes include absorption, reflection and scattering in the atmosphere and its surfaces. For shortwave radiation, the upward flux is the reflection due to surface albedo. Within the atmosphere the radiation responds to model predicted cloud and water vapor distributions, as well as specified carbon dioxide, and (optionally) tracer gas concentrations. All the radiation schemes in WRF currently are column (one–dimensional) schemes, so each column is treated independently, and the fluxes correspond to those in infinite horizontally uniform planes, which is a approximation if the vertical thickness of the model layers is much less than the horizontal grid length. This assumption would become less accurate at high horizontal resolution.

2.3.6.1 Outgoing Long wave Radiation (OLR)

Outgoing Longwave Radiation (OLR) is the energy radiating from the Earth as infrared radiation at low energy to Space. OLR is electromagnetic radiation emitted from Earth and its atmosphere out to space in the form of thermal radiation (Barkstrom and Coauthors, 1989). The flux of energy transported by OLR is measured in W/m^2.In a different context, OLR values are often used as a proxy for convection in tropical and subtropical region since cloud top temperatures (colder is higher) are an indicator of cloud height. OLR observations are made via the Advanced Very High Resolution Radiometer (AVHRR) instrument aboard the NOAA polar orbiting spacecraft. The raw ascending and descending swath data have been spatially and temporarily interpolated onto grids to facilitate use. The Earth Radiation budget is made up of the incoming solar flux and the outgoing Top–of–the–Atmosphere (TOA) radiative fluxes. The outgoing radiative fluxes consist of the reflected part of the incoming solar flux, as well as the thermal flux emitted by the Earth–atmosphere system. The thermal flux is often referred to as OLR. The OLR is a very important parameter for the Earth's radiation budget study as well as for weather/climate model validation purposes. Variations in the OLR reflect the response of the Earth–atmosphere system to solar diurnal forcing.

Those variations can be found in particular in surface temperature, cloud cover, cloud top height, and related quantities like precipitation. The OLR is therefore well suited for validation of general circulation models (GCMs) simulating the diurnal cycle, as it constitutes the combination of different model aspects. The OLR can be directly estimated from broadband radiance measurements by a satellite instrument such as the Geostationary Earth Radiation Budget (GERB). Alternatively, the OLR can be indirectly inferred from narrowband radiance observations. The Spinning Enhanced Visible and Infrared Imager (SEVIRI) OLR is obtained from the IR and WV radiance and the satellite viewing angle via a regression scheme. The OLR is currently not operationally derived – the show results are the outcome of a feasibility study. This product is a candidate product for a future reprocessing facility within European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) to support the derivation of climate–relevant parameters.

2.3.6.2 Downward Long wave Radiation

The downward long wave radiation is mostly from the atmosphere. It depends on the temperature and moisture of the atmosphere. The water vapor and other gases, aerosols absorb some solar energy and emit some long wave radiation energy computation of downward long wave radiation from the atmosphere is difficult, even when the distributions of water vapor, carbon dioxide, cloudiness, and temperature are measured. Some satellite measurements like Television Infrared Observation Satellite (TIROS) Operational Vertical Sounders (TOVS) estimates downward long wave radiation. Little long wave radiation is reflected by the surface: natural surface emission is dominant (Kruk *et al*., 2010). It is also difficult to measure and define the surface temperature especially vegetation surface. To combine the above four components makes the calculation of net radiation at the surface. This is not accurate because the errors in each accumulate. So it is developed the research to use some satellite measurements–NOAA, GOES etc.

Chapter III
Model Description and Methodology

3.1 Model Setup

In the present study the Weather Research and Forecast (WRF-ARW Version 3.5.1) model have been used to simulate the pre-monsoon rainfall all over Bangladesh. Advance Research WRF (ARW) is a dynamic solver (Skamarock *et al.,* 2008), 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 we have been used 6 microphysics schemes for the simulation of daily rainfall in the month of May 2015. The 6 MPs are Lin *et al.* (Lin), WSM6-class graupel, Thomson graupel, Morrison Double-Moment, Stony Brook University (SBU), and WDM6-class schemes. The Lin scheme contains prognostic equations for cloud water and rainwater mixing ratio, rainwater, cloud ice, snow, and graupel mixing ratio, WSM6 for cloud water, rainwater, cloud ice, snow, and graupel mixing ratio, Thompson for cloud water, rainwater, cloud ice, snow, and graupel mixing ratio, SBU for cloud water, rainwater, cloud ice and snow mixing ratio, WDM6 for cloud water, rainwater, cloud ice, snow, and graupel mixing ratio. The model has integrated by using initial and lateral boundary conditions (LBCs) from NCEP-FNL analysis at six hourly intervals. Surface layer is treated using Monin-Obukhov and planetary boundary layer (PBL) is treated with Yonsei University scheme (YSU). Dudhia (1989) scheme has been used for short wave radiation and Rapid Radiative Transfer Model (RRTM) for long wave (Mlawer *et al.,* 1997). Kain-Fritsch (KF) (1993) cumulus parameterization (CP) scheme has been used for simulating the pre-monsoon rainfall.

3.2 Model Domain and Configuration

The model has been configured in double domain, 18 km and 6 km horizontal grid spacing with 103×127 and 100×96 grids in the east-west and north-south directions and 30 vertical levels. Time step of integration is set to 30 and 90 seconds for maintaining computational stability as the model uses third-order Runge-Kutta time integration scheme. The model domain is given in Figure 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	2	
Central points of the domain	Central Lat.: 20°N, Central Long: 93°E	
Horizontal grid distance	6 km and 18 km	
Integration time step	30 s and 90 s	
Number of grid points	X-direction 96 and 103 points, Y-direction 100 and 127 points	
Map projection	Mercator	
Horizontal grid distribution	Arakawa C-grid	
Nesting	One way nesting	
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	(1) Lin *et al*.	(2) WSM6-class graupel
	(3) Thomson graupel	(4) Morrison Double-Moment
	(5) SBU	(6) WDM6-class
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)	

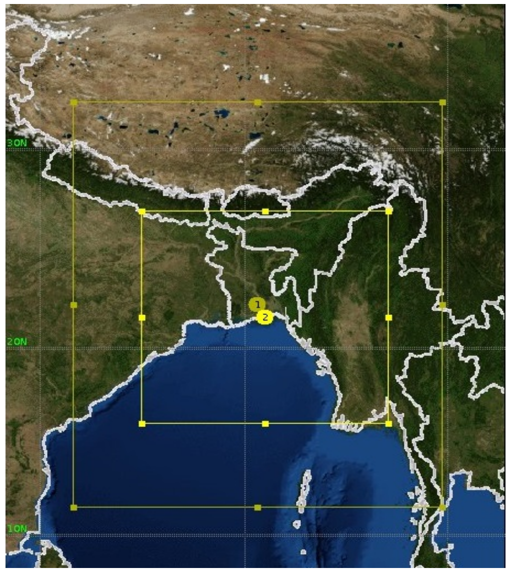


Figure 1: WRF Model Domain for the prediction rainfall in Bangladesh

3.3 Data and Methodology

Final Reanalysis (FNL) data (1^{o} x1^{o}) from National Centre for Environment Prediction (NCEP) is used as initial and lateral boundary conditions (LBCs) which is updated at six hourly interval i.e. the model will be initialized with 0000, 0600, 1200 and 1800 UTC initial field of corresponding date. The NCEP FNL data will be interpolated to the model horizontal and vertical grids. BMD rainfall and PERSIANN data will be used for verification. In the present study, the Weather Research and Forecast (WRF-ARW Version 3.8.1) model will be used to simulate the May 2015 rainfall over Bangladesh. The 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. Third-order Runge-Kutta time integration is used in the model. The model has different microphysics options but in our research Lin *et al*., WSM 6-class graupel, Thompson graupel, Morrison Double-Moment Scheme, Stony Brook University (SBU) and WDM6 schemes will be used to simulate the rainfall for the month of May 2015. The Lin *et al*., WSM6 and Thompson MP schemes contain prognostic equations for cloud water, rainwater, cloud ice, snow, and graupel mixing ratio. The model will be configured in double domain, 18 km and 6 km horizontal grid spacing with 100×96 and 103×127 grids in the east-west and north-south directions respectively and 30 vertical levels. Dudhia (1989) scheme will be used for short wave radiation and Rapid Radiative Transfer Model (RRTM) for long wave. KF cumulus parameterization scheme will also be used for simulating the rainfall for the month of May 2015.

In this research we have used six different MP schemes and Kain-Fritsch cumulus parameterization scheme. 3-hourly rain gauge data of 33 meteorological stations have been collected from Bangladesh Meteorological Department (BMD) all over Bangladesh.

Chapter IV

Results and Discussions

4.1 Observed and PERSIANN monthly rainfall of May 2015

4.1.1 Observed Rainfall for the month of May 2015

The distribution of observed rainfall over Bangladesh for the month of May 2015 all over Bangladesh is presented in Figure 2(a). From the distribution pattern, the maximum rainfall is observed at Sylhet and minimum rainfall is found at Satkhira. The maximum and minimum rainfalls are observed at Sylhet and Satkhira are 752 and 16 mm respectively. It is also seen from the spatial distribution pattern that the rainfall increases continuously from southwestern (SW) to northeastern (NE) region of Bangladesh. The minimum rainfall is also seen at Mongla, Cox-Bazar, Kutubdia, Chittagong, Barishal, Bhola, Khepupara and Patuakhali and is 98, 96, 83, 77, 72, 71, 39 and 38 mm respectively. The second maxima of rainfall are seen at Srimangal (517 mm) and the third maxima at Dinajpur (375 mm) of Bangladesh. Rainfall amount of 100 to 200 mm is seen in the central towards western region of the country and Dhaka gets 185 mm of rainfall during this month of May 2015.

4.1.2 Observed Heavy rainfall for the month of May 2015

Special distribution of observed heavy rainfall (HR) of May 2015 all over Bangladesh is presented in Figure 2(b). From the distribution pattern it is observed that the maximum amount of HR is observed at Sylhet and minimum HR in the southern region of Bangladesh. The highest HR observed at Sylhet is 379 mm. It is also seen from the spatial distribution pattern that the rainfall increases continuously from southwestern (SW) to northeastern (NE) and northwestern (NW) region of Bangladesh. The amounts of monthly HR are found at Srimangal, Rajshahi, Rangpur, and Cumilla region are 231,121, 113 and 108 mm respectively.

4.1.3 PERSIANN satellite precipitation for the month of May 2015

The distribution of Precipitation estimated from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) for the month of May 2015 allover Bangladesh is presented in Figure 2©. From the distribution pattern, the maximum rain is observed at Sylhet and minimum at Khepupara. The maximum and minimum rainfalls observed at Sylhet and Khepupara are 556 and 48 mm, respectively. The PERSIANN rainfall has increased continuously from SW to NE and NW region of Bangladesh. The second maxima of rainfall are seen at Srimangal (446 mm) of Bangladesh. At Rangpur and Sitakunda, the PERSIANN rainfall is seen 376 and 159 mm, respectively. The distribution pattern is almost similar to that of BMD observed rainfall.

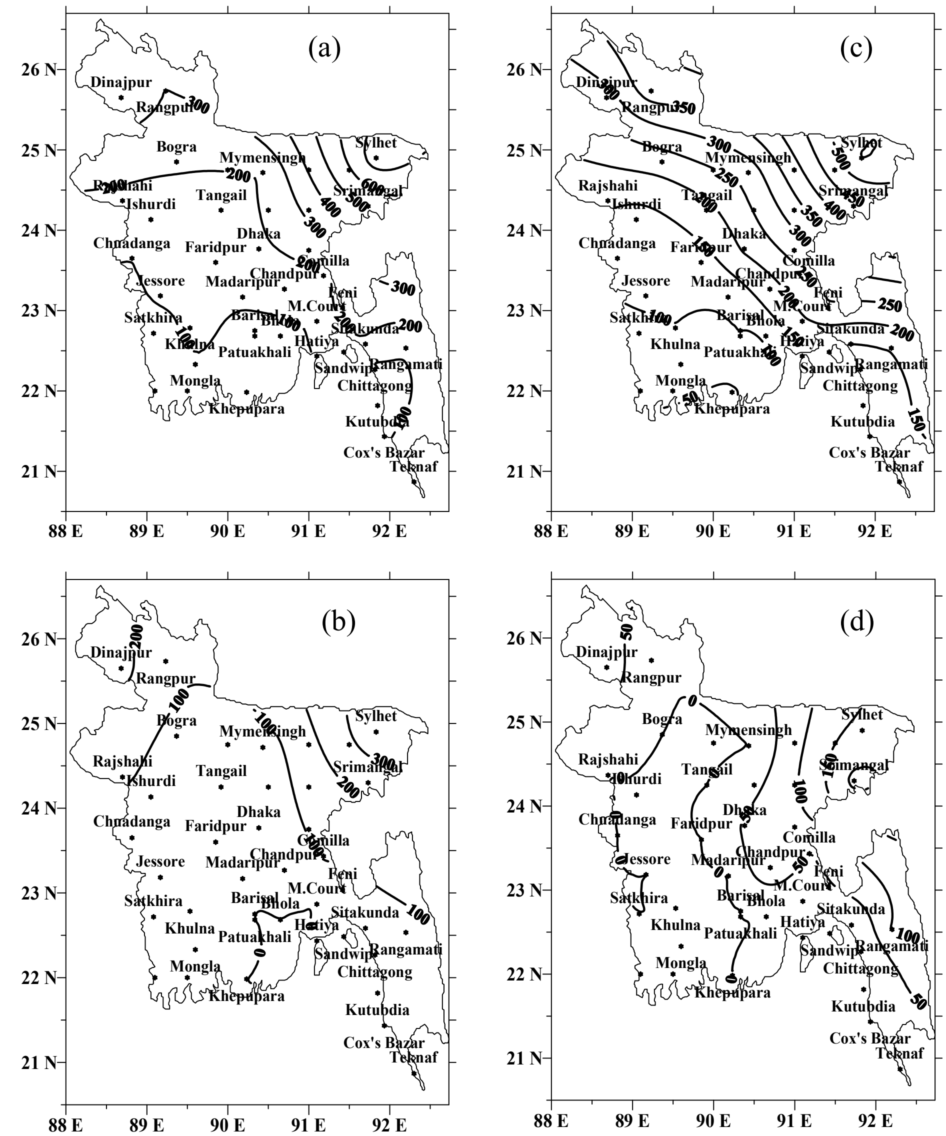


Figure 2: a) BMD Observed total rainfall, b) BMD observed Heavy rainfall, c) PERSIANN total rainfall and d) PERSIANN heavy rainfall for the month of May 2015

4.1.4 PERSIANN satellite heavy precipitation for the month of May 2015

Special distribution of PERSIANN HR of May 2015 all over Bangladesh is presented in Figure 2(d). From the distribution pattern, the highest HR is found at Srimangal and its amount was 213 mm. The second highest HR observed at Sylhet was 164 mm. The PERSIANN HR observed at Dhaka was 56 mm. The PERSIANN monthly special distribution of HR results indicated that maximum region of the country no HR. The PERSIANN HR is much lower than that of BMD observed HR.

4.2 Model simulated rainfall for the month of May 2015 at Domain 1 (D1)

4.2.1 Simulation of Monthly total rainfall at D1 for Day 1 prediction

The 24hourly simulated monthly rainfall distributions in D1 of May 2015 for different MP schemes in combination with KF cumulus parameterization (CP) scheme with the initial conditions of 0000UTC of everyday for the month of May are presented in Figures3(a-f). Lin *et al.* scheme (Figure 3a) has simulated maximum rainfall at Sylhet and minimum rainfall at Bhola. The highest and lowest rainfalls are simulated at Sylhet and Bhola are 861 and 45 mm, respectively. The spatial distribution pattern of rainfall shows that the rainfall increases continuously from SW to NE region of Bangladesh. The second maxima of rainfall are simulated at Dinajpur and the third maximum of rainfall is at Madaripur. The minimum rainfall is simulated in the southeastern region of Bangladesh. The amounts of minimum rainfall are 113, 115, 133, 134 and 135 mm at Rangamati, Feni, Sitakunda, Teknaf and Cox-Bazar, respectively. The simulated rainfall at Dhaka is 393 mm. The model simulated highest rainfall in the northeastern region is matched with the observed rainfall. The Lin *et al.* scheme has simulated 10 to 30% higher rainfall all over the country than that observed rainfall.

WSM6 scheme (Figure 3b) has simulated maximum rainfall at Sylhet and minimum rainfall at Bhola. Sylhet region has the highest rainfall of 831 mm and Bhola has the lowest rainfall of 44 mm. The second maxima of rainfall are seen at Srimangal region of Bangladesh. It is also seen from the spatial distribution pattern that the rainfall increases continuously from SW to NE region of Bangladesh. The highest rainfall amounts of 393 and 188 mm are also simulated using WSM6 scheme at Bogura and Sandwip of Bangladesh, respectively. In the central region of Bangladesh i.e. Tangail, the scheme has simulated highest rainfall of 430 mm. The minimum rainfall found at Teknaf, Chuadanga, Rangamati, Feni, Cox-Bazar and Kutubdia are 108, 112, 112, 125, 128 and 131 mm, respectively. The WSM6 scheme has simulated 10 to 30% higher rainfall all over the country than that observed rainfall.

Thompson scheme (Figure 3c) has simulated maximum rainfall at Sylhet (939 mm) and minimum rainfall at Bhola (50 mm). From the spatial distribution pattern of rainfall, it is found that the rainfall increases continuously from SW to NE region of Bangladesh. The significant amount of rainfall 273 mm has simulated at Dinajpur region. In the central region of Bangladesh i.e., Dhaka-Tangail region the simulated rainfall is greater than 300 mm. The Thompson scheme has simulated 20-34% higher rainfall all over the country than that observed rainfall.

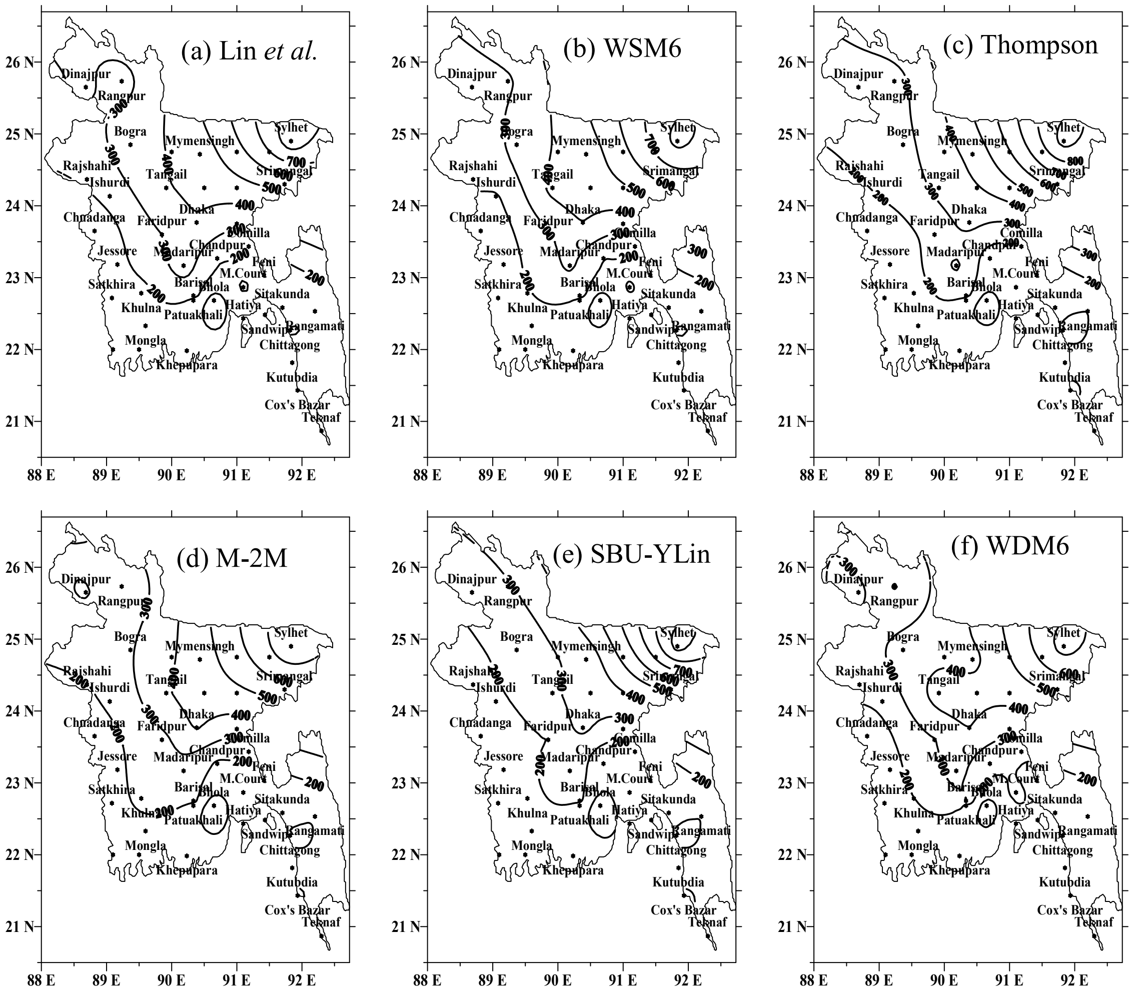


Figure 3: Spatial distribution of model simulated monthly total rainfall of May 2015 for day 1 prediction in D1 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

M-2Mscheme (Figure 3d) has simulated maximum rainfall at Sylhet (788 mm) and minimum rainfall at Bhola (33 mm).It is seen from the spatial distribution pattern that the rainfall increased continuously from south SW to NE region of Bangladesh. The maximum rainfall 311 mm has also simulated at Dinajpur. In the central region of Bangladesh i.e., Dhaka the simulated rainfall is 409 mm. The minimum rainfall is also seen at Chittagong and Cox-Bazar is 91 and 93 mm, respectively. The distribution pattern is similar but the scheme is simulated much higher rainfall in the central region. It is found that the M-2M scheme has simulated 17% higher rainfall than that observed rainfall.

SBU-YLin scheme (Figure 3e) has simulated maximum rainfall at Sylhet (941 mm) and minimum rainfall at Bhola (40 mm).The spatial distribution pattern shows that the rainfall increased continuously from SW to NE and NW region of Bangladesh. The maximum rainfall 289mm has also simulated at Rangpur. In the central region of Bangladesh i.e., Dhaka the scheme has simulated significant amount of rainfall 325 mm. The minimum rainfall is seen at Chittagong, Cox-Bazar and Chandpur are 86, 92 and 98 mm, respectively. The SBU-YLin scheme has simulated 20 to 24% higher rainfall all over the country than that observed rainfall.

WDM6 scheme (Figure 3f) has simulated maximum rainfall at Sylhet (742 mm) and minimum rainfall at Bhola (46 mm). The spatial distribution pattern shows that the rainfall increases continuously from SW to NE region of Bangladesh. The maximum rainfall 450 and 329 mm are also simulated in the central and NW region i.e., Tangail and Bogura respectively. The minimum rainfall is seen in the south SE region of the country. The simulated rainfall match with observed rainfall in the NE region i.e., highest rain region but overall the scheme has simulated 32% higher rainfall than that of observed rainfall.

4.2.2 Simulation of monthly total rainfall at D1 for Day 2 prediction

The 48 hourly simulated monthly rainfall distributions in D1 of May 2015 for different MP schemes in combination with KF scheme with the initial conditions of 0000UTC of everyday for the month of May are presented in Figures 4(a-f).

