STUDY ON CONVECTIVE AND NON-CONVECTIVE RAIN OF DIFFERENT HEAVY RAINFALL EVENTS IN THE MONSOON SEASON USING WRF-ARW MODEL

M. Sc. Thesis

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DECLARATION

This is to certify that the thesis work entitled "***Study on Convective and Non-Convective Rain of different Heavy Rainfall Events in the Monsoon season using WRF-ARW model***" has been carried out by Md. Razu Ahammed 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. Razu Ahammed*** entitled **"Study on Convective and Non-Convective Rain of Different Heavy Rainfall Events in the Monsoon Season using 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 13 December 2018.

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Md. Razu Ahammed

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Nomenclature

ARW	:	Advanced Research WRF
BMD	:	Bangladesh Meteorological Department
BMJ	:	Betts-Miller-Janjic
BoB	:	Bay of Bengal
BS	:	Bias Score
CP	:	Cumulus Parameterization
ETS	:	Equitable Threat Score
FNL	:	Final Reanalysis
GD	:	Grell Devenyi
GF	:	Grell Fritsch
G-3	:	Grell-3
KF	:	Kain-Fritsch
LCC	:	Lambert Conformal Conic Projection
MCS	:	Mesoscale Convective System
MP	:	Microphysics
MRF	:	Medium Range Forecast
MSKF	:	Multi-Scale Kain-Fritsch
MYDM	:	Milbrandt-Yau Double-Moment 7-class
NCAR	:	National Center for Atmospheric Research
NCEP	:	National Centers for Environmental Prediction
NE	:	Northeastern
NS	:	New Simplified Arakawa-Schubert
NSH	:	New SAS Hurricane Weather Research Forecast
NTD	:	New Tiedtke
N-NE	:	North-Northeastern
N-NW	:	North-Northwestern
NW	:	Northwestern
NWP	:	Numerical Weather Prediction
OLR	:	Outgoing Long Wave Radiation
OSAS	:	Old Simplified Arakawa-Schubert
PBL	:	Planetary Boundary Layer
PR	:	Precipitation Radar
QPFs	:	Quantitative Precipitation Forecasts
RRTM	:	Rapid Radiative Transfer Model
SE	:	Southeastern
S-SE	:	South-Southeastern
S-SW	:	South-Southwestern
SW	:	Southwestern

TD	:	Tiedtke
TH	:	Thomson
TRMM	:	Tropical Rainfall Measuring Mission
TS	:	Threat Score
USL	:	Updraft Source Layer
UTC	:	Universal Time Co-ordinate
WDM6	:	WRF double-moment 6-class
WMO	:	World Meteorological Organization
WRF	:	Weather Research and Forecasting
YSU	:	Yonsei University Scheme
ZM	:	Zhang-McFarlane

ABSTRACT

In the present study the Advanced Research WRF (ARW) model v3.8.1 have been used to simulate the convective and non-convective rain during 3-5 July 2017, 19-20 July 2017 and 23-24 July 2017, when heavy rain observed in different areas of Bangladesh. The initial and boundary conditions are drawn from the global operational analysis and forecast products of National Center for Environmental Prediction (NCEP) Final reanalysis (FNL) data available at $1^{o} \times 1^{o}$ resolution. The model was configured in nested domain with 18 km and 6 km horizontal grid spacing 100×96 and 103×127 grids in the east-west and north-south directions with 28 vertical levels. In this research 12 Cumulus parameterization (CP) schemes in combination with WDM6 microphysics (MP) scheme has been used to identify the convective and non-convective rain of different heavy rainfall (HR) events. The CP schemes used in this research are Kain-Fritsch (KF), Betts-Miller-Janjic (BMJ), Grell-Freitas (GF), Old simplified Arakawa-Schubert (OSAS), Grell-3 (G3), Tiedtke, Zhang-McFarlane (ZM), Multi-scale KF (MSKF), New SAS, New Tiedtke (NTD), New SAS-HWRF (NSH) and Grell-Devenyi (GD).