Lin *et al.* scheme (Figure 4a) has simulated maximum rainfall in the NE region and minimum rainfall in the SW region of Bangladesh. The highest rainfall simulated at Sylhet(1033 mm) and lowest rainfall at Khepupara(76 mm).The spatial distribution pattern shows that the rainfall increases continuously from SW to NE region of Bangladesh. The maximum rainfall 305 mm has also been simulated in the NW Rangpur. In the central region of Bangladesh i.e., Dhaka, the scheme has simulated 371 mm rainfall. The minimum rainfall is also found at Khulna, Chittagong and Satkhira are 85, 90 and 100 mm, respectively. The Lin *et al.* scheme has simulated 30 to 60% higher rainfall all over the country than observed rainfall. Day 2 simulation is higher (more deviation is found) than that of day 1 rainfall.

WSM6 scheme (Figure 4b) has simulated maximum rainfall in the NE region and minimum rainfall in the SW region. Sylhet has simulated the highest rainfall of 757 mm and Khepupara has the lowest rainfall of 71 mm. The spatial distribution pattern shows that the rainfall increases continuously from SW to NE and NW region of Bangladesh. The significant amount of rainfall 498 mm is also simulated at Rangpur region. In the central region of Bangladesh i.e., Dhaka, the scheme has simulated significant amount of rainfall 454 mm. The minimum rainfall found at Khulna, Chittagong, Patuakhali, Mongla and Satkhira are 76, 85, 86, 90 and 92 mm respectively. The WSM6scheme simulated rainfall is found to match with observed highest rainfall and this has simulated 55% higher rainfall than that observed lowest rainfall.

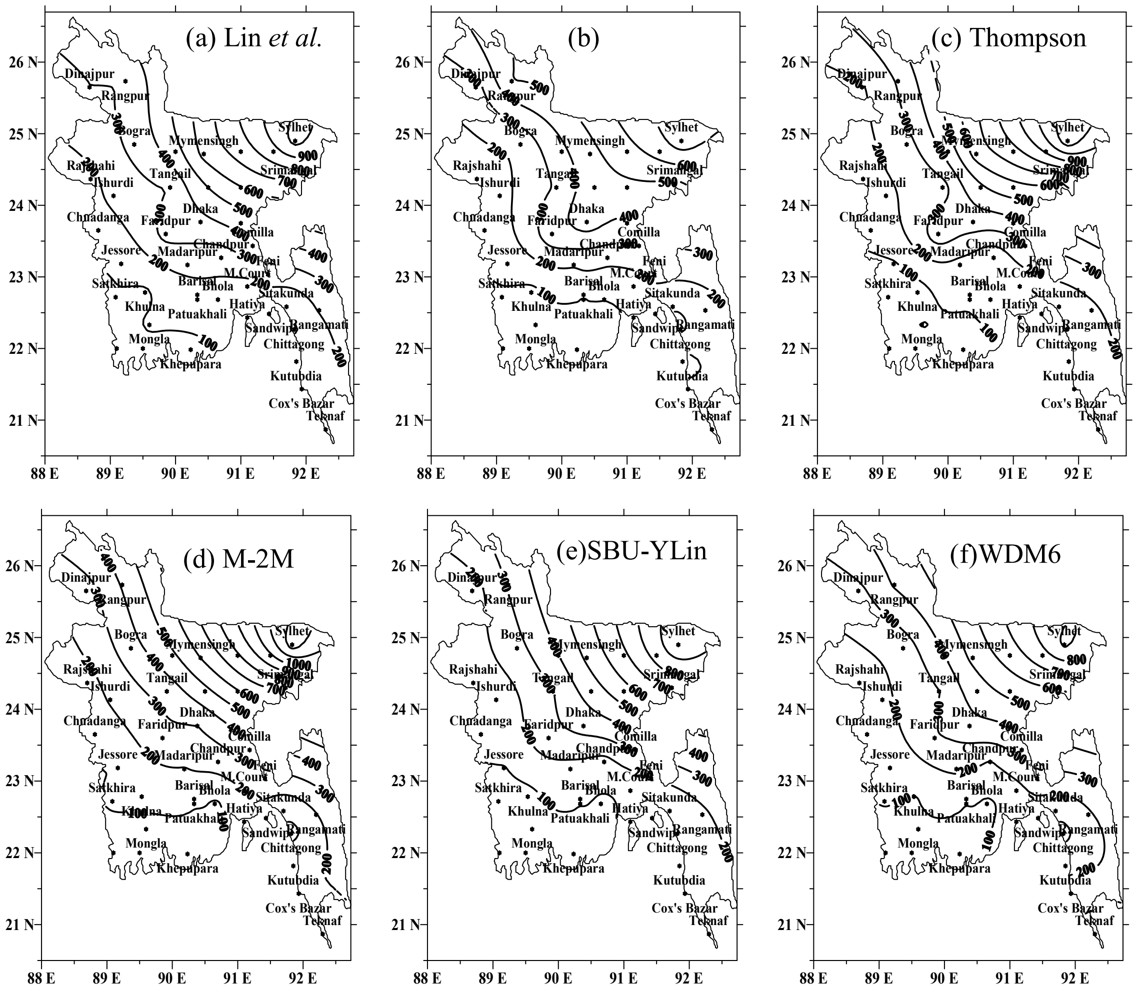


Figure 4: Spatial distribution of model simulated monthly total rainfall of May 2015 for day 2 prediction in D1 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

Thompson scheme (Figure 4c) has simulated maximum rainfall in the NE region and minimum rainfall in the SW region. Sylhet has simulated the highest rainfall of 1165 mm and Satkhira has the lowest rainfall of 49 mm. The spatial distribution pattern shows that the rainfall increases continuously from SW to NE region of Bangladesh. The maximum rainfall of 310 mm also simulated at Rangpur region. In the central region of Bangladesh i.e., Faridpur, the scheme has simulated significant amount of 363 mm rainfall. The minimum rainfall amounts found at Khepupara, Jashore and Chittagong are 75, 90 and 95 mm, respectively. The Thompson scheme has simulated 33 to 40% higher rainfall all over the country than observed rainfall. The simulated rainfall in Day 2 is much higher in the NE region of Bangladesh than that of day 1.

M-2M scheme (Figure 4d) has simulated maximum rainfall in the NE region and minimum rainfall in the south SW region. Sylhet has simulated the highest rainfall o f1246 mm and Mongla has the lowest rainfall of 62 mm. The spatial distribution pattern shows that the rainfall increases continuously from SW to NE and NW region of Bangladesh. The significant amount of 409 mm rainfall is also simulated at Rangpur region. In the central region of Bangladesh i.e., Tangail, the scheme has simulated 340 mm of rain. The minimum rainfall is seen at Khepupara, Chittagong and Bhola are 64, 70 and 81 mm respectively. The M-2M scheme has simulated 46 to 50% higher rainfall all over the country than observed rainfall. The simulated rainfall in Day 2 is much higher in the central to NE region of Bangladesh than that of day 1.

SBU-YLin scheme (Figure 4e) has simulated maximum rainfall in the NE region and minimum rainfall in the south SW region. Sylhet has simulated the highest rainfall of 981 mm and lowest rainfall at Bhola and Khepupara are 72 mm. The spatial distribution pattern shows that the rainfall increases continuously from SW to NE and NW region of Bangladesh. The significant amount of 313 mm rainfall is also simulated at Rangpur region. In the central region of Bangladesh i.e., Dhaka, the scheme has simulated 338 mm of rain during the month of May 2015 for day 2 simulation. The minimum rainfall is seen at Khulna, Satkhira, Mongla and Jashore are 77, 86, 87 and 96 mm, respectively. The SBU-YLin scheme has simulated 20 to 56% higher rainfall all over the country than observed rainfall. The simulated rainfall in Day 2 is much higher in the NE region of Bangladesh than that of day 1.

WDM6 scheme (Figure 4e) has simulated maximum rainfall in the NE region and minimum rainfall in the south SW region. Sylhet has simulated the highest rainfall of 916 mm and Chittagong has the lowest rainfall of 76 mm. The spatial distribution pattern shows that the rainfall increases continuously from SW to NE and NW region of Bangladesh. The significant amount of 410 mm rainfall is simulated at Rangpur region. In the central region of Bangladesh i.e., Dhaka, the scheme has simulated significant amount of 374 mm rainfall. The minimum rainfall is seen at Bhola, Khepupara and Mongla and the amounts are79, 89 and 94 mm, respectively. The WDM6 scheme has simulated 19 to 60% higher rainfall all over the country than observed rainfall. Simulated rainfall on Day 2 is much higher in the central to NE region of Bangladesh than that of day 1.

4.2.3 Simulation of monthly total rainfall at D1 for Day 3 prediction

The distributions of simulated monthly rainfall at D1 of May 2015 for day 3 prediction of different MP schemes in combination with KF scheme with the initial conditions of 0000UTC of everyday for the month of May 2015 are presented in Figures 5(a-f). Lin *et al.* scheme (Figure 5a) has simulated maximum rainfall in the NE region and minimum rainfall in the south SW region. Sylhet has simulated the highest rainfall of 1008 mm and Bhola has the lowest rainfall of 25 mm. The spatial distribution pattern of rainfall shows that the rainfall increases continuously from SW to NE region of Bangladesh. The minimum rainfall is seen at Khepupara, Mongla, Satkhira, Cox-Bazar and Kutubdia are 68, 78, 93, 94 and 98 mm respectively. For day 3 prediction, the Lin *et al.* scheme has simulated 9 to 25% higher rainfall all over the country than that observed.

WSM6 scheme (Figure 5b) has simulated maximum rainfall in the NE region and minimum rainfall in the south SW region. Sylhet has simulated the highest rainfall of 741 mm and Bhola has the lowest rainfall of 39 mm. The spatial distribution pattern of rainfall shows that the rainfall increases continuously from SW to NE region of Bangladesh. The significant amount of rainfall has simulated in the NW Bogura is 328 mm. The highest rainfall of 328 and 218 mm have also simulated usingWDM6 scheme at Bogura and Sandwip region respectively. In the central region of Bangladesh i.e., Dhaka, the scheme has simulated significant amount of rainfall of 304 mm. The minimum rainfall is seen at Kutubdia and Khepupara are 97 and 80 mm, respectively. For day 3 prediction, the WDM6 scheme has simulated 19% higher rainfall than that of observed.

Thompson scheme (Figure 5c) has simulated maximum rainfall in the NE region and minimum rainfall in the south SW region. Sylhet has simulated the highest rainfall of 1179 mm and Bhola has the lowest rainfall of 52 mm. The spatial distribution pattern of rainfall shows that the rainfall increases continuously from SW to NE region of Bangladesh. The significant amount of rainfall of 281 mm has simulated at Bogura region. In the central region of Bangladesh i.e., Dhaka, the scheme has simulated significant amount of rainfall 289 mm. The minimum rainfall is seen at Mongla and Patuakhali are 55 mm. For day 3 prediction, the Thompson scheme has simulated 36 to 41% higher rainfall all over the country than that observed.

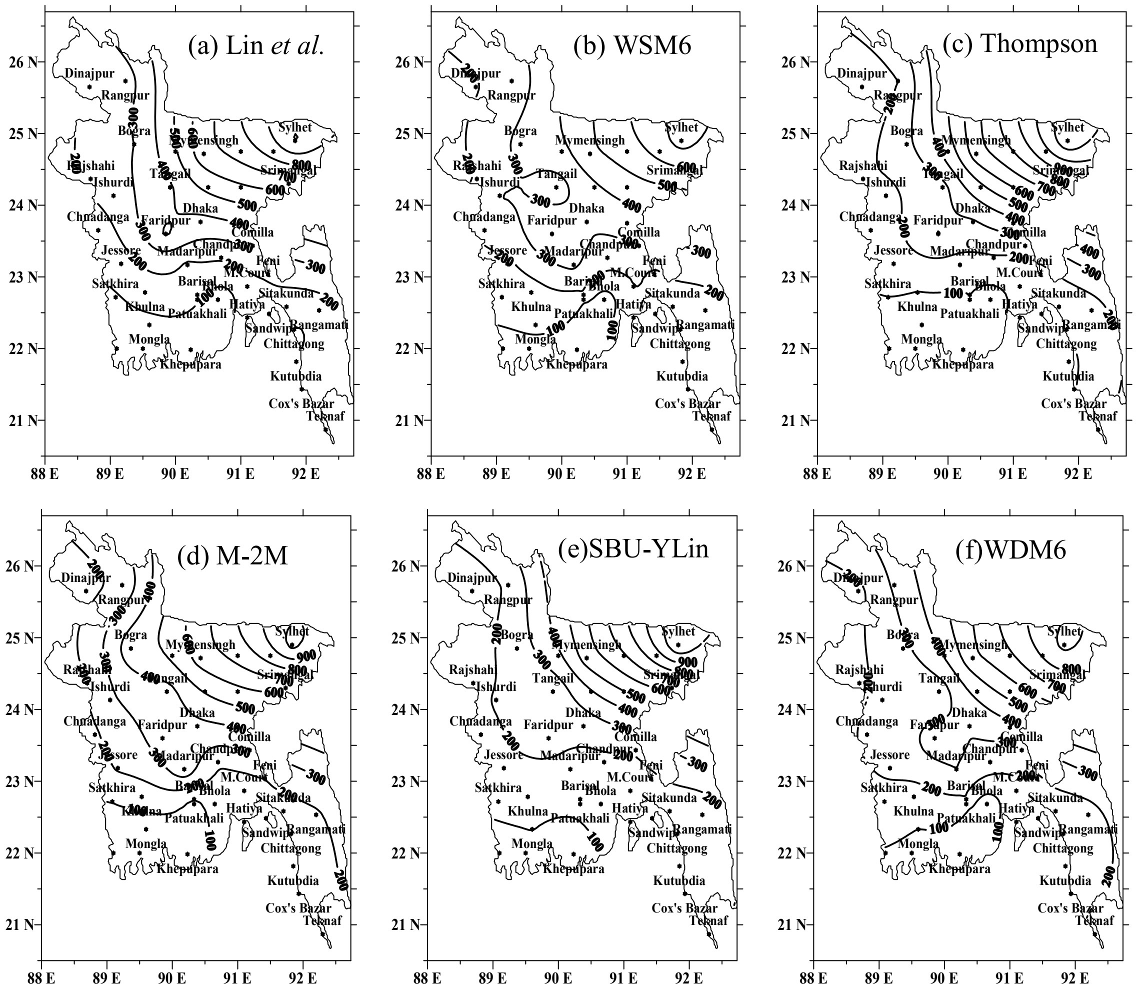


Figure 5: Spatial distribution of model simulated monthly total rainfall of May 2015 for day 3 prediction in D1 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

M-2M scheme (Figure 5d) has simulated maximum rainfall in the NE region and minimum rainfall in the south SW region. Sylhet has simulated the highest 1030 mm of rainfall and Mongla has the lowest 66 mm of rainfall. The spatial distribution pattern of rainfall shows that the rainfall increased continuously from SW to NE region of Bangladesh. The significant amount of 465 mm rainfall is simulated at Bogura region. In the central region of Bangladesh i.e., Dhaka, the scheme has simulated significant amount of 377 mm of rainfall. The minimum rainfall is seen at Khepupara and Patuakhali region are 78 and 67 mm respectively. For day 3 prediction, the M-2M scheme has simulated 27 to 50% higher rainfall all over the country than that observed.

SBU-YLin scheme (Figure 5e) has maximum rainfall in the NE region and minimum rainfall in the south SW region. Sylhet has simulated the highest rainfall 1088 mm and Khepupara has the lowest rainfall of 55 mm. The spatial distribution pattern of rainfall shows that the

rainfall increased continuously from SW to NE region of Bangladesh. The significant amount of rainfall 255 mm has simulated at Rangpur region. The simulated rainfall at Faridpur is 262 mm i.e., the central region of Bangladesh. The minimum rainfall is also seen at Chittagong and Mongla are 112 and102 mm, respectively. For day 3 prediction the SBU-YLin scheme has simulated 25 to 39 % higher rainfall all over the country than that observed rainfall.
WDM6 scheme (Figure 5f) has simulated maximum rainfall in the NE region and minimum rainfall in the south SW region. Sylhet has simulated the highest rainfall 925 mm and Bhola has the lowest rainfall of 25 mm. The spatial distribution pattern of rainfall shows that the rainfall increased continuously from SW to NE region of Bangladesh. There is a pocket of higher rainfall is also simulated in the central region of the country. The significant amount of rainfall 315 mm has simulated at Rangpur region. The simulated rainfall at Faridpur is 349 mm i.e., the central region of Bangladesh. The minimum rainfall is also seen at Mongla and Khepupara are 100 and 77 mm respectively. The WDM6 scheme has predicted 9 to 17% higher rainfall than that of observed rainfall for day 3 prediction all over the country. For day 3 prediction, WDM6 scheme gives the better performance among six studied microphysics.

4.3 Model simulated rainfall for the month of May 2015 at Domain 2 (D2)

4.3.1 Simulation of monthly total rainfall at D2 for Day 1 prediction

The simulated monthly rainfall distributions of domain 2 (D2) for different MP schemes in combination with KF scheme with the initial conditions of everyday for the month of May 2015 are presented in Figures 6(a-f). Lin *et al.* scheme (Figure 6a) has simulated maximum rainfall in the NE region and minimum rainfall in the south SW region. Sylhet has simulated the highest rainfall of 923 mm and Bhola has the lowest rainfall of 33 mm. The spatial distribution pattern of rainfall shows that the rainfall increases continuously from SW to NE region of Bangladesh. The significant amount 315 mm of rainfall has also simulated at Bogura region. In the central region of Bangladesh i.e., Dhaka, the scheme has simulated significant amount 440 mm of rainfall. The minimum rainfall is also seen at Teknaf and Cox-Bazar is 107 and 106 mm, respectively. 16 to 18% higher rainfall has simulated all over the country by Lin *et al.* scheme.

WSM6 scheme (Figure 6b) has simulated maximum rainfall in the NE region and minimum rainfall in the south SW region. Sylhet has simulated the highest rainfall of 999 mm and Bhola has the lowest rainfall of 25 mm. The spatial distribution pattern shows that the rainfall increased continuously from SW to NE region of Bangladesh. The significant amount of rainfall of 391 mm has also been simulated at Bogura region. In the central region of

Bangladesh i.e., Dhaka, the scheme has simulated the significant amount of rainfall of 423 mm. The minimum rainfall is also seen at Teknaf is 74 mm. 9 to 24 % higher rainfall has simulated all over the country for day 1 prediction by WSM6 scheme

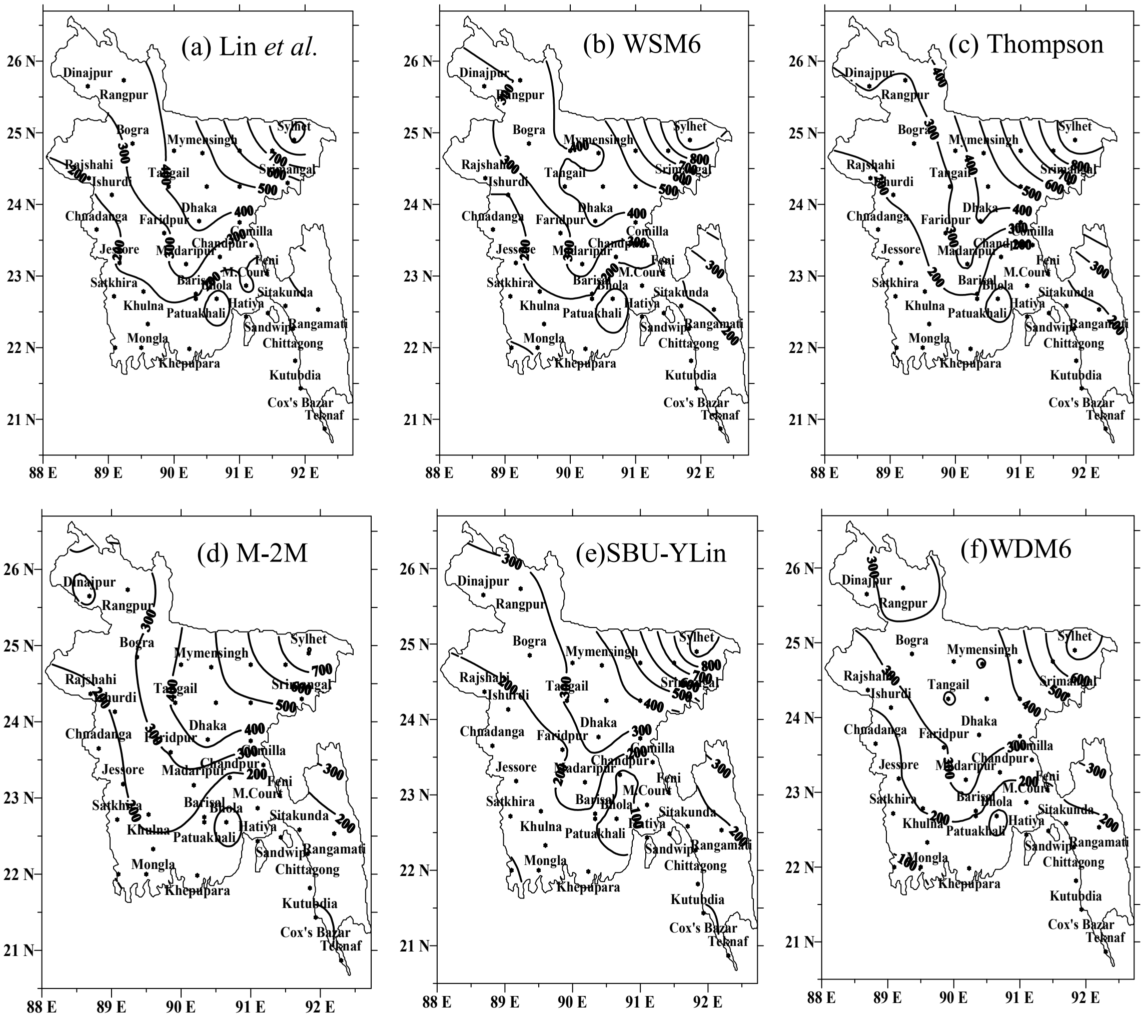


Figure 6: Spatial distribution of model simulated monthly total rainfall of May 2015 for day 1 prediction in D2 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

Thompson scheme (Figure 6c) has simulated maximum rainfall in the NE region and minimum rainfall in the S-SW region. Sylhet has simulated the highest rainfall 1000 mm and Bhola has the lowest rainfall of 47 mm. The spatial distribution pattern shows that the rainfall increases continuously from SW to N-NE region of Bangladesh. The significant amount of rainfall 310 mm has also simulated at Dinajpur region. In the central region of Bangladesh i.e., Dhaka the scheme has also simulated significant amount of rainfall 412 mm. The minimum rainfall is also seen at Chuadanga, Teknaf and Cox-Bazar region are 128, 104 and

95 mm respectively. Thompson scheme has simulated 24 to 31% higher rainfall all over the country than that observed rainfall.

M-2M scheme (Figure 6d) has simulated maximum rainfall in the NE region and minimum rainfall in the S-SW region. Sylhet has simulated the highest rainfall 807 mm and Bhola has the lowest rainfall of 30 mm. The spatial distribution pattern shows that the rainfall increases continuously from SW to N-NE region of Bangladesh. The significant amount of rainfall 317 mm has simulated at Dinajpur region. In the central region of Bangladesh i.e., Dhaka the scheme has simulated significant amount of rainfall 446 mm. The minimum rainfall is also seen in Teknaf and Cox-Bazar region are 109 and 82 mm respectively. TheM-2M scheme has simulated 5 to 14% higher rainfall all over the country than that observed rainfall.

SBU-YLin scheme (Figure 6e) has simulated maximum rainfall in the NE region and minimum rainfall in the S-SW region. Sylhet has simulated the highest rainfall 950 mm and Bhola has the lowest rainfall of 22 mm. The spatial distribution pattern has shown that the rainfall increases continuously from SW to NE region of Bangladesh. The significant amount of rainfall 267 mm has simulated at Dinajpur region. In the central region of Bangladesh i.e., Dhaka the scheme has simulated significant amount of rainfall 446 mm. The minimum rainfall is also seen at Patuakhali, Satkhira, Mongla, Teknaf, Cox-Bazar and Chandpur are 114, 114, 112, 108, 86 and 73 mm respectively. The SBU-YLin scheme has simulated 6 to 20 % higher rainfall all over the country than that observed rainfall.

WDM6 scheme (Figure 6e) has simulated maximum rainfall in the NE region and minimum rainfall in the S-SW region. Sylhet has simulated the highest rainfall 744 mm and Bhola has the lowest rainfall of 58 mm. The spatial distribution pattern has shown that the rainfall increases continuously from SW to NE region of Bangladesh. The significant amount of rainfall 375 mm has also simulated at Bogura region. In the central region of Bangladesh i.e., Tangail the scheme has simulated significant amount of rainfall 415 mm. The minimum rainfall is also seen at Chandpur, Mongla and Teknaf region are 128, 116 and 90 mm, respectively. The rainfall simulated by WDM6scheme is matched with the observed highest rainfall.

4.3.2 Simulation of monthly total rainfall at D2 for Day 2 prediction

The day 2 simulated monthly rainfall distributions in D2 of May 2015 for different MP schemes in combination with KF scheme with the initial conditions of 0000UTC of everyday for the month of May are presented in Figures 7(a-f). Lin *et al.* scheme (Figure 7a) has simulated maximum rainfall in the NE region and minimum rainfall in the S-SW region. Sylhet has simulated the highest rainfall 1075 mm and Chittagong has the lowest rainfall of 69 mm. The spatial distribution pattern shows that the rainfall increases continuously from SW to NE region of Bangladesh. The significant amount of rainfall 377 mm has simulated at Bogura region. In the central region of Bangladesh i.e., Dhaka the scheme has simulated significant amount of rainfall 398 mm. The minimum rainfall is also seen at Teknaf, Satkhira, Mongla, Khepupara and Khulna region are 98, 92, 91, 78 and 73 mm respectively. The Lin *et al.* scheme has simulated 31 to 53% higher rainfall at day 2 all over the country than that observed rainfall.

WSM6 scheme (Figure 7b) has simulated maximum rainfall in the NE region and minimum rainfall in the S-SW region. Sylhet has simulated the highest rainfall 714 mm and Khulna has the lowest rainfall of 73mm. The spatial distribution pattern shows that the rainfall increases continuously from SW to NE region of Bangladesh. The significant amount of rainfall 593 mm has simulated at Rangpur region. In the central region of Bangladesh i.e., Dhaka the scheme has simulated significant amount of rainfall 465 mm. The minimum rainfall is also seen at Bhola, Mongla, Satkhira, Khepupara and Khulna region are 105, 104, 100, 94 and 73 mm respectively. The WSM6scheme has shown 4% lower rainfall than that of observed highest rainfall and 57% higher rainfall than that observed lowest rainfall for day 2 simulation.

Thompson scheme (Figure 7c) has simulated maximum rainfall in the NE region and minimum rainfall in the S-SW region. Sylhet has simulated the highest rainfall 1071 mm and Khulna has the lowest rainfall of 55 mm. The spatial distribution pattern shows that the rainfall increases continuously from SW to NE region of Bangladesh. The significant amount of rainfall 315 mm has simulated at Rangpur region. In the central region of Bangladesh i.e., Faridpur the scheme has simulated significant amount of rainfall 438 mm. The minimum rainfall is also seen at Chandpur, Teknaf, Khepupara, Mongla, Patuakhali, Chittagong and Satkhira are 96, 95, 89, 87, 81, 76 and 68 mm respectively. The Thompson scheme has simulated 31 to 39% higher rainfall for day 2 simulation all over the country than that observed rainfall.

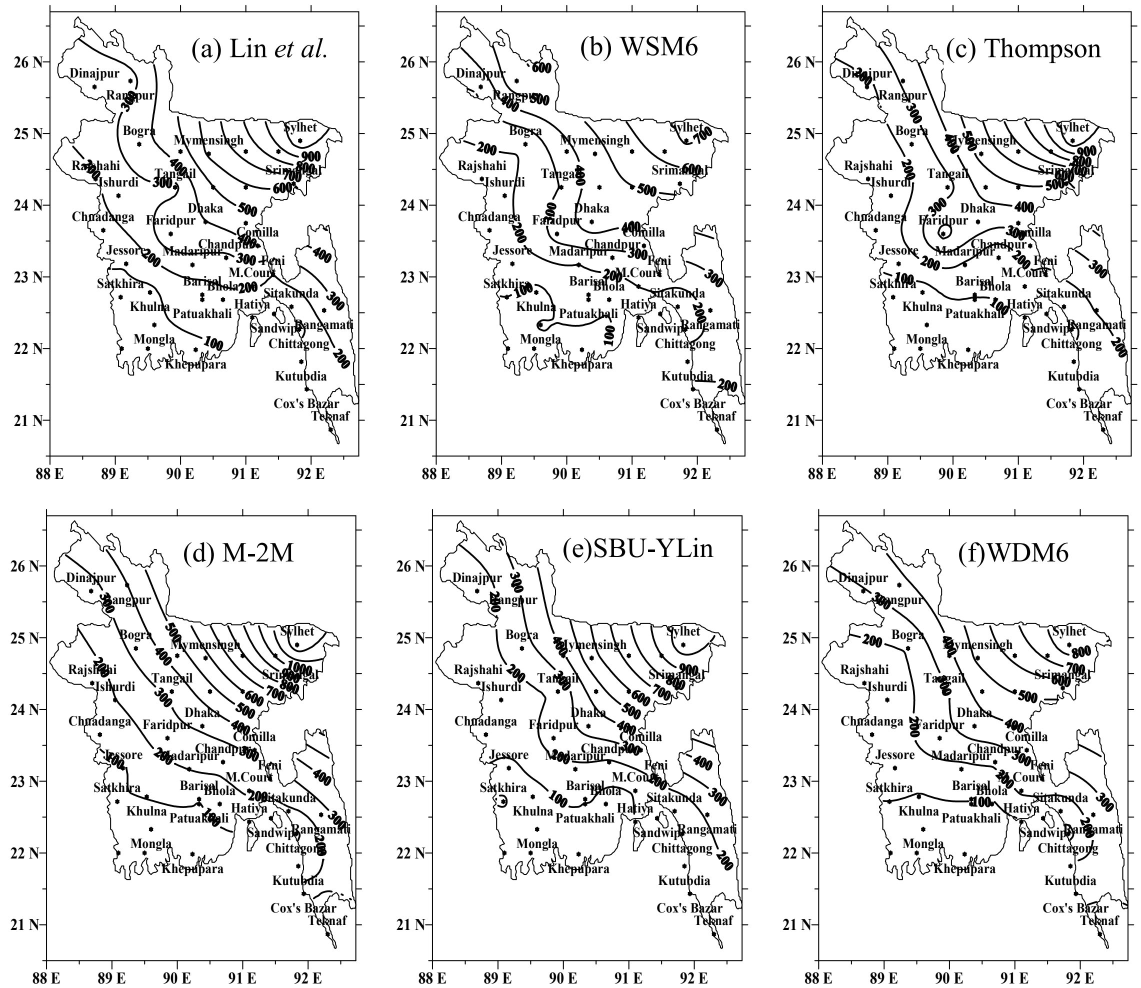


Figure 7: Spatial distribution of model simulated monthly total rainfall of May 2015 for day 2 prediction in D2 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

M-2M scheme (Figure 7d) has simulated maximum rainfall in the NE region and minimum rainfall in the S-SW region. Sylhet has simulated the highest rainfall 1268 mm and Mongla has the lowest rainfall of 53 mm. The spatial distribution pattern has shown that the rainfall increases continuously from SW to N-NE region of Bangladesh. The significant amount of rainfall 398 mm has simulated at Rangpur region. In the central region of Bangladesh i.e., Tangail the scheme has simulated significant amount of rainfall 320 mm. The minimum rainfall is also seen at Jashore, Patuakhali, Teknaf, Chittagong and Khepupara region are 92, 88, 85, 80 and 70 mm respectively. The M-2M scheme has simulated 37 to 50 % higher rainfall all over the country than that observed rainfall for day 2 prediction.

SBU-YLin scheme (Figure 7e) has simulated maximum rainfall in the NE region and minimum rainfall in the S-SW region. Sylhet has simulated the highest rainfall 1059 mm and

Bhola has the lowest rainfall of 33 mm. The spatial distribution pattern shows that the rainfall increases continuously from SW to N-NE region of Bangladesh. The significant amount of rainfall 278 mm has simulated at Rangpur region. In the central region of Bangladesh i.e., Dhaka the scheme has simulated significant amount of rainfall 339 mm. The minimum rainfall is also seen at Hatiya, Teknaf, Patuakhali, Jashore, Khepupara, Mongla and Khulna region are 99, 99, 93, 77, 73, 69 and 63 mm respectively. The SBU-YLin scheme has simulated 16 to 25% higher rainfall all over the country than that observed rainfall for day 2 prediction.

WDM6 scheme (Figure 3f) has simulated maximum rainfall in the NE region and minimum rainfall in the S-SW region. Sylhet has simulated the highest rainfall 877 mm and Mongla and Chittagong are the lowest rainfall of 66 mm. The spatial distribution pattern shows that the rainfall increases continuously from SW to N-NE region of Bangladesh. The significant amount of rainfall 373 mm has simulated at Rangpur region. In the central region of Bangladesh i.e., Dhaka the scheme has simulated significant amount of rainfall 359 mm. The minimum rainfall is also seen at Satkhira, Khepupara, Khulna, Hatiya, Bhola and Patuakhali region are 99, 99, 91, 90, 88 and 76 mm, respectively.TheWDM6scheme has simulated 11 to 50% higher rainfall all over the country than that observed rainfall for day 2 prediction.

4.3.3 Simulation of monthly total rainfall at D2 for Day 3 prediction

The day 3 simulated monthly rainfall distributions in D2 of May 2015 for different MP schemes in combination with KF scheme with the initial conditions of 0000 UTC of everyday for the month of May are presented in Figures 8(a-f). Lin *et al.* scheme (Figure 8a) has simulated maximum rainfall in the NE region and minimum rainfall in the S-SW region. Sylhet has simulated the highest rainfall 998 mm and Bhola has the lowest rainfall of 39 mm. The spatial distribution pattern has shown that the rainfall increases continuously from SW to N-NE region of Bangladesh. The significant amount of rainfall 332 mm has simulated at Bogura region. In the central region of Bangladesh i.e., Faridpur the scheme has simulated significant amount of rainfall 492 mm. The minimum rainfall is also seen at Satkhira, Kutubdia and Khepupara region are 128, 107 and 79 mm, respectively. The Lin *et al.* scheme has simulated 19 to 24% higher rainfall all over the country for day 3 prediction.

WSM6 scheme (Figure 8b) has simulated maximum rainfall in the NE region and minimum rainfall in the S-SW region. Sylhet has simulated the highest rainfall 802 mm and Bhola has the lowest rainfall of 29 mm. The spatial distribution pattern has shown that the rainfall increases continuously from S-SW to N-NE region of Bangladesh. The significant amount of rainfall 342 mm has simulated at Bogura region. In the central region of Bangladesh i.e., Faridpur the scheme has simulated significant amount of rainfall 414 mm. The minimum rainfall is also seen at Hatiya, Chittagong, Khepupara and Mongla region are 125, 105, 101 and 90 mm respectively. The WSM6 scheme has simulated 5 to 13% higher rainfall all over the country for day 3 prediction.

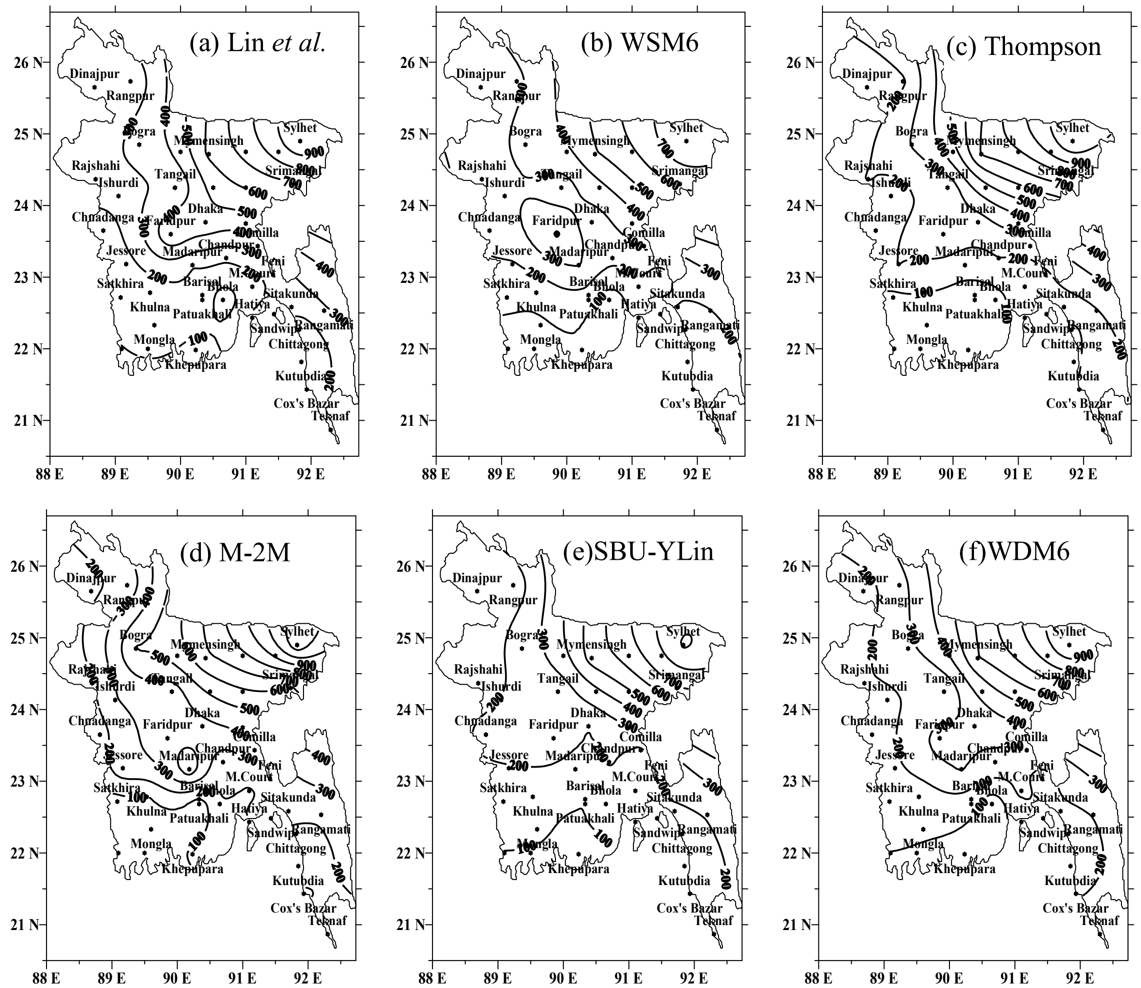


Figure 8: Spatial distribution of model simulated monthly total rainfall of May 2015 for day 3 prediction in D2 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

Thompson scheme (Figure 8c) has simulated maximum rainfall in the NE region and minimum rainfall in the S-SW region. Sylhet has simulated the highest rainfall 1102 mm and Mongla has the lowest rainfall of 31 mm. The spatial distribution pattern has shown that the rainfall increases continuously from SW to N-NE region of Bangladesh. The significant amount of rainfall 305 mm has simulated at Bogura region. In the central region of

Bangladesh i.e., Faridpur the scheme has simulated significant amount of rainfall 293 mm. The minimum rainfall is also seen in the month of May 2015 at Kutubdia, Satkhira, Chittagong, Khepupara, Bhola, Barishal and Patuakhali region are 90, 80, 78, 73, 69, 61 and 39 mm, respectively. The Thompson scheme has simulated 15 to 35% higher rainfall all over the country for day 3 prediction.M-2M scheme (Figure 8d) has simulated maximum rainfall in the NE region and minimum rainfall in the S-SW region. Sylhet has simulated the highest rainfall 1167 mm and Patuakhali has the lowest rainfall of 38 mm. The spatial distribution pattern has shown that the rainfall increases continuously from SW to N-NE region of Bangladesh. The significant amount of rainfall 506 mm has simulated at Bogura region. In the central region of Bangladesh i.e., Faridpur the scheme has simulated significant amount of rainfall 375 mm. The minimum rainfall is also seen at Barishal, Khulna, Satkhira and Mongla region are 101, 91, 66 and 48 mm respectively. The M-2M scheme has simulated 22 to 41% higher rainfall all over the country for day 3 prediction.

SBU-YLin scheme (Figure 8e) has simulated maximum rainfall in the NE region and minimum rainfall in the S-SW region. Sylhet has simulated the highest rainfall 913 mm and Khepupara has the lowest rainfall of 43 mm. The spatial distribution pattern has shown that the rainfall increases continuously from S-SW to N-NE region of Bangladesh. The significant amount of rainfall 247 mm has simulated at Bogura region. In the central region of Bangladesh i.e., Faridpur the scheme has simulated significant amount of rainfall 292 mm. The minimum rainfall is also seen at Rangpur, Kutubdia, Mongla, Cox-Bazar and Patuakhali region are 139, 125, 125, 125 and 100 mm respectively. The SBU-YLin scheme has simulated 16 to 27% higher rainfall all over the country for day 3 prediction.

WDM6 scheme (Figure 8f) has simulated maximum rainfall in the NE region and minimum rainfall in the S-SW region. Sylhet has simulated the highest rainfall 1004 mm and Bhola has the lowest rainfall of 27 mm. The spatial distribution pattern has shown that the rainfall increases continuously from south to N-NE region of Bangladesh. The significant amount of rainfall 282 mm has simulated at Bogura region. In the central region of Bangladesh i.e., Faridpur the scheme has simulated significant amount of rainfall 345 mm. The minimum rainfall is also seen at Khulna, Chittagong, Mongla and Khepupara region are 143, 137, 112 and 74 mm respectively. The WDM6 scheme has simulated 11 to 25% higher rainfall all over the country for day 3 prediction.

4.4 Model simulated heavy rainfall (HR) for the month of May 2015 at D1

4.4.1 Simulation of monthly total heavy rainfall at D1 for Day 1 prediction

The distributions of simulated monthly heavy rainfall (HR) on day 1in D1 of May 2015 for different MP schemes in combination with KF scheme with the initial conditions of 0000 UTC of everyday for the month of May are presented in Figures 9(a-f). Lin *et al.* scheme (Figure 9a) has simulated maximum HR in the NE region and no HR in the central to S-SE, SW and NW region of Bangladesh. Highest monthly HR has been simulated at Sylhet 654 mm and in the NW region i.e., Bogura is seen 100 mm of HR. The Lin *et al.* scheme has simulated 4 to 30% higher rainfall all over the country than that observed rainfall. The distribution pattern of HR is similar to that of observed HR all over the country but the scheme has simulated much higher HR in the NE region and lowers in the NW region.

WSM6 scheme (Figure 9b) has simulated maximum HR in the NE region and no HR in the central to S-SE and SW region of Bangladesh. Highest monthly HR has been simulated at Sylhet499 mm. Heavy rainfall is also seen at Dhaka 144 mm. The distribution pattern of HR is similar to that of observed HR all over the country. Thompson scheme (Figure 9c) has simulated maximum HR in the NE region and no HR in the S-SE, SW and NW region of Bangladesh. Highest monthly HR has been simulated at Sylhet619 mm. The distribution pattern of HR is similar to that of observed HR all over the country but the scheme has simulated much higher HR in the NE region and lowers in the NW region.

M-2M scheme (Figure 9d) has simulated maximum HR in the NE region and no HR in the S-SE, SW and NW region of Bangladesh. Highest monthly HR has been simulated at Sylhet523 mm and at Dhaka 175 mm. In the NW region of Bangladesh i.e., Bogura is seen at heavy rainfall 92 mm. The distribution pattern of HR is similar to that of observed HR all over the country but the scheme has simulated higher HR in the NE region and lowers in the NW region. SBU-YLin scheme (Figure 9e) has simulated maximum HR in the NE region and no HR in the S-SE, SW and NW region of Bangladesh. Highest monthly HR has been simulated at Sylhet 781 mm. The distribution pattern of HR is similar to that of observed HR all over the country but the scheme has simulated much higher HR in the NE region and much lower in the NW region.

WDM6 scheme (Figure 9f) has simulated maximum HR in the NE region and no HR in the S-SE, SW and NW region of Bangladesh. Highest monthly HR has been simulated at Sylhet 445 mm. In the NW region of Bangladesh i.e., Bogura is seen at 104 mm. The distribution pattern of HR is similar to that of observed HR all over the country but the scheme has simulated much higher HR in the NE region and much lower in the NW region.

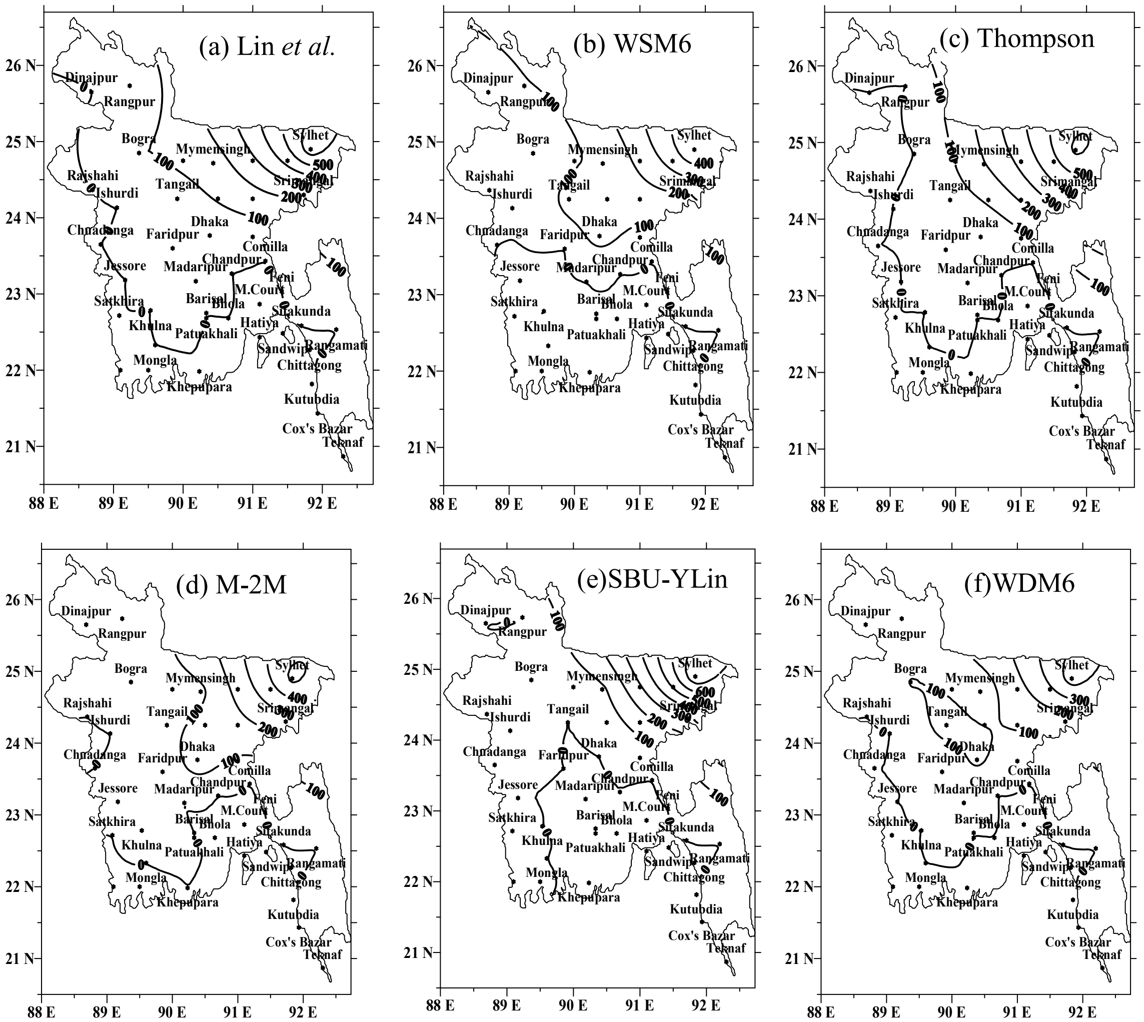


Figure 9: Spatial distribution of model simulated monthly total heavy rainfall of May 2015 for day 1 prediction in D1 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

4.4.2 Simulation of monthly total heavy rainfall at D1 for Day 2 prediction

The day 2 simulated monthly HR distributions in D1 of May 2015 for different MP schemes in combination with KF scheme with the initial conditions of 0000 UTC of everyday for the month of May are presented in Figures 10(a-f).Lin *et al.* scheme (Figure 10a) has simulated maximum HR in the NE region and no HR in the central to SW, SE and western region of Bangladesh. Highest monthly HR has been simulated at Sylhet 737 mm and in the NW region i.e., Bogura is seen 111 mm of HR. In the southern region of Bangladesh i.e., Bhola is observed HR 155 mm. The distribution pattern of HR is similar to that of observed HR all over the country but the scheme has simulated much higher HR in the NE region and lowers in the NW region. WSM6 scheme (Figure 10b) has simulated maximum HR in the NE region and no HR in the S-SE, SW and western region of Bangladesh. Highest monthly HR has been simulated at Sylhet 398 mm. HR is also seen in the SE region of Bangladesh i.e., Kutubdia 161mm.The distribution pattern of HR is similar to that of observed HR all over the country except Kutubdia region.

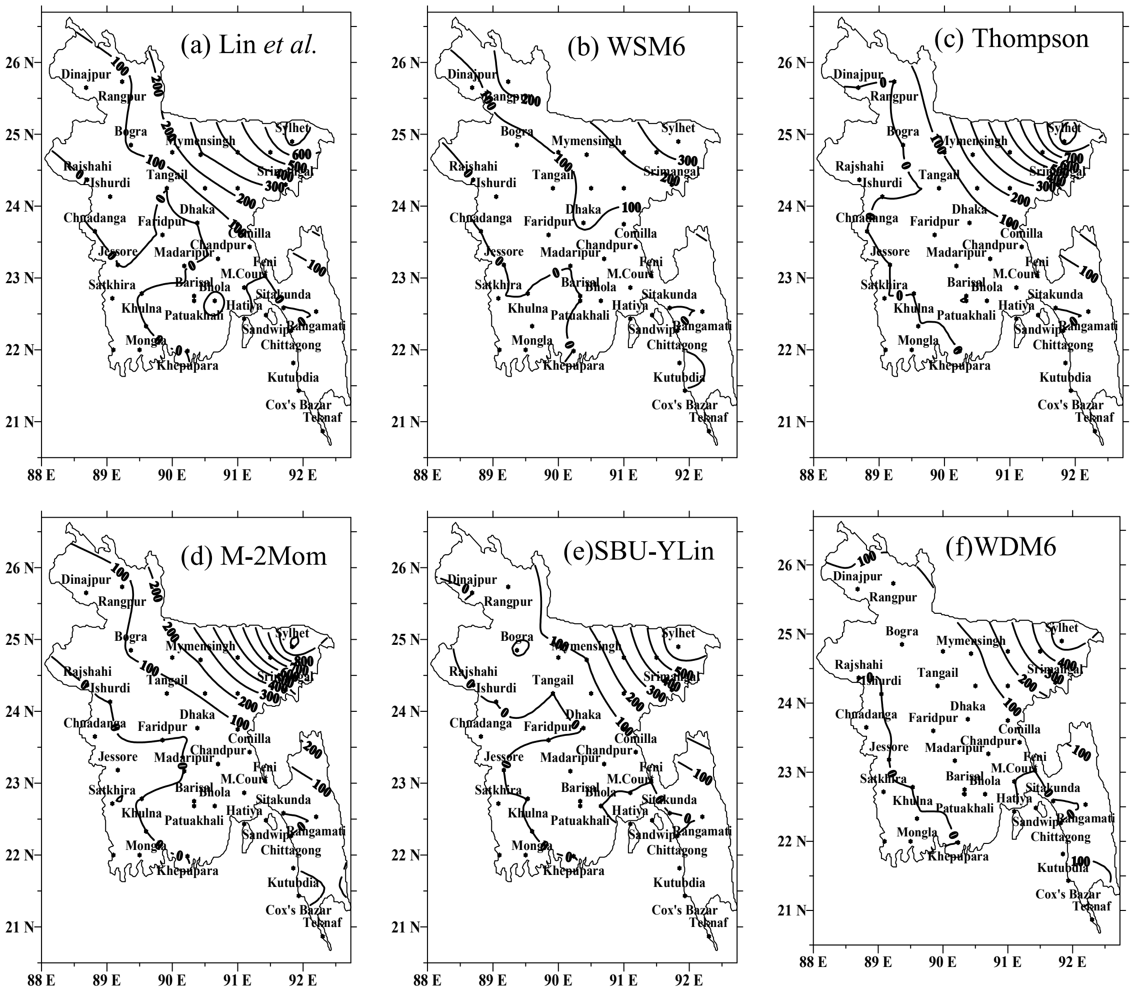


Figure 10: Spatial distribution of model simulated monthly total heavy rainfall of May 2015 for day 2 prediction in D1 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

Thompson scheme (Figure 10c) has simulated maximum HR in the NE region and no HR in the central south, SW, NW and western region of Bangladesh. Highest monthly HR has been simulated at Sylhet 940 mm. In the SE region of Bangladesh i.e., Cox-Bazar is seen 161 mm. The distribution pattern of HR is similar to that of observed HR all over the country but the simulated HR in the NE region much higher than that of observed. M-2M scheme (Figure

10d) has simulated maximum HR in the NE region and no HR in the central to west and SW region of Bangladesh. Highest monthly HR has been simulated at Sylhet 1022 mm. In the SE region of Bangladesh i.e., Cox-Bazar is seen HR 121 mm. The distribution pattern of HR is similar to that of observed HR all over the country but the scheme has simulated much higher HR in the NE region.

SBU-YLin scheme (Figure 10e) has simulated maximum HR in the NE region and no HR in the central to west and SW region of Bangladesh. Highest monthly HR has been simulated at Sylhet 699 mm. The distribution pattern of HR is similar to that of observed HR all over the country except NW region but the scheme has simulated much higher HR in the NE region and lowers in the NW region. WDM6 scheme (Figure 10f) has simulated maximum HR in the NE region and no HR in the western and SW region of Bangladesh. Highest monthly HR has been simulated at Sylhet 558 mm. In the SE region of Bangladesh i.e., Cox-Bazar is seen 199 mm. The distribution pattern of HR is similar to that of observed HR all over the country but the scheme has simulated much higher HR in the NE region and lower HR in the NW region.

4.4.3 Simulation of monthly total HR at D1 for Day 3 prediction

The day 3 simulated monthly HR distributions in D1 of May 2015 for different MP schemes in combination with KF scheme with the initial conditions of 0000 UTC of everyday for the month of May are presented in Figures 11(a-f).Lin *et al.* scheme (Figure 11a) has simulated maximum HR in the NE region and no HR in the central to SW region of Bangladesh. Highest monthly HR has been simulated at Sylhet694 mm. The monthly secondary peak of HR is seen at Mymensingh 471 mm. The distribution pattern of HR is similar to that of observed HR all over the country except Mymensingh but the scheme has simulated much higher HR in the north NE region of Bangladesh.WSM6 scheme (Figure 11b) has simulated maximum HR in the NE region and no HR in the SE, SW, NW and western region of Bangladesh. Highest monthly HR has been simulated at Sylhet364 mm. The distribution pattern of HR is similar to that of observed HR all over the country except NW region. The HR simulated by this scheme is almost with the observed rain all over the country except NW region.

Thompson scheme (Figure 11c) has simulated maximum HR in the NE region and no HR in the central to east, south, SW, west and NW region of Bangladesh. Highest monthly HR has been simulated at Sylhet751 mm. The monthly total HR is also seen at Mymensingh is 323mm. The distribution pattern of HR is similar to that of observed HR all over the country except NW region. The HR simulated by this scheme is almost with the observed rain all over the country except NW region. M-2M scheme (Figure 11d) has simulated maximum HR in the NE region and no HR in the SW, west and NW region of Bangladesh. Highest monthly HR has been simulated at Sylhet 751 mm. In the NW and central region of Bangladesh i.e., Bogura and Dhaka are also seen HR 181 and 153 mm respectively. The distribution pattern of HR is similar to that of observed HR all over the country except central and NW region.

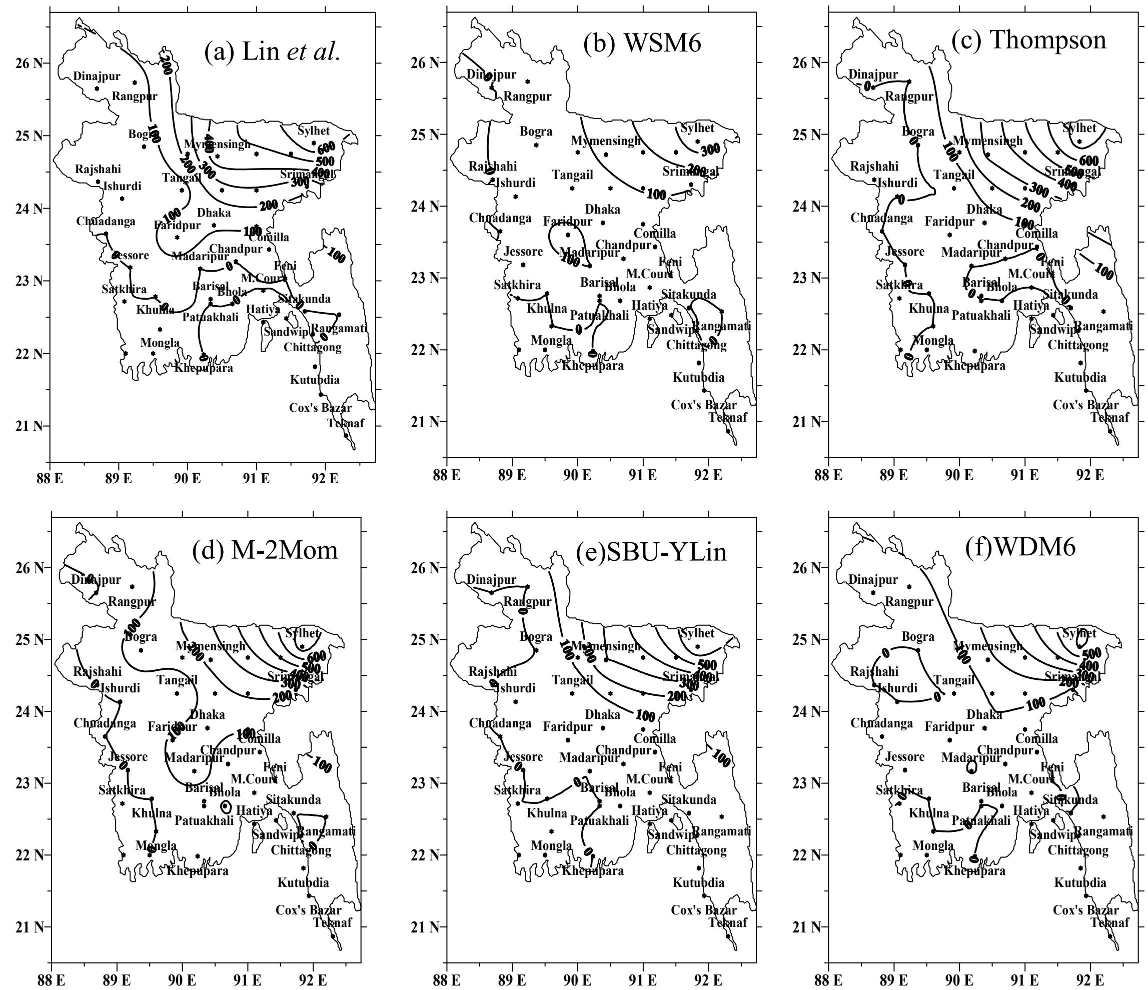


Figure 11: Spatial distribution of model simulated monthly total heavy rainfall of May 2015 for day 3 prediction in D1 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

SBU-YLin scheme (Figure 11e) has simulated maximum HR in the NE region and no HR in the SW, west and NW region of Bangladesh. Highest monthly HR has been simulated at Sylhet 692 mm. The distribution pattern of HR is similar to that of observed HR all over the country except NW region. WDM6 scheme (Figure 11f) has simulated maximum HR in the NE region and no HR in the SW, west and NW region of Bangladesh. Highest monthly HR has been simulated at Sylhet619 mm. In the SE region of Bangladesh i.e., Teknaf is also seen HR of 103 mm. The distribution pattern of HR is similar to that of observed HR all over the country except NW region.

4.5 Model simulated HR for the month of May 2015 at D2

4.5.1 Simulation of monthly heavy rainfall at D2 for Day 1 prediction

The day 1 simulated monthly HR distributions in D2 of May 2015 for different MP schemes in combination with KF scheme with the initial conditions of 0000 UTC of everyday for the month of May are presented in Figures 12(a-f). Lin *et al.* scheme (Figure 12a) has simulated maximum HR in the NE region and no HR in the S-SE region of Bangladesh. Highest monthly HR has been simulated at Sylhet 687 mm. In the NW region of Bangladesh i.e., Rangpur is seen HR 100 mm. The distribution pattern of HR is similar to that of observed HR all over the country but much higher HR is simulated NE region.

WSM6 scheme (Figure 12b) has simulated maximum HR in the NE region and no HR in the S-SE region of Bangladesh. Highest monthly HR has been simulated at Sylhet 681 mm. Dhaka is also simulated higher HR 217 mm during the month of May 2015. In the NW region of Bangladesh i.e., Bogura is seen 138 mm of HR. The distribution pattern of HR is similar to that of observed HR all over the country but much higher HR is simulated NE region. Thompson scheme (Figure 12c) has simulated maximum HR in the NE region and no HR in the S-SE, SW and western region of Bangladesh. Highest monthly HR has been simulated at Sylhet780 mm. The distribution pattern of HR is similar to that of observed HR all over the country but much higher HR is simulated in the NE region.M-2M scheme (Figure 12d) has simulated maximum HR in the NE region and no HR in the S-SE, SW and western region of Bangladesh. Highest monthly HR has been simulated at Sylhet 503 mm. In the Capital of Bangladesh i.e., Dhaka observed 207 mm of HR and in the NW Bogura observed HR is 190 mm. The distribution pattern of HR is similar to that of observed HR all over the country but total amount of monthly HR is almost matched with the observed HR.
SBU-YLin scheme (Figure 12e) has simulated maximum HR in the NE region and no HR in the S-SE, SW and western region of Bangladesh. Highest monthly HR has been simulated at Sylhet 808 mm. HR is seen at Dhaka at 90 mm in the central region of Bangladesh. The distribution pattern of HR is similar to that of observed HR all over the country but much higher HR is simulated in the NE region. WDM6 scheme (Figure 12f) has simulated maximum HR in the NE region and no HR in the S-SE, SW and western region of Bangladesh. Highest monthly HR has been simulated at Sylhet 383 mm. In the NW region of

Bangladesh i.e., Bogura is seen 123 mm of HR. The distribution pattern of HR is similar to that of observed HR all over the country but lower amount of HR is simulated in the NE region.

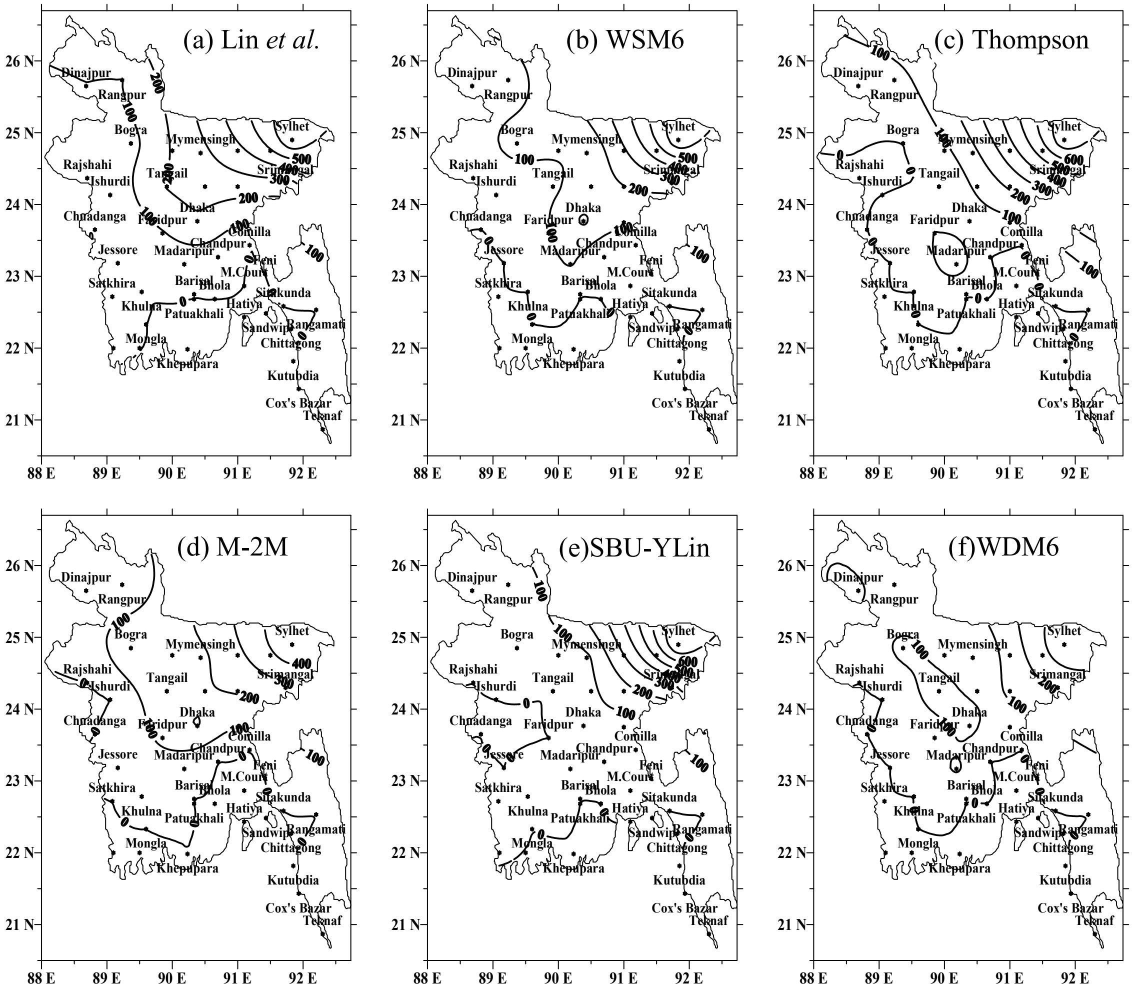


Figure 12: Spatial distribution of model simulated monthly total heavy rainfall of May 2015 for day 1 prediction in D2 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

4.5.2 Simulation of monthly heavy rainfall at D2 for Day 2 prediction

The day 2 simulated monthly HR distributions in D2 of May 2015 for different MP schemes in combination with KF scheme with the initial conditions of 0000 UTC of everyday for the month of May are presented in Figures 13(a-f). Lin *et al.* scheme (Figure 13a) has simulated maximum HR in the NE region and no HR in the S-SW region of Bangladesh. Highest monthly HR has been simulated at Sylhet 711 mm. The monthly total HR is also seen at Mymensingh is 281mm. The distribution pattern of HR is similar to that of observed HR all over the country but much higher HR is simulated in the NE region.WSM6 scheme (Figure

13b) has simulated maximum HR in the NE region and no HR in the S-SW region of Bangladesh. Highest monthly HR has been simulated at Sylhet334 mm. In the NW region of Bangladesh i.e., Dinajpur is observed 150 mm. The scheme is also simulated monthly higher HR at Kutubdia202mm.The distribution pattern of HR is similar and also matched with the observed HR all over the country.

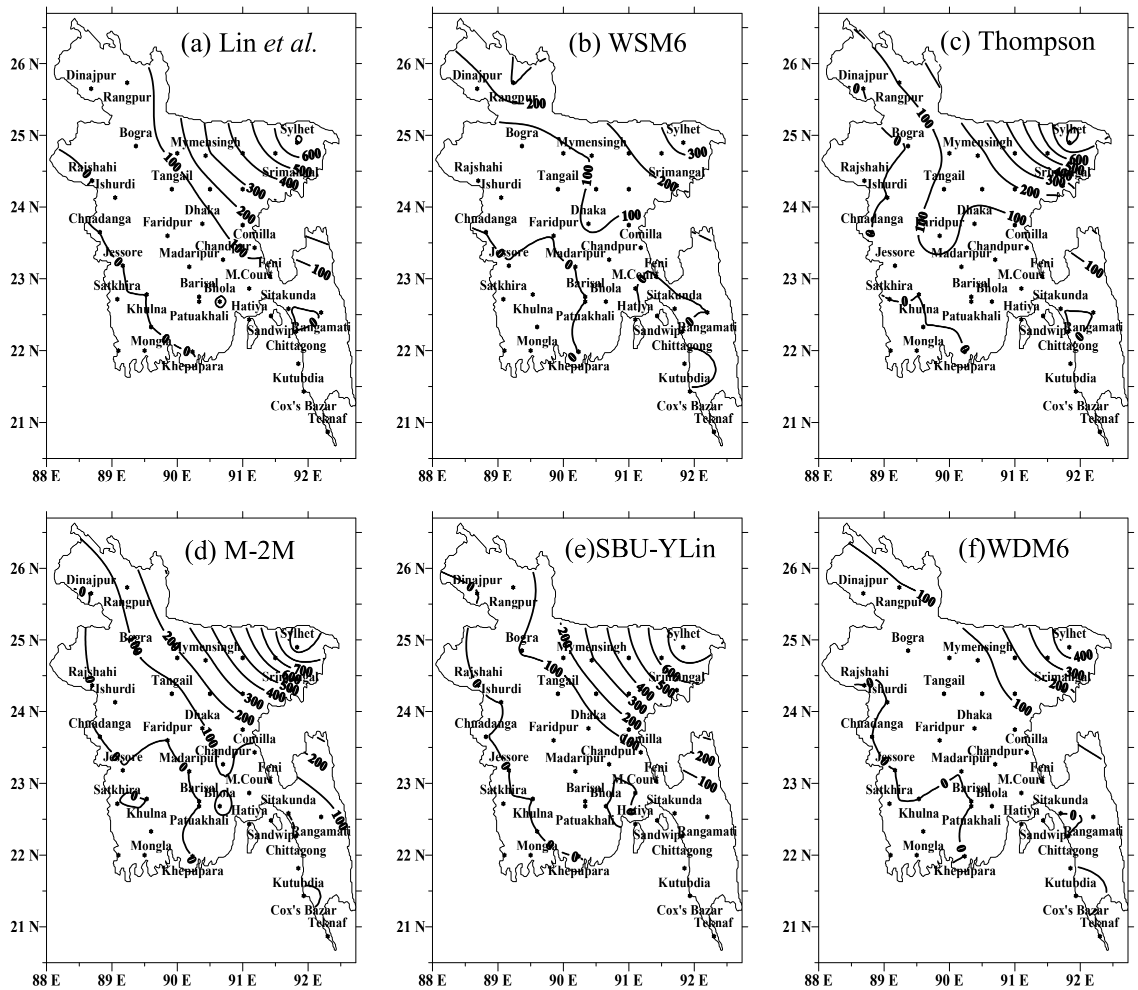


Figure 13: Spatial distribution of model simulated monthly total heavy rainfall of May 2015 for day 2 prediction in D2 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

Thompson scheme (Figure 13c) has simulated maximum HR in the NE region and no HR in the S-SW and western region of Bangladesh. Highest monthly HR has been simulated at Sylhet 825 mm. HR is also seen at Faridpur 159 mm in the central region of Bangladesh and in the NW Rangpur 105 mm. The distribution pattern of HR is similar to that of observed HR all over the country but much higher HR is simulated in the NE region. M-2M scheme (Figure 13d) has simulated maximum HR in the NE region and no HR in the SW and western region of Bangladesh. Highest monthly total HR has been simulated at Sylhet 997 mm. In the NW and SE region of Bangladesh i.e., Rangpur and Cox-Bazar are seen HR of 138 and 152 mm, respectively. The distribution pattern of monthly total HR is similar to that of observed HR all over the country but much higher HR is simulated in the NE region. SBU-YLin scheme (Figure 13e) has simulated maximum HR in the NE region and no HR in the S-SW, NW and western region of Bangladesh. Highest monthly total HR has been simulated at Sylhet 779 mm and. In the NW and SE region of Bangladesh i.e., Bogura and Sandwip are seen HR of 110 and 100 mm, respectively. The distribution pattern of monthly total HR is similar to that of observed HR all over the country but much higher HR is simulated in the NE region. WDM6 scheme (Figure 13f) has simulated maximum HR in the NE region and no HR in the S-SW, NW and western region of Bangladesh. Highest monthly total HR has been simulated at Sylhet 476 mm. In the SE region of Bangladesh i.e., Cox-Bazar is seen HR of 154 mm. The distribution pattern of HR is similar and also matched with the observed HR all over the country except NW region.

4.5.3 Simulation of monthly heavy rainfall at D2 for Day 3 prediction

The day 3 simulated monthly HR distributions in D2 of May 2015 for different MP schemes in combination with KF scheme with the initial conditions of 0000 UTC of everyday for the month of May are presented in Figures 14(a-f). Lin *et al.* scheme (Figure 14a) has simulated maximum HR in the NE region and no HR in the S-SW region of Bangladesh. Highest monthly HR has been simulated at Sylhet 688 mm. The monthly total significant amount of HR is also seen at Faridpur is 235 mm. The distribution pattern of HR is similar to that of observed HR all over the country but much higher HR is simulated in the NE region.WSM6 scheme (Figure 14b) has simulated maximum HR in the NE region and no HR in the S-SW region of Bangladesh. Highest monthly HR has been simulated at Sylhet 507 mm. Significant amount of HR is also seen at Faridpur 163 mm. The distribution pattern of HR is similar and also matched with the observed HR all over the country except NW region. Thompson scheme (Figure 14c) has simulated maximum HR in the NE region and no HR in the SW region of Bangladesh. Highest monthly HR has been simulated at Sylhet 825 mm. Significant HR is also seen at Faridpur 159 mm i.e. in the central region of Bangladesh. The distribution pattern of HR is similar to that of observed HR all over the country but much higher HR is simulated in the NE region.

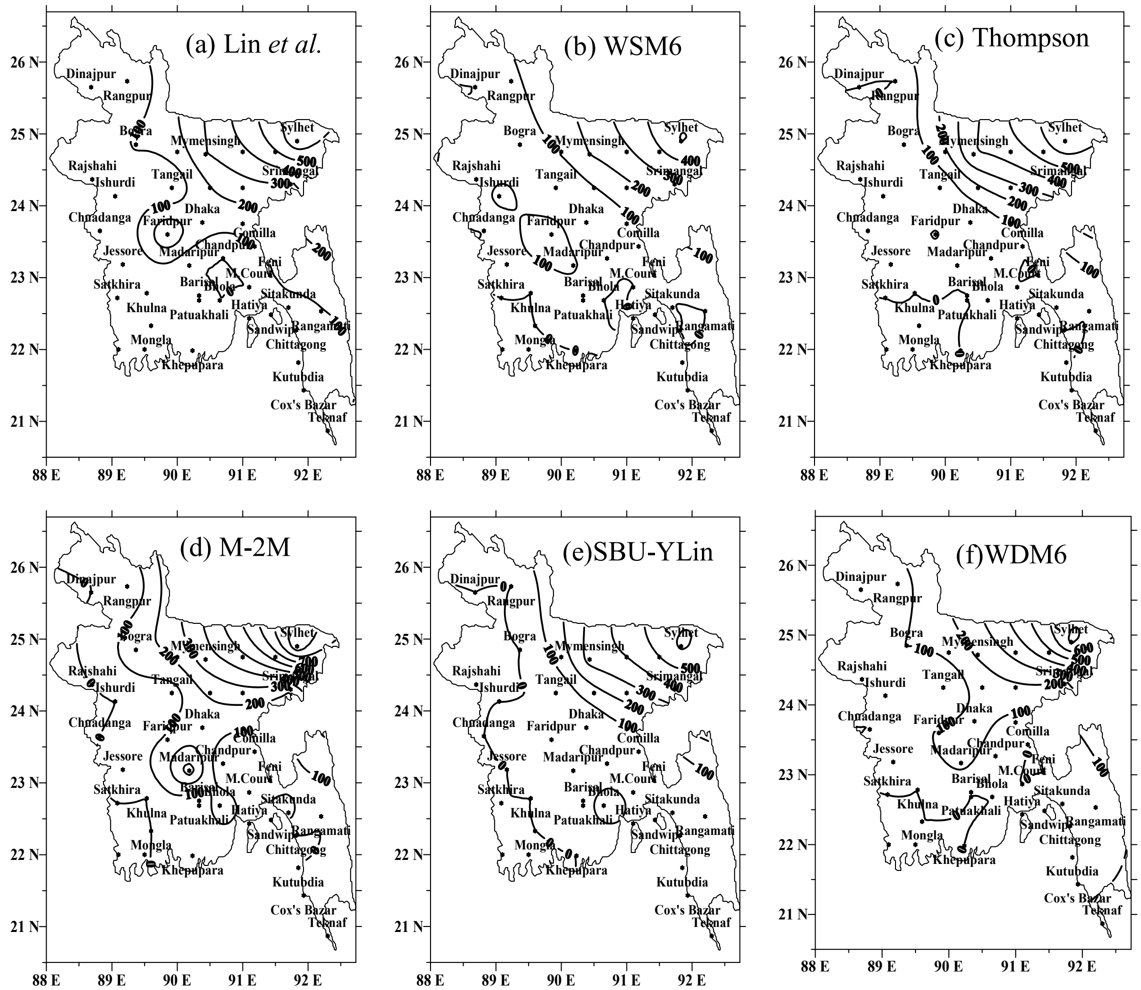


Figure 14: Spatial distribution of model simulated monthly total heavy rainfall of May 2015 for day 3 prediction in D2 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

M-2M scheme (Figure 14d) has simulated maximum HR in the NE region and no HR in the SW, west and NW region of Bangladesh. Highest monthly HR has been simulated at Sylhet972 mm. In the central region of Bangladesh i.e., Madaripur is also simulated significant amount of HR 353 mm. The distribution pattern of HR is similar to that of observed HR all over the country except Madaripur region but much higher HR is simulated in the NE region. SBU-YLin scheme (Figure 14e) has simulated maximum HR in the NE region and no HR in the SW, west and NW region of Bangladesh. Highest monthly HR has been simulated at Sylhet 614 mm. In the SE region of Bangladesh i.e., Teknaf is seen HR of 117 mm. The distribution pattern of HR is similar to that of observed HR all over the country but much higher HR is simulated in the NE region. WDM6 scheme (Figure 14f) has simulated maximum HR in the NE region and no HR in the SW, west and NW region of Bangladesh. Highest monthly HR has been simulated at Sylhet 720 mm. In the central region of Bangladesh i.e. Dhaka 124 mm HR is also simulated. The distribution pattern of HR is similar to that of observed HR all over the country but much higher HR is simulated in the NE region.

4.6 Observed Rainy Days for the month of May 2015

4.6.1 BMD and PERSIANN Observed rainy days for the month of May 2015

The distributions of observed total rainy days and PERSIANN total rainy days for the month of May 2015 all over Bangladesh are presented in Figures15(a-d). From the distribution pattern, the maximum and minimum rainy days (Figure 15a) are observed at Sylhet and Khepuparawith27 and 5days, respectively. It is seen from the spatial distribution that the rainy days increases continuously from SW to N-NE region of Bangladesh. The maximum rainy days (20 days) with also observed at Rangpur. The maximum rainy days observed at Dhaka, Mymensingh, Dinajpur, Feni and Faridpur are 19, 19, 15, 15 and 13 days, respectively. The maximum and minimum number of PERSIANN rainy days are observed at Sylhet and Khepupara with 28 and 10 days, respectively. It is seen from the spatial distribution pattern that the PERSIANN rainy day increases continuously from SW to N-NE region of Bangladesh. The maximum rainy days observed at Bhola, Rajshahi, Rangamati, Satkhira and Sitakunda are 19 days each and Madaripur and M.Court are 18 days each and Ishwardi, Kutubdia and Patuakhali are 17 days each and Chittagong and Jashore are 16 days each and Chuadanga, Faridpur and Mongla are 15 days each.

4.6.2 Observed BMD and PERSIANN heavy rainy days for the month of May 2015

Observed station wise distribution of heavy rainy days and PERSIANN HR days for the month of May 2015 all over Bangladesh is presented in Figures 15(c-d). The maximum number of BMD observed HR days (Figure 15c) is found at Sylhet and no HR days at central to south, SE, SW and western region of the country. It is also seen from the spatial distribution pattern that the HR days increased continuously from SW to NE region of Bangladesh. The second peak of HR days are also observed at Dinajpur. From the distribution pattern, the maximum PERSIANN distribution of HR days (Figure 15d) is observed at Srimangal (4 days) and no HR days at maximum region of the country. In the NW and SE region of Bangladesh i.e., Rangpur and Rangamati observed 2 days.

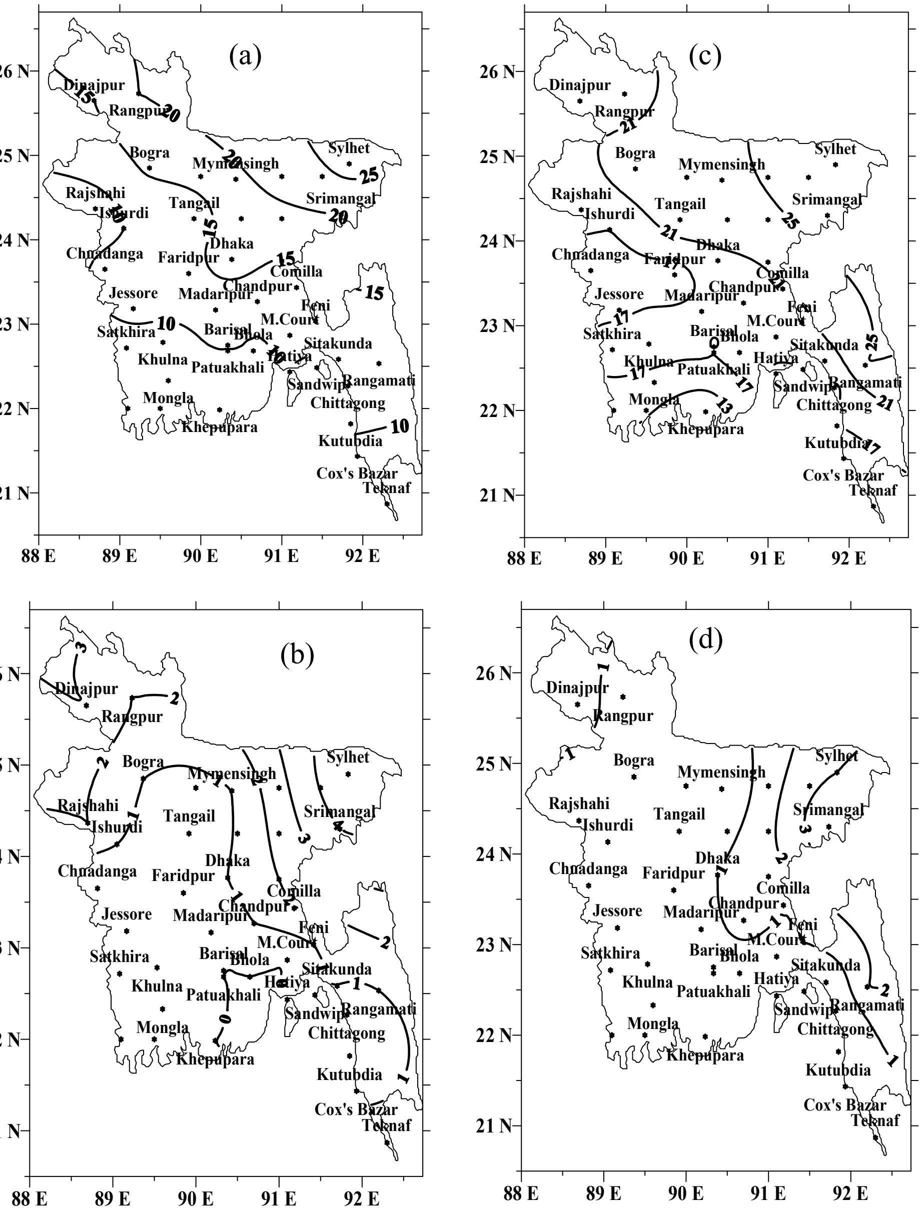


Figure 15: BMD Observed (a-b) total rainy days and Heavy rainy days, and PERSIANN (c-d) total rainy days and heavy rainy days all over Bangladesh for the month of May 2015

4.7 Model simulated rainy days for the month of May 2015 at D1

4.7.1 Simulated rainy days at D1 for Day 1 prediction

The distributions of day 1 simulated monthly total rainy days in D1 for different MP schemes in combination with KF scheme with the initial conditions of 0000UTC of everyday for the month of May 2015 are presented in Figures 16(a-f). Lin *et al.* scheme (Figure 16a) has simulated monthly highest rainy days at Barishal and Madaripur with 28 days and lowest rainy days at Bhola are 14 days. The scheme has also simulated 26rainy days, which is almost similar to the observed rainy days (27 days) at Sylhet. In the NW region of Bangladesh i.e., Bogura and Rangpur, there are seen 20 rainy days in this month.WSM6 scheme (Figure 16b) has simulated monthly highest 29 rainy days at Barishal and Madaripur and lowest 12 rainy days at Bhola. The monthly second highest rainy days are seen at Cumilla with 27 days. In Cox-Bazaar, Sitakunda and Teknaf same rainy days are simulated. The monthly minimum rainy days at Dinajpur, Jashore and Chuadanga are 20, 19 and 18 days respectively.

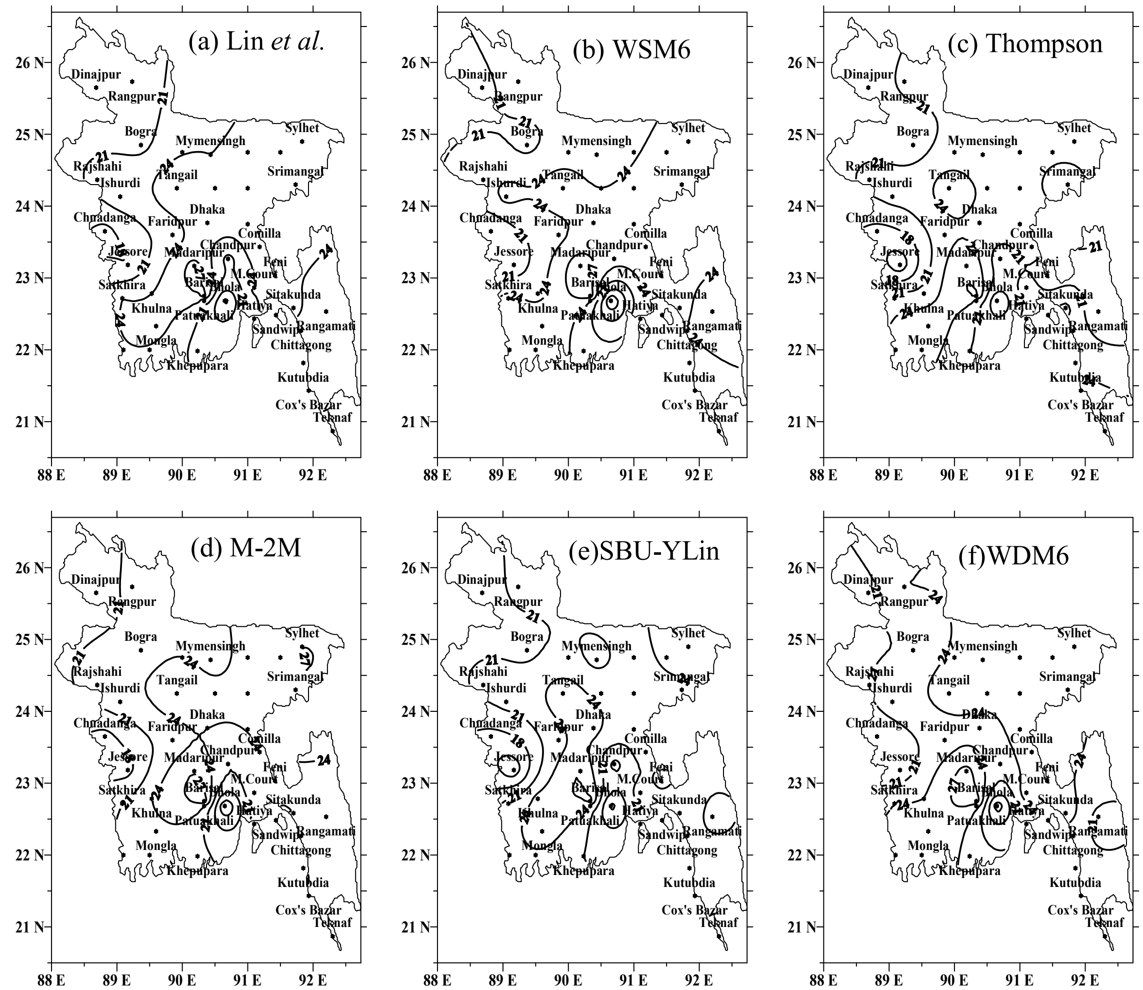


Figure 16: Spatial distribution of model simulated monthly total rainy days of May 2015 for day 1 prediction in D1 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

Thompson scheme (Figure 16c) has simulated monthly highest rainy days (28 days) at Barishal and lowest rainy days (13 days) at Jashore. The monthly second highest 27 rainy days are seen at Madaripur. 26 days rain is also simulated at Teknaf and Mongla. The monthly rainy days (2 days) is also seen at Sylhet, Patuakhali, Kutubdia, Faridpur, Cumilla and M.Court. M-2M scheme (Figure 16d) has simulated monthly highest rainy days (29 days) at Barishal and lowest rainy days (12 days) at Bhola. The monthly second highest rainy days (27 days) are seen at Tangail, Srimangal and Sylhet. The M-2M scheme has simulated 23-24 days in the maximum region of the country.

SBU-YLin scheme (Figure 16e) has simulated monthly highest rainy days (28 days) at Barishal and lowest rainy days (13 days) at Jashore. The monthly second highest rainy days (27 days) are seen at Sylhet. In the NW and SE of Bangladesh i.e., Rangpur and Teknaf have simulated rainfall days of 22 and 25, respectively. The monthly minimum rainy days are also seen at Dinajpur, Chandpur, Chuadanga and Bhola with19, 17, 17 and 14 days respectively. WDM6 scheme (Figure 16f) has simulated monthly highest rainy days (29 days) at Barishal and lowest rainy days (13 days) at Bhola. The rainy days are also simulated by this scheme are 26 and 28 days at Tangail and Madaripur respectively. The monthly minimum rainy days are also seen at Dinajpur, Rangamati, Jashore and Chuadanga, and are 20, 20, 19 and 18 days, respectively.

4.7.2 Simulated rainy days at D1 for Day 2 prediction

The day 2 simulated monthly distributions of total rainy days in D1 of May 2015 for different MP schemes in combination with KF scheme with the initial conditions of 0000UTC of everyday are presented in Figures 17(a-f). Lin *et al.* scheme (Figure 17a) has simulated monthly highest rainy days (30 days) at Mymensingh and lowest rainy days (9 days) at Bhola. The rain has simulated 28 and 29 days at Rangpur and Tangail respectively. The monthly minimum rainy days is also seen at Chittagong, Khepupara and Patuakhali are (18 days) and Khulna and Mongla (17 days).WSM6 scheme (Figure 17b) has simulated monthly highest rainy days (29 days) at Srimangal and lowest rainy days (13 days) at Bhola. The monthly second highest rainy days are seen at Sylhet and Mymensingh (28 days). The monthly minimum rainy days are also seen 19 days at Rajshahi and Satkhira and17 days at Bogura, Jashore and Khepupara. Thompson scheme (Figure 17c) has simulated maximum rainy days in the NE region and minimum in the SW region of Bangladesh. The monthly highest rainy days (29 days) have simulated at Sylhet and lowest rainy days (14 days) at Bhola. Rangpur has simulated monthly second highest rainy days (28 days). In the SE region of Bangladesh i.e., Cox-Bazar and Sandwip have simulated rainfall at 26 days. M-2M scheme (Figure 17d) has simulated maximum rainy days in the NE region and minimum in the SW region of Bangladesh. The monthly highest rainy days (28 days) have simulated at Sylhet and lowest rainy days (9 days) at Bhola. The monthly second highest rainy days are seen at Rangpur and Mymensingh at 27 days.

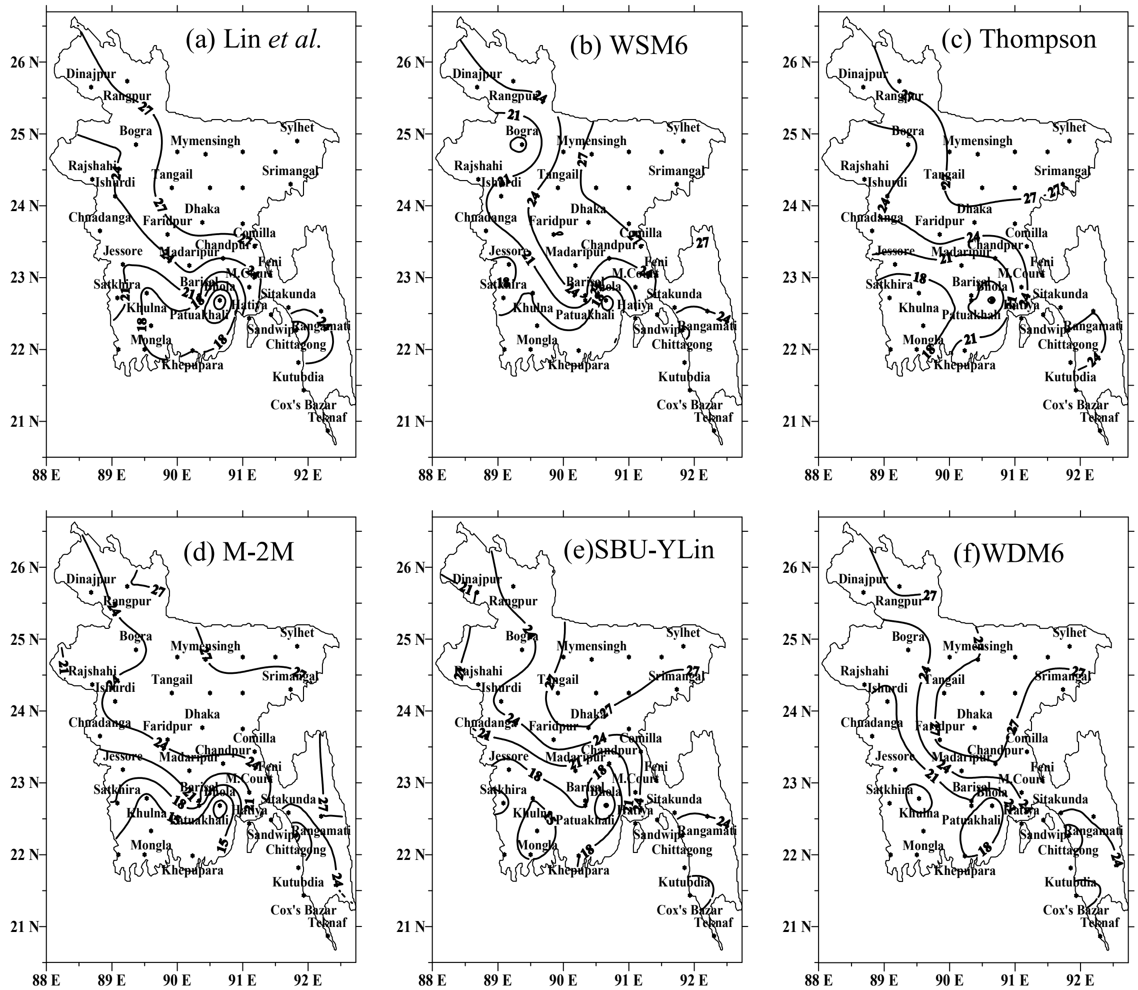


Figure 17: Spatial distribution of model simulated monthly total rainy days of May 2015 for day 2 prediction in D1 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

In the NW and SE region of Bangladesh i.e., Rangpur and Sandwip are seen rainfall at 24 and 26 days respectively. SBU-YLin scheme (Figure 17e) has simulated maximum rainy days in the NE region and minimum in the SW region of Bangladesh. The monthly highest rainy days (28 days) have simulated at Mymensingh and lowest rainy days (11days) at Bhola. The monthly second highest rainy days are seen at Sylhet and Tangail at 28 days. In the NW and SE region of Bangladesh i.e., Rangpur, Cox-Bazar and Sandwip are seen at 26rainfall days. The monthly minimum rainy days are also seen at Khulna and Mongla are 15 and 13 days respectively. WDM6 scheme (Figure 17f) has simulated maximum rainy days in the central to NE region and minimum in the SW region of Bangladesh. The monthly highest rainy days (29 days) have simulated at Dhaka and lowest rainy days (15 days) at Bhola. The monthly second highest rainy days (28 days) are seen at Faridpur, Rangpur, Sylhet and Tangail. The monthly minimum rainy days (16 days) is also seen at Khulna.

4.7.3 Simulated rainy days at D1 for Day 3 prediction

The day 3 simulated monthly distributions of total rainy days in D1 of May 2015 for different MP schemes in combination with KF scheme with the initial conditions of 0000UTC of everyday are presented in Figures 18(a-f). Lin *et al.* scheme (Figure 18a) has simulated maximum rainy days in the central to NE region and minimum in the SW region of Bangladesh. The monthly highest rainy days (29 days) have simulated at Sylhet and Tangail and lowest rainy days (12 days) at Bhola and Mongla. The monthly second highest rainy days (27 days) have simulated at Mymensingh and Srimangal. The monthly minimum rainy days have also simulated at Patuakhali, Satkhira, Chittagong, Khulna and Khepupara are 19, 18, 17, 17 and 13 days respectively.WSM6 scheme (Figure 18b) has simulated maximum rainy days in the central to NE region and minimum in the southern region of Bangladesh. The monthly highest rainy days (28 days) have simulated at Tangail and lowest rainy days (8 days) at Bhola. The monthly second highest rainy days (26 days) have simulated at Madaripur, Sandwip and Sylhet. The monthly minimum rainy days are also seen at Dinajpur, Chittagong, Patuakhali and Khulna are 19, 18, 17 and 15 days, respectively.

Thompson scheme (Figure 18c) has simulated maximum rainy days in the NE region and minimum in the SW region of Bangladesh. The monthly highest rainy days (29 days) have simulated at Tangail and lowest rainy days (11 days) at Bhola. The monthly second highest rainy days (28 days) has simulated at Sylhet. The monthly minimum rainy days (14 days) have also simulated at Dinajpur, Barishal and Patuakhali. M-2M scheme (Figure 18d) has simulated maximum rainy days in the NE region and minimum in the south SW region of Bangladesh. The monthly highest rainy days (29 days) have simulated at Sylhet and lowest rainy days (7 days) at Bhola. The monthly second highest rainy days (28 days) are seen at Mymensingh and 27 days at Dhaka, Tangail and Faridpur. The monthly minimum rainy days (11 days) is also seen at Mongla.

SBU-YLin scheme (Figure 18e) has simulated maximum rainy days in the NE region and minimum in the SW region of Bangladesh. The monthly highest rainy days (28 days) have simulated at Sylhet and lowest rainy days (10 days) at Bhola. The monthly second highest rainy days are seen at Dhaka and Srimangal are 27 days. The monthly minimum rainy days are also seen at Khepupara, Chandpur, Rangamati, Dinajpur, Satkhira Khulna and Mongla are 19, 18, 18, 17, 17, 15 and 13 days respectively.WDM6scheme (Figure 18f)has simulated monthly highest rainy days (28 days) at Tangail and lowest rainy days (11 days) at Bhola. The monthly second highest rainy days (27 days) are seen at Sylhet. The monthly minimum rainy days are also seen at Dinajpur, Chittagong, Mongla, Khulna and Khepupara are 19, 18, 17, 16 and 14 days, respectively.

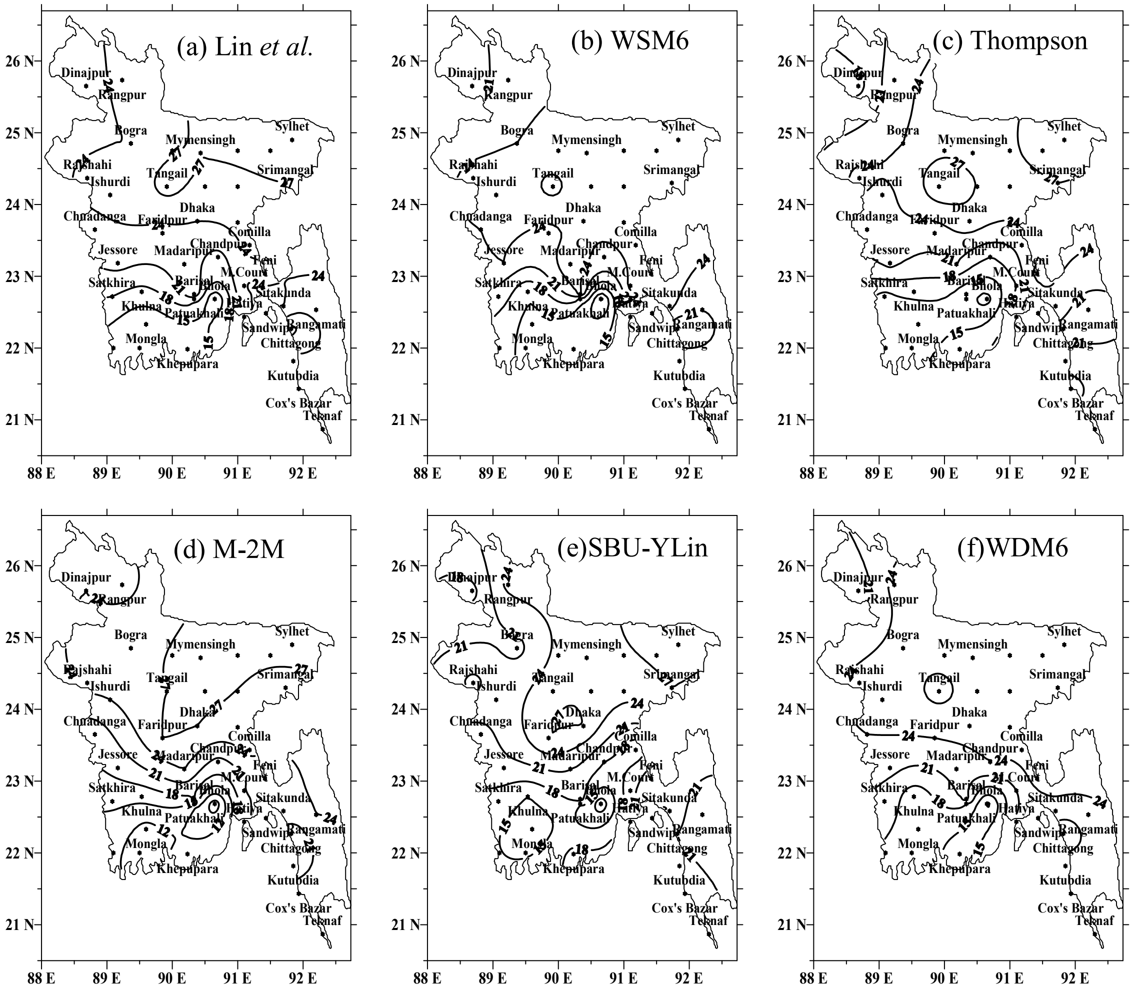


Figure 18: Spatial distribution of model simulated monthly total rainy days of May 2015 for day 3 prediction in D1 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

4.8 Model simulated rainy days for the month of May 2015 at D2

4.8.1 Simulated rainy days at D2 for Day 1 prediction

The day 1 simulated monthly distributions of total rainy days in D2 of May 2015 for different MP schemes in combination with KF scheme with the initial conditions of 0000UTC of everyday are presented in Figures19(a-f). Lin *et al.* scheme (Figure 19a) has simulated maximum rainy days in the central to NE region and minimum in the southern and western region of Bangladesh. The monthly highest rainy days (27 days) are simulated at Dhaka and lowest rainy days (12 days) at Bhola. The monthly second highest rainy days (26 days) are seen at Cumilla and Sylhet. The monthly minimum rainy days (18 days) are also seen at Ishwardi and Satkhira and 17 days at Chuadanga, Dinajpur, Faridpur and Khepupara.

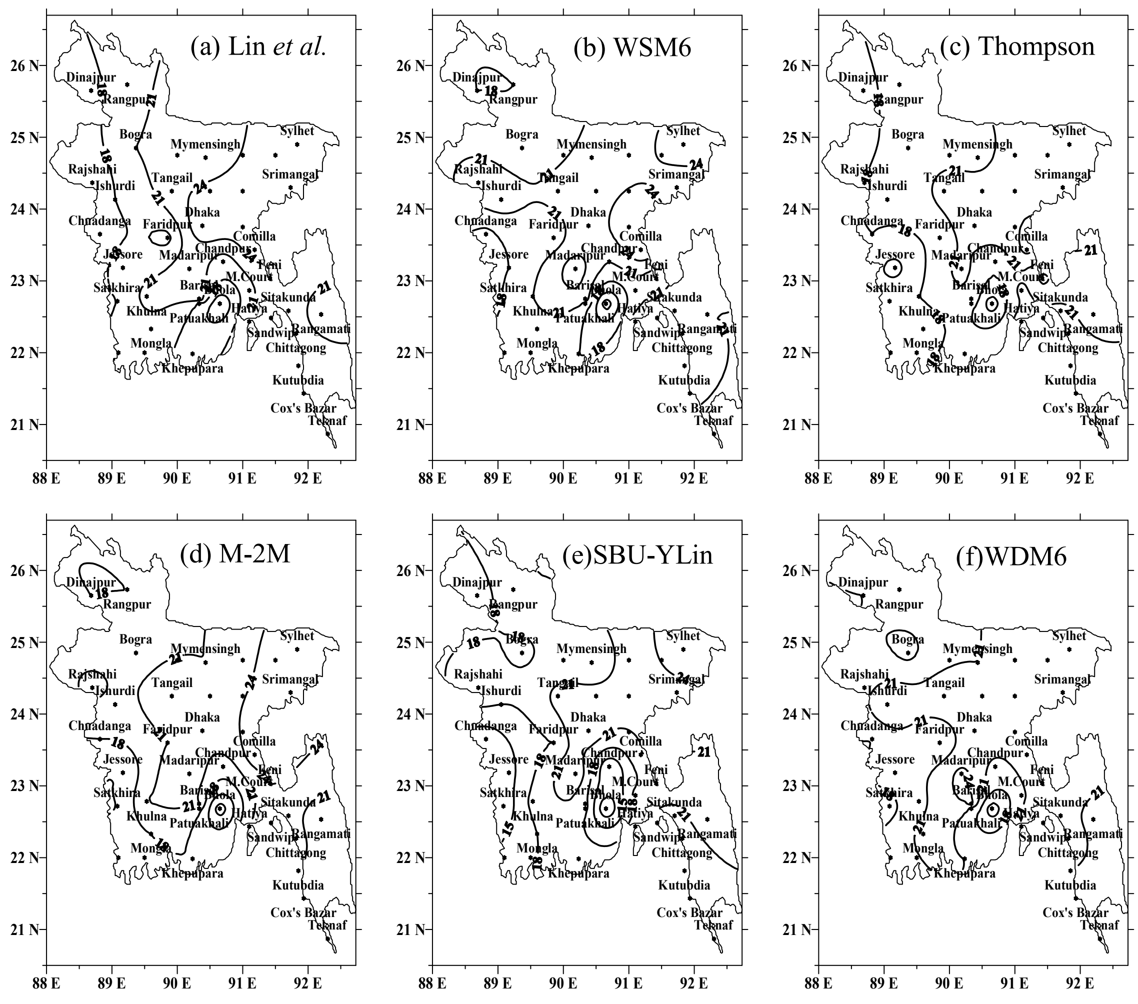


Figure 19: Spatial distribution of model simulated monthly total rainy days of May 2015 for day 1 prediction in D2 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

WSM6 scheme (Figure 19b) has simulated maximum rainy days in the central to NE region and minimum in the southern and western region of Bangladesh. The monthly highest rainy days (26 days) have simulated at Madaripur and lowest rainy days (10 days) at Bhola. The monthly second highest rainy days are seen at Sylhet at 25 days. The monthly minimum rainy days are also seen at Bogura, Dinajpur, Jashore, Khepupara, Rangpur and Satkhira are 18 days and Chuadanga and Teknaf are 17 days. Thompson scheme (Figure 19c) has simulated maximum rainy days in the central to east NE region and minimum in the southern and SW region of Bangladesh. The monthly highest rainy days (25 days) have simulated at Cumilla and lowest rainy days (13 days) at Bhola. The monthly second highest rainy days are seen at Srimangal and Teknaf at 24 days and Dhaka, Chittagong, Cox-Bazaar, Hatiya, Kutubdia, Sylhet observed 23 days.

M-2M scheme (Figure 19d) has simulated maximum rainy days in the NE region and minimum in the south SW region of Bangladesh. The monthly highest rainy days (26 days) have simulated at Sylhet and lowest rainy days (10 days) at Bhola. The monthly second highest rainy days (25 days) are seen at Srimangal. The monthly rainy days (23 days) are also seen at Madaripur, Feni, Chittagong, Dhaka, Rajshahi and Sitakunda. SBU-YLin scheme (Figure 19e) has simulated maximum rainy days in the NE region and minimum in the south SW region of Bangladesh. The monthly highest rainy days (26 days) have simulated at Sylhet and lowest rainy days (9 days) at Bhola. The monthly second highest rainy days (24 days) are seen at Dhaka and Madaripur. The monthly minimum rainy days (19 days) are also seen at Feni, Khulna, Mymensingh, M.Court and Patuakhali and 18 days at Faridpur, Ishwardi, Mongla and Rangamati and 14 days at Jashore, respectively.

WDM6 scheme (Figure 19f) has simulated maximum rainy days in the NE region and minimum in the south SW region of Bangladesh. The monthly highest rainy days (26 days) have simulated at Sandwip and lowest rainy days (13 days) at Bhola. The monthly second highest rainy days (25 days) are seen at Barishal and Madaripur. The monthly minimum rainy days (18 days) are also seen at Chuadanga, Dinajpur, Faridpur and 17 days at Bogura and Satkhira, respectively. The simulated total rainy days for all MP schemes are almost similar in the NE and NW region but higher in the S-SE and SW region.

4.8.2 Simulated rainy days at D2 for Day 2 prediction

The day 2 simulated monthly distributions of total rainy days in D2 of May 2015 for different MP schemes in combination with KF scheme with the initial conditions of 0000UTC of everyday are presented in Figures 20(a-f).Lin *et al.* scheme (Figure 20a) has simulated maximum rainy days in the NE region and minimum in the SW region of Bangladesh. The simulated number of rainy days increases continuously from south to north NE directions. The monthly highest rainy days (29 days) have simulated at Mymensingh and lowest rainy days (8 days) at Mongla. The monthly second highest 28 days are seen at Sylhet and third highest 27 days at Faridpur. The monthly minimum rainy days (9 days) are also seen at Bhola.WSM6 scheme (Figure 20b) has simulated maximum rainy days in the central to NE region and minimum in the SW region of Bangladesh. The simulated number of rainy days increases continuously from south to north NE directions. The monthly highest rainy days (28 days) have simulated at Sylhet and Faridpur and lowest rainy days (11 days) at Bhola. The monthly second highest 26 rainy days are seen at Mymensingh, Rangpur and Srimangal. The monthly minimum 12 rainy days is also seen at Mongla.

Thompson scheme (Figure 20c) has simulated maximum rainy days in the NE region and minimum at Khulna region of Bangladesh. The monthly highest rainy days (29 days) have simulated at Sylhet and Khulna has the lowest rainy days (8 days). The monthly second highest 26 rainy days are seen at Mymensingh and Sitakunda and Dhaka observed 25 days. The monthly minimum 11 rainy days is also seen at Patuakhali and Mongla. M-2M scheme (Figure 20d) has simulated maximum rainy days in the NE region and minimum in the SW region of Bangladesh. The simulated number of rainy days increases continuously from south to north NE directions. The monthly highest rainy days (29 days) have simulated at Sylhet and lowest 7 rainy days at Bhola. The monthly second highest rainy days (26) are seen at Dhaka and Srimangal. The monthly minimum 10 and 9 rainy days is also seen at Khulna and Mongla.

SBU-YLin scheme (Figure 20e) has simulated maximum rainy days in the NE region and minimum in the SW region of Bangladesh. The simulated number of rainy days increases continuously from south to north NE directions. The monthly highest rainy days (28 days) have simulated at Sylhet and lowest rainy days (9 days) at Bhola and Khulna. Monthly second highest rainy days (25 days) are seen at Dhaka, Rangpur and Sandwip. The monthly minimum rainy days (10 days) is also seen at Mongla. WDM6 scheme (Figure 20f) has simulated maximum rainy days in the central to NE region and minimum in the SW region of Bangladesh. The monthly highest rainy days (28 days) have simulated at Dhaka and lowest rainy days (12 days) at Bhola and Mongla. The second highest rainy days (26 days) is seen at Rangpur. The monthly minimum rainy days are also seen at Barishal, Khepupara and Khulna are 16, 15 and 14 days respectively.

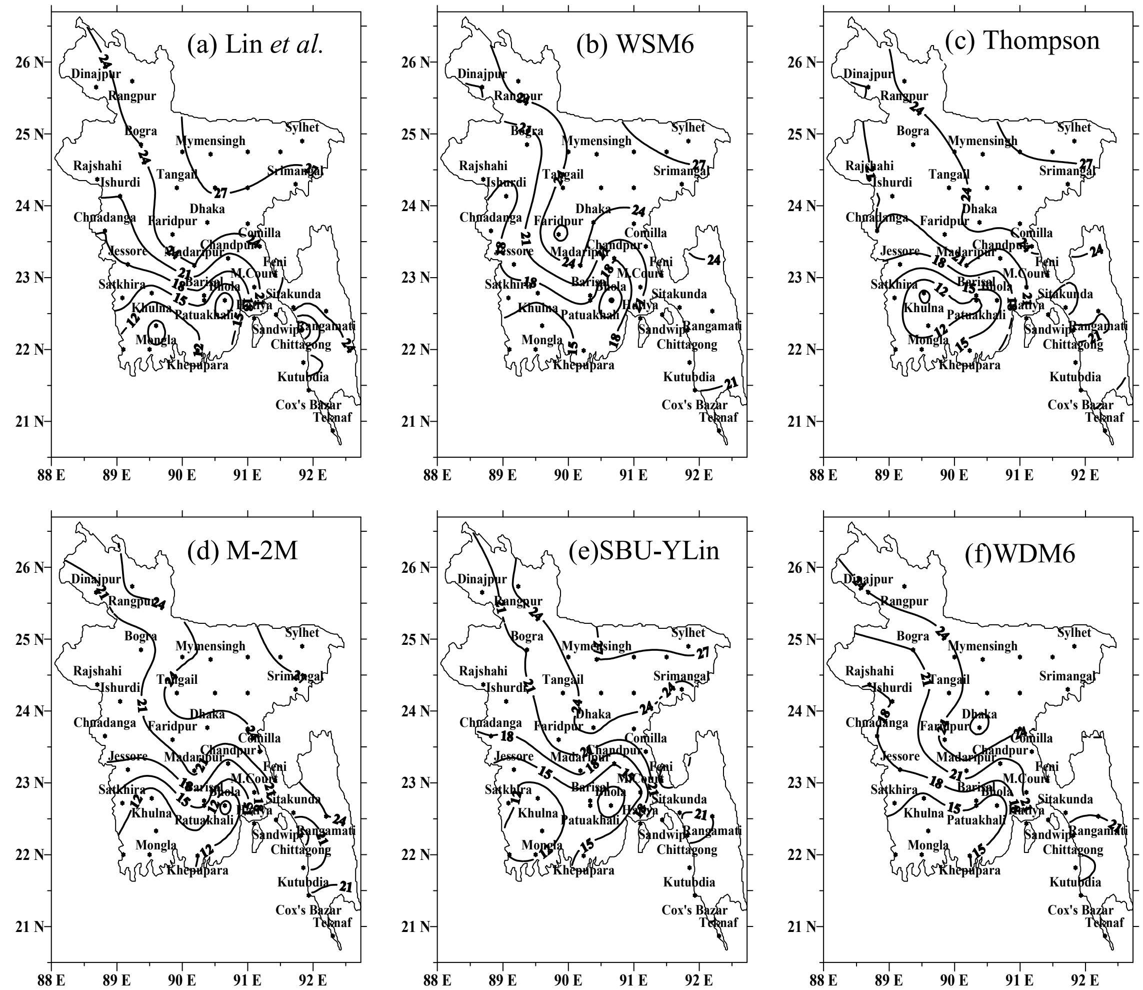


Figure 20: Spatial distribution of model simulated monthly total rainy days of May 2015 for day 2 prediction in D2 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

4.8.3 Simulated rainy days at D2 for Day 3 prediction

The day 3 simulated monthly distributions of total rainy days in D2 of May 2015 for different MP schemes in combination with KF scheme with the initial conditions of 0000UTC of everyday are presented in Figures 21(a-f).Lin *et al.* scheme (Figure 21a) has simulated maximum rainy days in the northern region and minimum in the SW region of Bangladesh. The simulated number of rainy days increases continuously from south to N-NE directions. The monthly highest rainy days (28 days) have simulated at Mymensingh and lowest rainy days (11 days) at Bhola. The monthly second highest rainy days (27 days) are seen at Tangail. In the NW and SE region of Bangladesh i.e., Bogura-Rangpur and Cox-Bazar are seen at rainfall 24 days. The monthly minimum rainy days are also seen at Satkhira and Khepupara are 13 and 12 days respectively. WSM6 scheme (Figure 21b) has simulated monthly highest rainy days (26 days) at Cumilla and Srimangal and lowest rainy days (8 days) at Bhola. The monthly second highest rainy days (25 days) are seen at Tangail.The monthly minimum rainy days (13 days) are also seen at Khepupara and Khulna and 12 days at Mongla.

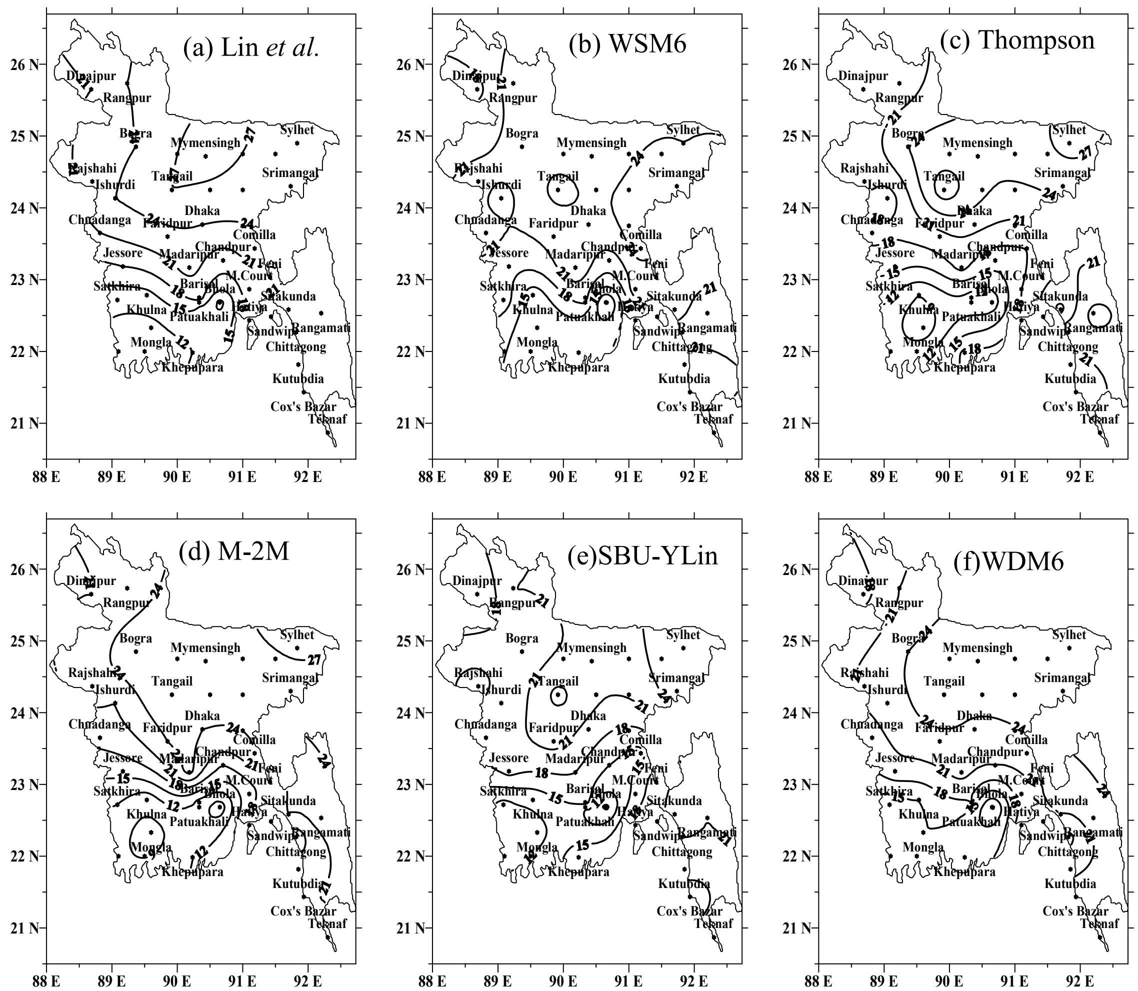


Figure 21: Spatial distribution of model simulated monthly total rainy days of May 2015 for day 3 prediction in D2 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

Thompson scheme (Figure 21c) has simulated maximum rainy days in the NE region and minimum in the SW region of Bangladesh. The simulated number of rainy days increases continuously from south to N-NE directions. The monthly highest rainy days (29 days) have simulated at Tangail and lowest rainy days (7 days) at Mongla. The monthly second highest rainy days (28 days) is seen at Sylhet. The monthly minimum rainy days (11 days) are also seen at Barishal and Patuakhali, 10 days at Bhola and 9 days Khulna. M-2M scheme (Figure 21d) has simulated maximum rainy days in the NE region and minimum in the SW region of

Bangladesh. The monthly highest rainy days (28 days) have simulated at Sylhet and lowest rainy days (7 days) at Bhola. The monthly second highest rainy days (27 days) are seen at Tangail. The monthly minimum rainy days (11 days) are also seen at Barishal and Patuakhali and 8 days at Mongla.

SBU-YLin scheme (Figure 21e) has simulated maximum rainy days in the NE region and minimum in the SW region of Bangladesh. The monthly highest rainy days (26 days) have simulated at Sylhet and Srimangal and lowest rainy days (8 days) at Bhola. The monthly second highest rainy days (25 days) are seen at Tangail. The monthly minimum rainy days (11 days) are also seen at Mongla and Satkhira. WDM6 scheme (Figure 21f) has simulated maximum rainy days in the NE region and minimum in the SW region of Bangladesh. The monthly highest rainy days (27 days) have simulated at Sylhet and Tangail and lowest rainy days (8 days) at Bhola. The monthly second highest rainy days are seen at Srimangal (26 days). The monthly minimum rainy days are also seen at Khepupara and Satkhira are 14 and 13 days, respectively.

4.9 Model simulated heavy rainy days for the month of May 2015 at D1

4.9.1 Simulated heavy rainy days at D1 for Day 1 prediction

The distributions of day 1 simulated monthly heavy rainy days in D1 of May 2015 for different MP schemes in combination with KF scheme with the initial conditions of 0000UTC of everyday are presented in Figures 22(a-f).Lin *et al.* scheme (Figure 22a) has simulated number of heavy rainy (HR) days in the NE region and no HR days in the central to south, SE, SW and western region of Bangladesh for the month of May 2015.The scheme has simulated highest HR days (9 days) at Sylhet. The distribution pattern of HR days is similar to that of observed HR days in the NE region of the country but the scheme has simulated much higher HR days in the NE region and lowers in the NW region. WSM6 scheme (Figure 22b) has simulated number of HR days in the NE region and no HR days in the central to south, SE, SW and western region of the country. The scheme has simulated highest HR days (6 days) at Sylhet. The distribution pattern of HR days is similar to that of observed HR days in the NE region but lowers in the NW region of the country.

Thompson scheme (Figure 22c) has simulated number of HR days in the NE region and no HR days in the central to south, SE, SW, NW and western region of the country. The scheme has simulated highest HR days (8 days) at Sylhet. The distribution pattern of HR days is similar to that of observed HR days in the NE region but the scheme has not simulated HR days in the NW region of the country.

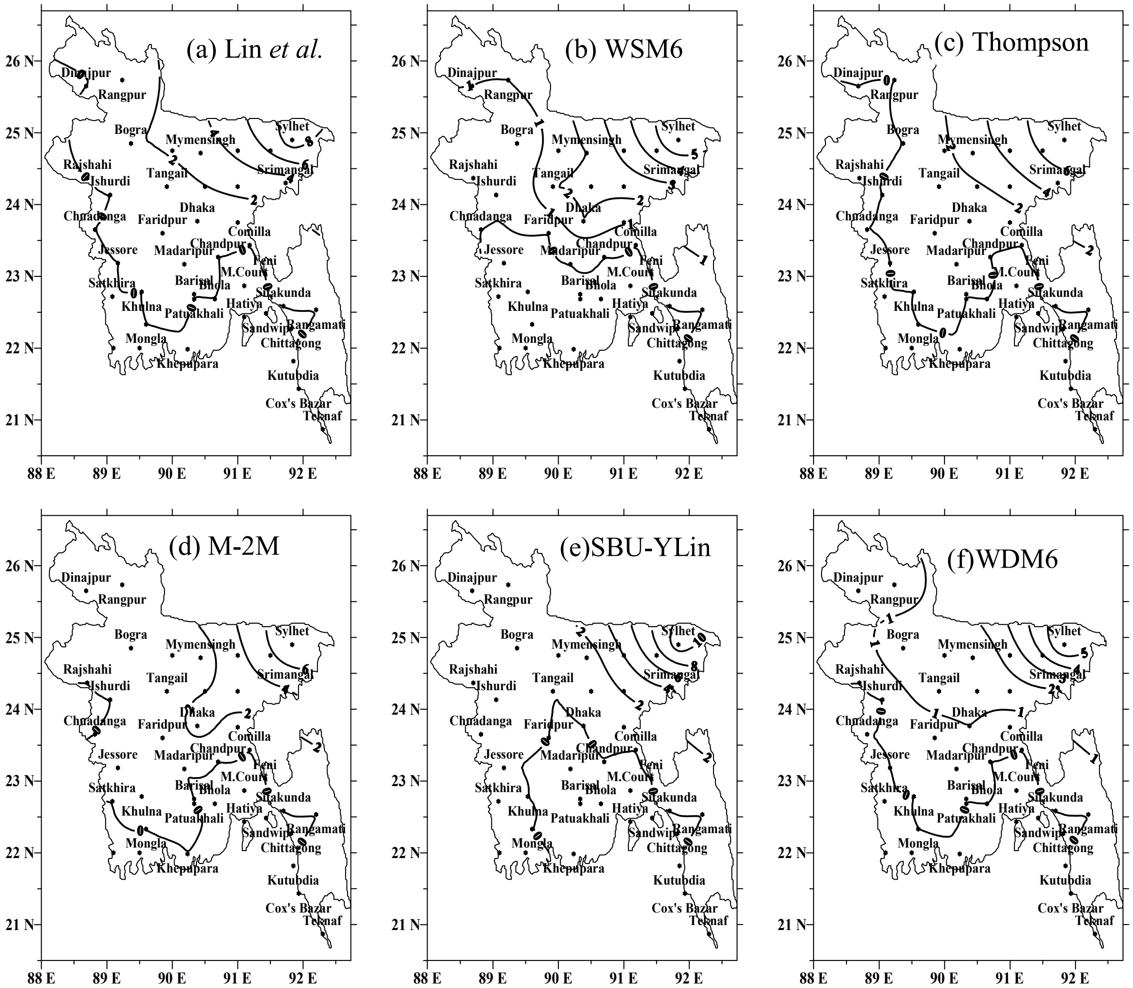


Figure 22: Spatial distribution of model simulated monthly total heavy rainy days of May 2015 for day 1 prediction in D1 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

M-2M scheme (Figure 22d) has simulated number of HR days in the NE region and no HR days in the south, SE, SW and western region of the country. The scheme has simulated highest HR days (8 days) at Sylhet. The distribution pattern of HR days is similar to that of observed HR days in the NE region of the country but the scheme has simulated much higher HR days in the NE region and lowers in the NW region. SBU-YLin scheme (Figure 22e) has simulated significant number of HR days in the NE region and no HR days in the central to south, SE, SW and western region of the country. The scheme has simulated highest HR days (11 days) at Sylhet. The monthly second highest HR days is seen at Srimangal 4 days. The distribution pattern of HR days is similar but simulated much higher HR days to that of observed HR days in the NE region and lowers in the NW region. WDM6 scheme (Figure 22f) has simulated number of HR days in the NE region and no HR days in the south, SE, SW and western region of the country. The scheme has simulated highest HR days (6 days) at Sylhet. The distribution pattern of HR days is similar to that of observed HR days in the NE region and lowers in the NW region.

4.9.2 Simulated heavy rainy days at D1 for Day 2 prediction

The distributions of day 2 simulated monthly heavy rainy days in D1 of May 2015 for different MP schemes in combination with KF scheme with the initial conditions of 0000UTC of everyday are presented in Figures 23(a-f). Lin *et al.* scheme (Figure 23a) has simulated number of heavy rainy (HR) days in the NE region and no HR days in the central to south, SE, SW and western region of Bangladesh for the month of May 2015. The scheme has simulated highest HR days (10 days) at Sylhet. The distribution pattern of HR days is similar to that of observed HR days in the NE region of the country but the scheme has simulated much higher HR days in the NE region and lowers in the NW region. WSM6 scheme (Figure 23b) has simulated number of HR days in the NE region and no HR days in the central to south, SE, SW and western region of the country. The scheme has simulated highest HR days (7 days) at Sylhet and second highest HR days are seen at Rangpur 4 days. The distribution pattern of HR days is similar to that of observed HR days in the NE and NW region of the country.

Thompson scheme (Figure 23c) has simulated number of HR days in the NE region and no HR days in the south, SE, SW and western region of the country. The scheme has simulated highest HR days (11 days) at Sylhet and second highest HR days are seen at Srimangal 5 days. The distribution pattern of HR days is similar to that of observed HR days in the NE region but the scheme has simulated much higher HR days in the NE region and lowers in the NW region of the country. M-2M scheme (Figure 23d) has simulated number of HR days in the NE region and no HR days in the central to SW and west and SE region of the country. The scheme has simulated highest HR days (13 days) at Sylhet and second highest HR days are seen at Srimangal 5 days. The distribution pattern of HR days is similar to that of observed HR days in the NE region but the scheme has simulated much higher HR days in the NE region and lowers in the NW region of the country.

SBU-YLin scheme (Figure 23e) has simulated number of HR days in the NE region and no HR days in the central to south, SE, SW and western region of the country. The scheme has simulated highest HR days (9 days) at Sylhet and second highest HR days are seen at Srimangal5 days. The distribution pattern of HR days is similar to that of observed HR days in the NE region but the scheme has simulated higher HR days in the NE region and lowers in the NW region of the country.WDM6scheme (Figure 23f)has simulated number of HR days in the NE region and no HR days in the central to south, SE, SW and western region of the country. The scheme has simulated highest HR days (7 days) at Sylhet. The distribution pattern of HR days is similar to that of observed HR days in the NE region but the scheme has not simulated higher HR days in the NW region of the country.

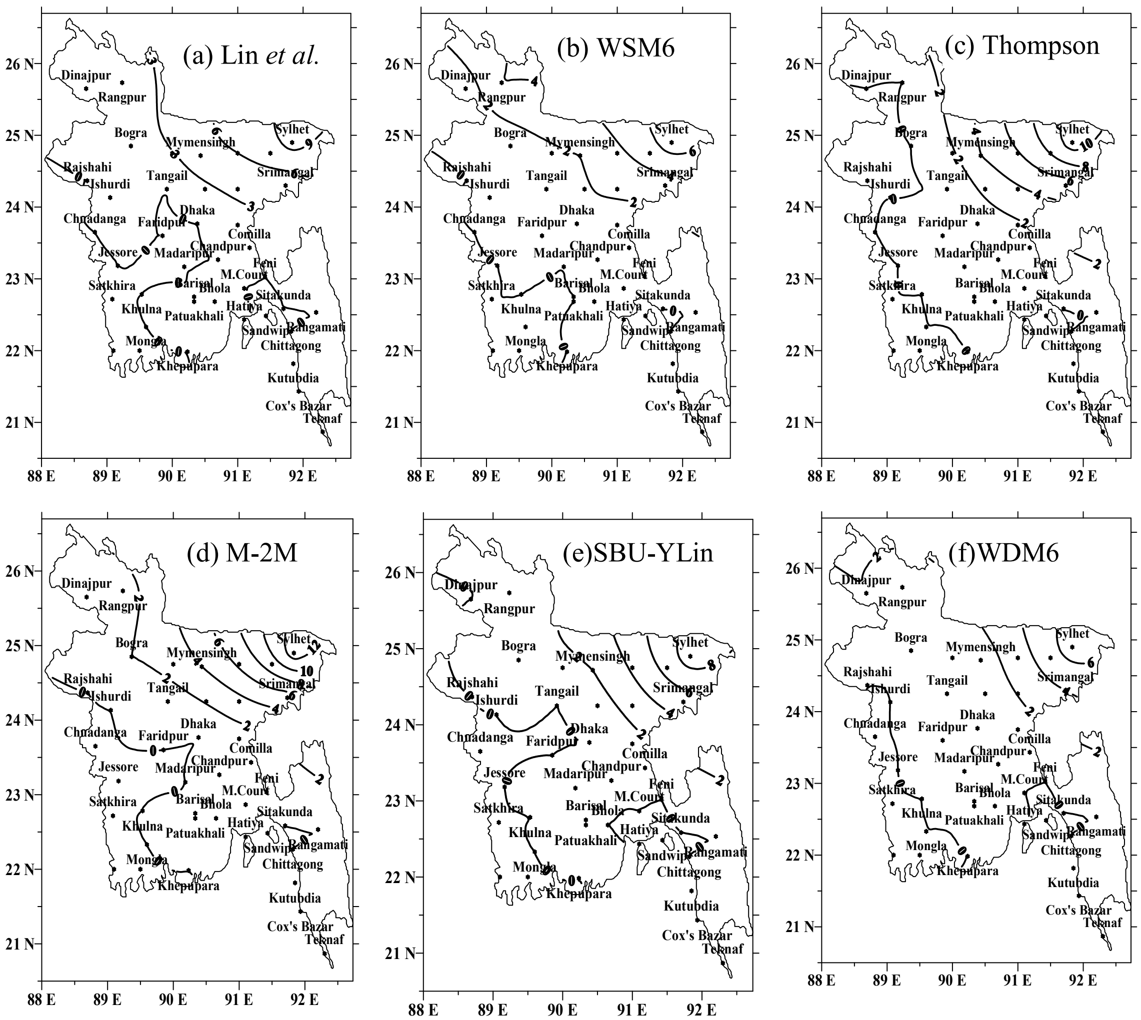
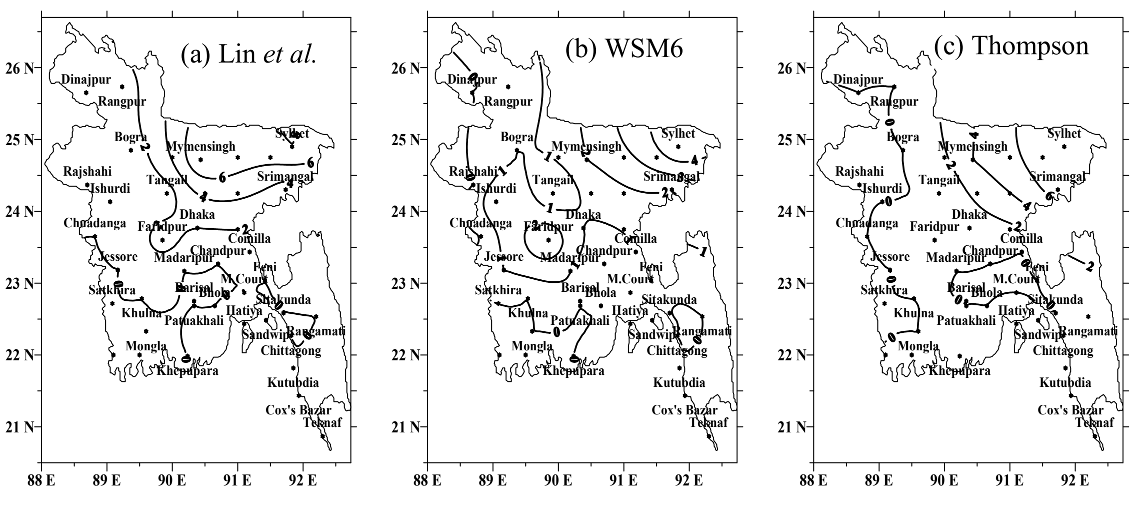


Figure 23: Spatial distribution of model simulated monthly total heavy rainy days of May 2015 for day 2 prediction in D1 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

4.9.3 Simulated heavy rainy days at D1 for Day 3 prediction

The distributions of day 3 simulated monthly heavy rainy days in D1 of May 2015 for different MP schemes in combination with KF scheme with the initial conditions of 0000UTC of everyday are presented in Figure 24(a-f).Lin *et al.* scheme (Figure 24a) has simulated number of HR days in the NE region and no HR days in the central to south, SE and SW region of the country. The scheme has simulated highest HR days (8 days) at Sylhet and Mymensingh. The distribution pattern of HR days is similar to that of observed HR days in the NE and NW region of the country. WSM6 scheme (Figure 24b) has simulated number of HR days in the NE region and no HR days in the south, SE, SW and western region of the country. The scheme has simulated highest HR days (5 days) at Sylhet. The distribution pattern of HR days is matched with the observed HR days in the NE and could not match in the NW region of the country. Thompson scheme (Figure 24c) has simulated number of HR days in the NE region and no HR days in the east, SE, SW and western region of the country. The scheme has simulated highest HR days (8 days) at Sylhet and second highest HR days are seen at Srimangal 7 days. The distribution pattern of HR days is similar to that of observed HR days in the NE region but the scheme has simulated higher HR days in the NE region and lowers in the NW region of the country.

M-2M scheme (Figure 24d) has simulated number of HR days in the NE region and no HR days in the SE, SW, NW and western region of the country. The scheme has simulated highest HR days (10 days) at Sylhet and second highest HR days are seen at Mymensingh and Srimangal 4 days. The distribution pattern of HR days is similar to that of observed HR days in the NE region but the scheme has simulated higher HR days in the NE region and lowers in the NW region of the country. SBU-YLin scheme (Figure 24e) has simulated number of HR days in the NE region and no HR days in the central to south, SE, SW and western region of the country. The scheme has simulated highest HR days (9 days) at Sylhet. The distribution pattern of HR days is similar to that of observed HR days in the NE region but the scheme has simulated higher HR days in the NE region and lowers in the NW region of the country.



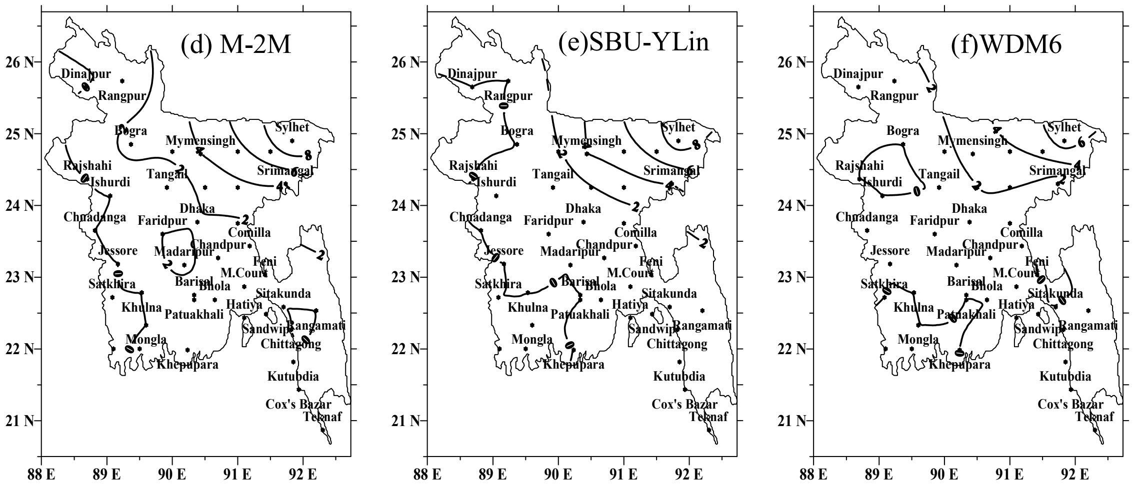


Figure 24: Spatial distribution of model simulated monthly total heavy rainy days of May 2015 for day 3 prediction in D1 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

WDM6scheme (Figure 24f) has simulated number of HR days in the NE region and no HR days in the south, SE and western region of the country. The scheme has simulated highest HR days (7 days) at Sylhet. The distribution pattern of HR days is similar to that of observed HR days in the NE region but the scheme has simulated higher HR days in the NE region and lowers in the NW region of the country.

4.10 Model simulated heavy rainy days for the month of May 2015 at D2

4.10.1 Simulated heavy rainy days at D2 for Day 1 prediction

The distributions of day 1 simulated monthly heavy rainy days in D2 for different MP schemes with the initial conditions of 0000UTC of everyday of May 2015 are presented in Figure 25(a-f). Lin *et al.* scheme (Figure 25a) has simulated number of HR days in the NE region and no HR days in the S-SE region of the country. The scheme has simulated highest HR days (9 days) at Sylhet and 2nd highest at Mymensingh (5 days). In the NW region of Bangladesh i.e., Rangpur and Dinajpur have seen HR days (2 days). The distribution pattern of HR days is similar to that of observed HR days in the NE and NW region but little bit higher in the NE and lowers in the NW region of the country. WSM6 scheme (Figure 25b) has simulated number of HR days in the NE region and no HR days in the S-SE and SW region of the country. The scheme has simulated highest HR days (6 days) at Sylhet and 2nd highest at Srimangal (4 days) and Dhaka observed 3 days. The distribution pattern of HR days is similar to that of observed HR days in the NE and NW region of the country. The simulated HR days is almost matched with the observed HR days all over the country.

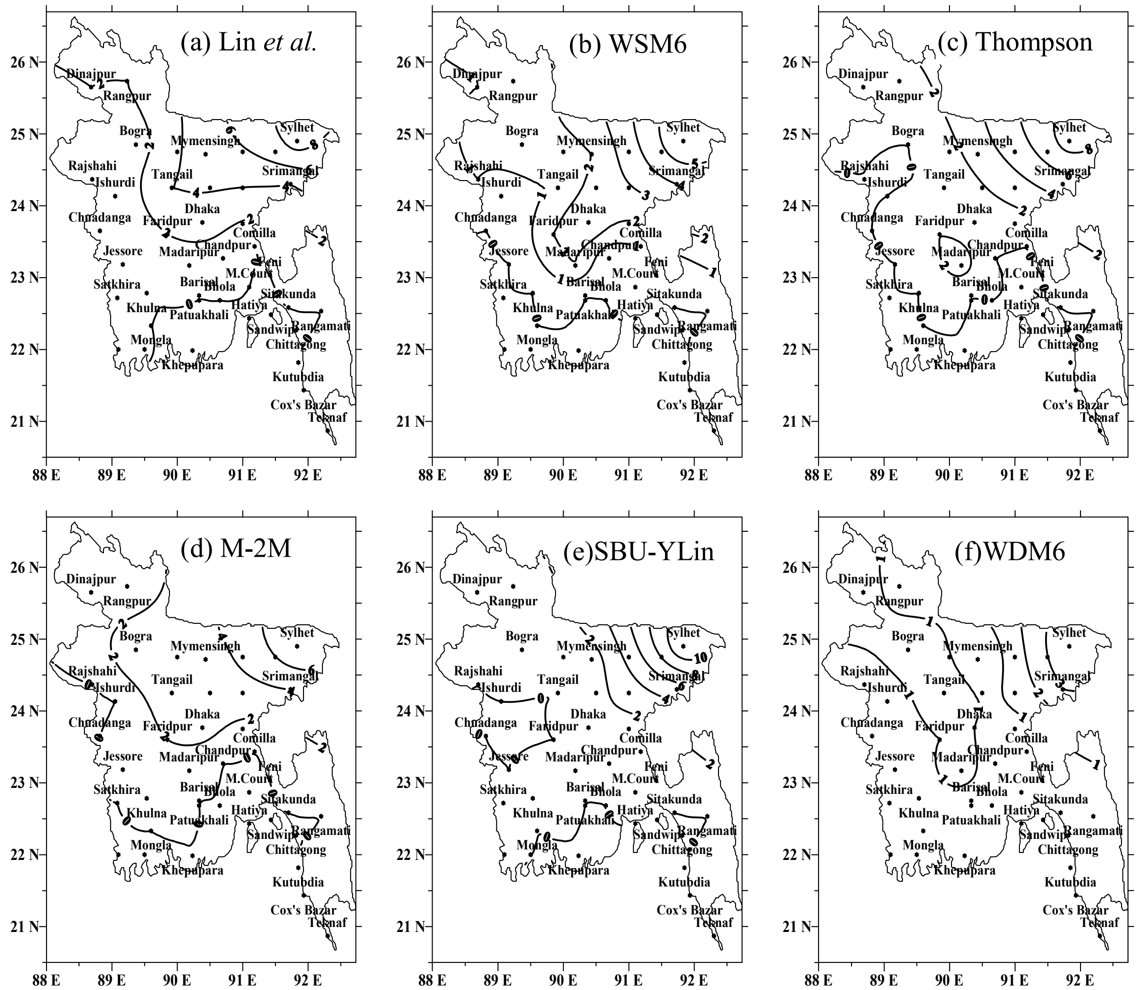


Figure 25: Spatial distribution of model simulated monthly total heavy rainy days of May 2015 for day 1 prediction in D2 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

Thompson scheme (Figure 25c) has simulated number of HR days in the NE region and no HR days in the S-SE, SW and western region of the country. The scheme has simulated highest HR days (9 days) at Sylhet and 2nd highest at Srimangal (5 days). The distribution pattern of HR days is similar to that of observed HR days in the NE and NW region but little bit higher in the NE and lowers in the NW region of the country. M-2M scheme (Figure 25d) has simulated number of HR days in the NE region and no HR days in the south-SE and SW region of the country. The scheme has simulated highest HR days (8 days) at Sylhet and 2nd highest at Srimangal (4 days) and Dhaka observed 3 days. The distribution patterns of HR days is similar to that of observed HR days in the NE region but little bit higher in the NE and did not match in the NW region of the country.

SBU-YLin scheme (Figure 25e) has simulated significant number of HR days in the NE region and no HR days in the S-SE and western region of the country. The scheme has simulated highest HR days (12 days) at Sylhet and 2nd highest at Srimangal (5 days). The scheme has simulated much higher HR days in the NE region and lowers in the NW region of the country. WDM6 scheme (Figure 25f) has simulated number of HR days in the NE region and no HR days in the S-SE and SW region of the country. The scheme has simulated highest HR days (4 days) at Sylhet and 2nd highest at Srimangal (3 days). The distribution pattern of HR days is similar to that of observed HR days in the NE region of the country. The simulated HR days is almost matched with the observed HR days in the NE region and could not match in the NW region of the country.

4.10.2 Model simulated heavy rainy days at D2 for Day 2 prediction

The distributions of day 2 simulated monthly heavy rainy days in D2 of May 2015 for different MP schemes in combination with KF scheme with the initial conditions of 0000UTC of everyday are presented in Figure 26(a-f). Lin *et al.* scheme (Figure 26a) has simulated number of HR days in the NE region and no HR days in the SE, SW and western region of the country. The scheme has simulated highest HR days (8 days) at Sylhet and 2nd highest at Srimangal (6 days). In the NW region of Bangladesh i.e., Rangpur and Dinajpur have seen HR days (2 days). The distribution pattern of HR days is similar to that of observed HR days in the NE region but simulated little bit higher HR days in the NE region of the country. WSM6 scheme (Figure 26b) has simulated number of HR days in the NE region and no HR days in the S-SE, SW and western region of the country. The scheme has simulated highest HR days (8 days) at Sylhet and 2nd highest at Rangpur (4 days). The distribution pattern of HR days is similar to that of observed HR days in the NE and NW region of the country. The simulated HR days is almost matched with the observed HR days all over the country.

Thompson scheme (Figure 26c) has simulated number of HR days in the NE region and no HR days in the SE, SW and western region of the country. The scheme has simulated highest HR days (10 days) at Sylhet and 2nd highest at Srimangal (4 days), Faridpur, and Mymensingh observed 3 HR days. The distribution pattern of HR days is similar to that of observed HR days in the NE and NW region but little bit higher in the NE and lowers in the NW region of the country. M-2M scheme (Figure 26d) has simulated number of HR days in the NE region and no HR days in the S-SW and western region of the country. The scheme has simulated highest HR days (11 days) at Sylhet and 2nd highest at Srimangal (6 days) and

Mymensingh observed 5 HR days. The distribution pattern of HR days is similar to that of observed HR days in the NE region but much higher in the NE and did not match in the NW region of the country.

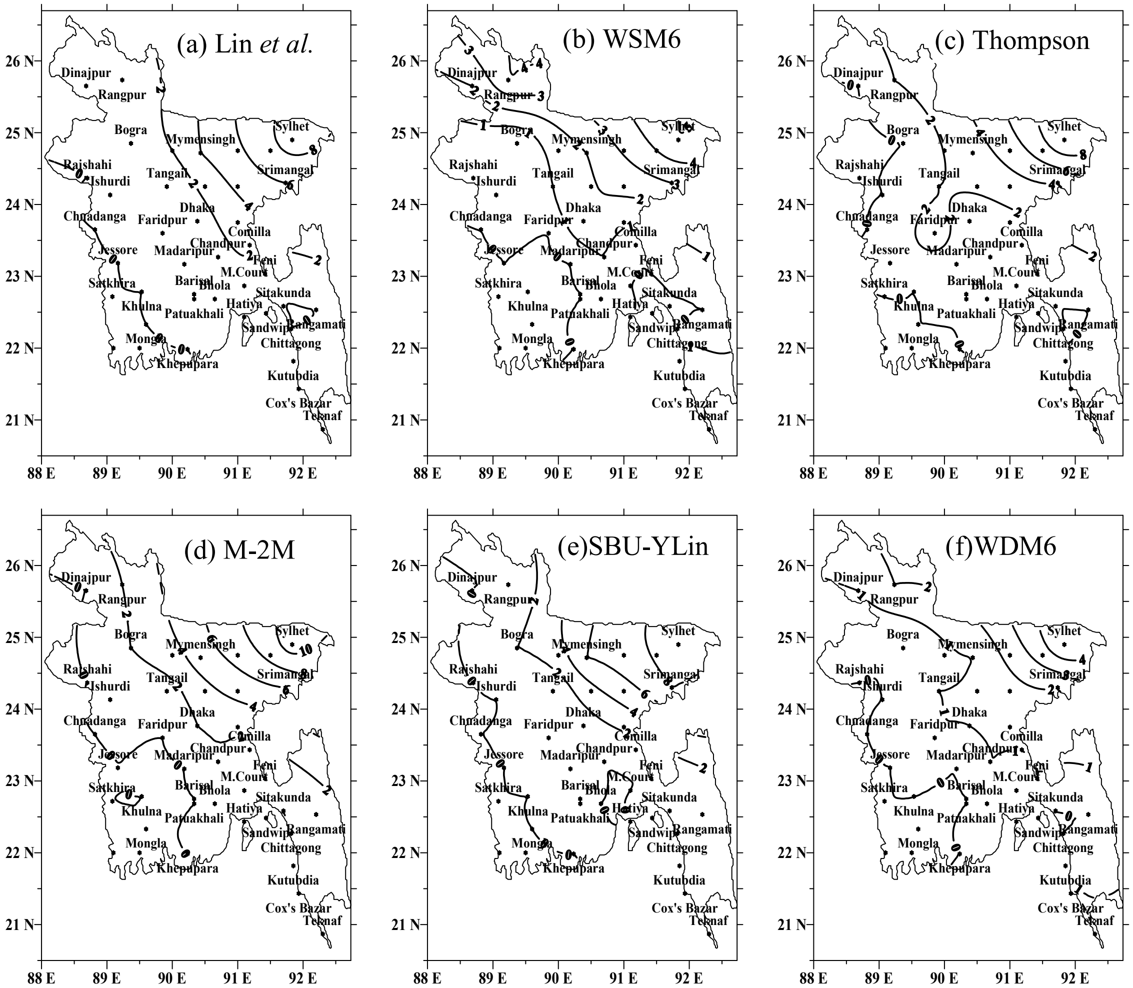


Figure 26: Spatial distribution of model simulated monthly total heavy rainy days of May 2015 for day 2 prediction in D2 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

SBU-YLin scheme (Figure 26e) has simulated significant number of HR days in the NE region and no HR days in the S-SW, NW and western region of the country. The scheme has simulated highest HR days (9 days) at Sylhet and 2nd highest at Srimangal (8 days) and Mymensingh observed 6 HR days. The scheme has simulated higher HR days in the NE region and could not simulate HR days in the NW region of the country. WDM6 scheme (Figure 26f) has simulated number of HR days in the central to NE and NW region and no HR days in the SW and western region of the country. The scheme has simulated highest HR days (5 days) at Sylhet and 2nd highest at Rangpur and Srimangal (2 days). The distribution pattern of HR days is similar to that of observed HR days in the NE region of the country. The simulated HR days is almost matched with the observed HR days in the NE and NW region of the country.

4.10.3 Simulated heavy rainy days at D2 for Day 3 prediction

The day 3 simulated monthly distributions of heavy rainy days in D2 of May 2015 for different MP schemes in combination with KF scheme with the initial conditions of 0000UTC of everyday are presented in Figure 27(a-f). Lin *et al.* scheme (Figure 27a) has simulated number of HR days in the NE region and no HR days in the SE, SW and western region of the country. The scheme has simulated highest HR days (7 days) at Sylhet and 2nd highest at Faridpur, Mymensingh and Srimangal (4 days). The distribution pattern of HR days is similar to that of observed HR days in the NE region but simulated little bit higher HR days in the NE region could not match in the NW region of the country.

WSM6 scheme (Figure 27b) has simulated number of HR days in the central to east, NE and NW region and no HR days in the S-SE and SW region of the country. The scheme has simulated highest HR days (6 days) at Sylhet and 2nd highest at Srimangal (4 days) and 3 HR days at Faridpur and Mymensingh. The distribution pattern of HR days is similar to that of observed HR days in the NE region of the country. The simulated HR days is almost matched with the observed HR days from central to NE region and could not match in the NW region of the country.

Thompson scheme (Figure 27c) has simulated number of HR days in the central to east, NE and NW region and no HR days in the S-SE and SW region of the country. The scheme has simulated highest HR days (6 days) at Sylhet and Srimangal and 2nd highest at Mymensingh (4 days). The distribution pattern of HR days is similar to that of observed HR days in the NE region of the country. M-2M scheme (Figure 27d) has simulated number of HR days in the NE region and no HR days in the S-SW region of the country. The scheme has simulated highest HR days (12 days) at Sylhet and 2nd highest at Mymensingh (6 days). The distribution pattern of HR days is similar to that of observed HR days in the NE region of the country but the scheme has simulated much higher HR days in the NE region of the country. SBU-YLin scheme (Figure 27e) has simulated significant number of HR days in the NE region and no HR days in the SW, NW and western region of the country. The scheme has simulated highest HR days (9 days) at Sylhet and 2nd highest at Srimangal (6 days). The scheme has simulated much higher HR days in the NE region of the country.WDM6scheme (Figure 27f) has simulated significant number of HR days in the NE region and no HR days in the SW region of the country. The scheme has simulated highest HR days (6 days) at Sylhet. The scheme has simulated higher HR days in the central and NE region of the country.

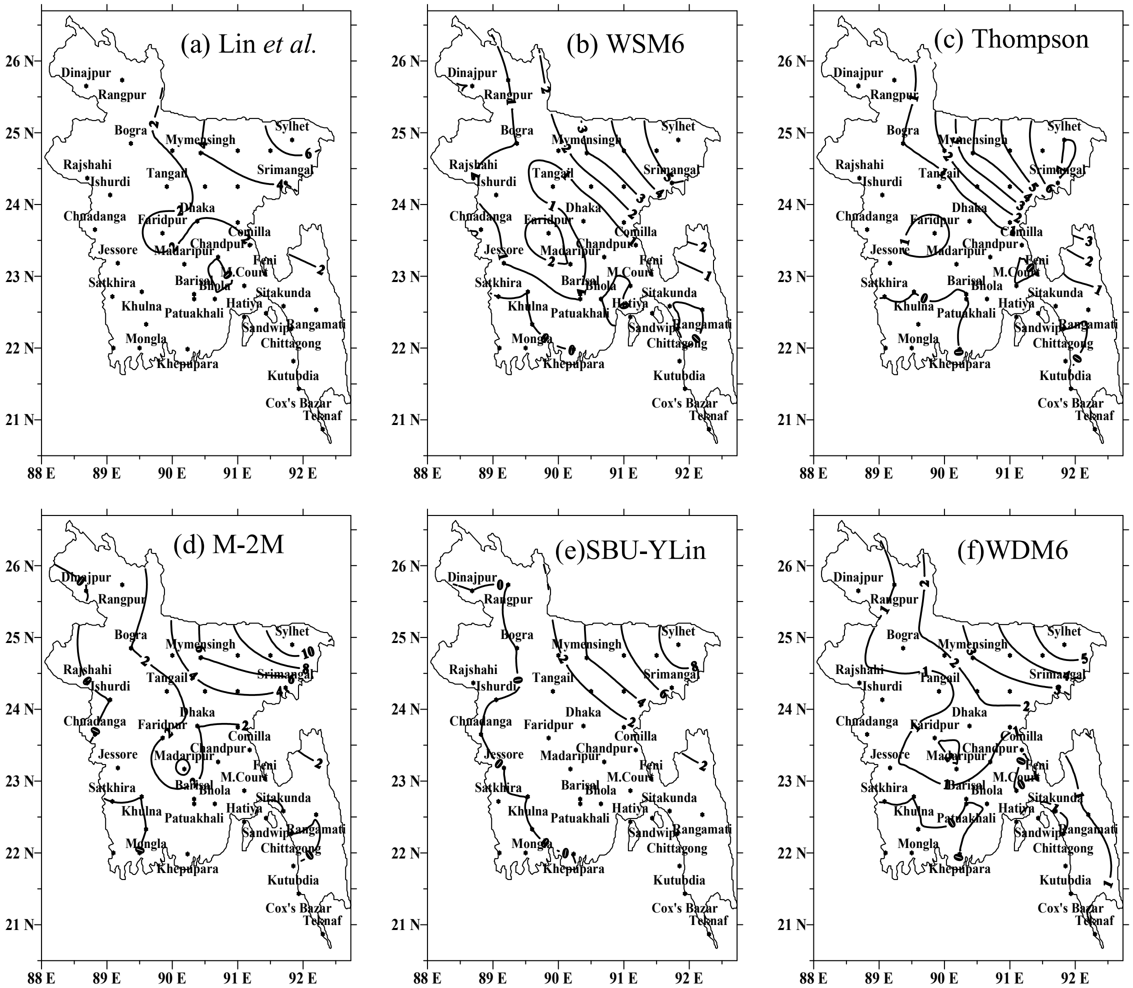


Figure 27: Spatial distribution of model simulated monthly total heavy rainy days of May 2015 for day 3 prediction in D2 using a) Lin, b) WSM6, c) Thompson, d) M-2M, e) SBU-YLin and f) WDM6 schemes coupling with KF scheme all over Bangladesh.

Chapter V
Conclusions

In the present study, the Advanced Research WRF (ARW) v3.8.1 model have been used to simulate the monthly total rain, monthly total heavy rain, monthly total rainy days, and monthly total heavy rainy days for the month of May 2015 all over Bangladesh. The model has been configured in double domain, 18 km and 6 km horizontal grid spacing with 100×96 and 103×127 grids in the east-west and north-south directions and 30 vertical levels. Time step of integration is set to 30 and 90 seconds for maintaining computational stability as the model uses third-order Runge-Kutta time integration scheme. The six different microphysics schemes such as Lin *et al.*, WSM6, Thomson, Morrison Double-Moment, Stony Brook University, and WDM6have been used to simulate the monthly total rainfall, monthly total heavy rainfall, rainy days and heavy rainy days for the month of May 2015. The different microphysics output is compared with the observed output at 33 meteorological stations of BMD and PERSIANN output. Standard deviation of all observed, PERSIANN and model simulated parameters have been analyzed and compared. On the basis of our findings the following conclusions have been drawn:

- The maximum monthly observed rain of May 2015 at Sylhet 752 mm but WSM6, M-2M and WDM6 schemes have simulated 831, 788 and 742 mm for day 1 prediction; WSM6, WDM6 and SBU-Lin schemes have simulated 757, 916 and 981 mm rainfall for day 2 prediction, and WSM6 and WDM6 schemes are 741 and 925 mm rainfall for day 3 prediction, respectively and all other MPs have simulated much higher rainfall at D1.
- The WDM6, M-2M and Lin *et al.* schemes have simulated 744, 807 and 923 mm rainfall for day 1 prediction, WSM6 and WDM6 schemes have simulated714 and 877 mm rainfall for day 2 prediction and WSM6, SBU-Lin and Lin *et al.* schemes have simulated802 and 913 and 998 mm rainfall, respectively for day 3 prediction at D2.
- The maximum monthly observed HR of May 2015 at Sylhet is 379 mm rainfall but WDM6, WSM6 and M-2M have simulated 445, 499 and 523 mm rainfall for day 1 prediction; WSM6 and WDM6 schemes 398 and 558 mm rainfall for day 2 prediction and 364 and 619 mm rainfall for day 3 prediction at D1.

- The WDM6 and M-2M schemes have simulated 383 and 503 mm HR at Sylhet for day 1 prediction; WSM6 and WDM6 schemes are 334 and 476 mm HR for day 2 prediction and WSM6 and SBU-Lin schemes are 507 and 614 mm HR for day 3 prediction at D2.
- The simulated number of total rainy days at Sylhet and Bhola for all MPs is almost matched with the observed total rainy days. All MPs have simulated much higher total rainy days for day 1, day 2 and day 3 predictions with little exceptions all over the country for the month of May 2015. The number of observed rainy days in the south-southeastern region is very few but different MPs have simulated much higher rainy days in those region. The distribution pattern of heavy rainy days for different microphysics schemes is similar in the central to NE, S-SE and SW region but in the NW region the number of heavy rainy days is insignificant.
- Lin *et al*., WSM6, Thompson, M-2M, SBU-YLin and WDM6 schemes have simulated much higher rain at domain 1 (308, 292, 257, 271, 264 and 310%) and at domain 2 (298, 273, 258, 259, 214, and 283%) at Dhaka, Faridpur, Barishal, Patuakhali, Khepupara, Madaripur, Satkhira and Tangail and all other stations have simulated 25, 24, 13, 21, 7 and 26% at domain 1 and 34, 31, 20, 25, 8 and 31% higher rainfall at domain 2 than that of observed rain at day 1.
- The SD has minimum at D1 and D2 for WDM6 scheme for day 1 prediction and WSM6 scheme for day 2 and day 3 predictions for the rainfall of May 2015.
- WDM6 scheme gives the better performance of rainfall and rainy days all over the country.

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Conference Publication

1. **Md. Salman Khan and M. M. Alam, 2018:** Simulation of Rainfall for the month of May 2015 over Bangladesh using High Resolution WRF-ARW Model, Conference on Weather Forecasting & Advances in Physics, KUET, Khulna, 11-12 May 2018.

2. **Md. Salman Khan and M. M. Alam, 2019:** Sensitivity of Microphysics for the Simulation of Rainfall for the month of May 2015 over Bangladesh using High Resolution WRF-ARW Model, Conference on Bangladesh Physical Society, Dhaka University, 07- 09 February 2019.