The model simulated rainfall mainly convective for KF, GF, OSAS, G-3, TD, ZM, NTD, NSH and schemes and mainly non-convective for BMJ, MSKF and NS schemes during all over Bangladesh during 3-5 July 2017. BMJ, MSKF and NS schemes have simulated higher non convective rain (NCR) and all other cumulus parameterization schemes have simulated higher convective rain (CR) all over Bangladesh during 19-20 July 2017. OSAS and NSH schemes have simulated higher convective rain and all other cumulus parameterization schemes have simulated higher non-convective rain all over Bangladesh during 23-24 July 2017. It is also seen that during the two simulation periods (i.e., 3-5 and 23-24 July 2017) the CR is found to decrease continuously and NCR increased during the period and opposite in case of 19-20 July 2017. GF and G-3, GF and MSKF schemes give the better performance for daily and 48 hour prediction respectively on the basis of Threat Score, Equivalent Threat Score and Bias Score during 3-5 July 2017. On the basis of Threat Score, Equitable Threat Score and Bias Score for the prediction of HR KF and MSKF schemes during 19-20 July 2017, TD and KF schemes during 23-24 July 2017 give the better performance.

Chapter I
Introduction

In Bangladesh heavy rainfall occurs in the monsoon period extending from the month of June to September (BMD, 2000). With the exception of the relatively dry western region of Bangladesh, where the annual rainfall is about 1600 mm, most parts of the country receive at least 2000 mm/year of rainfall. Because of its location just south of the foothills of the Himalayas, where monsoon winds turn west and northwest, the regions in northeastern Bangladesh receives the greatest average precipitation, sometimes over 4000 mm/year. About 80% rainfalls occurred during the monsoon season in Bangladesh. Prediction of heavy rainfall is one of the challenging problems in meteorology, but very important for issuing timely warnings for the agencies engaged in disaster preparedness and mitigation. Widespread floods associated with heavy precipitation are common in the northeastern (NE), southern and southeastern (SE) region of Bangladesh during monsoon season (June-September).

Convective rain is the rain which happens when the sun heats a water source to the point so that water turns into vapor and rises. By the time it reaches the condensation level, the vapor becomes cooled enough to turn back into water and fall in the form of rain. The rest rainfalls which are not caused by this kind of process are called non-convective rain. This type of precipitation occurs when large air masses rise diagonally as larger-scale atmospheric dynamics force them to move over each other (Eltahir and Pal 1996; Berg *et al.* 2009). Non-convective precipitation falls from nimbostratus clouds, while convective precipitation falls from active cumulus and cumulonimbus clouds. These cloud types may occur separately or entangled with each other in the same cloud complex. Tropical rainfall may appear to be essentially convective in nature, but experiments over the eastern tropical Atlantic, northern Australia, and the western equatorial Pacific have shown that almost all convection occurs in association with non-convective rain. The younger parts of the cumulonimbus clouds are 100% convective. Later, when convection decays, clouds become non-convective and co-exist with the embedded convective columns of rapid updraft. It is sometimes difficult to distinguish between convective and non-convective rains.

Cumulus parameterization (CP) schemes must estimate the rate of sub 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). The Advanced Research Weather Research and Forecasting model (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). Alam (2014) studied the effects of microphysics and cumulus parameterization 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.

The Convective properties and structures of precipitation systems have been investigated extensively (Petersen and Rutledeg, 2001) case by case, period by period, or on regional to global scale. Their research is motivated to examine variations of convection types of those three archetypical rainfall regimes over the tropics using 13 years of tropical rainfall measuring mission (TRMM) observations. In addition, 12 years of monsoon convection in actives and breaks over South China and North Australia are placed under the global regime context. Gierens and Brinkop (2002) have shown that extreme values of the convective rain rate and the maximum convective height occur more frequently during the 1971 to 1980 period than during the 1981 to 1990 period. The frequency of highest-reaching convective events increases, and the same holds for events with low cloud-top heights. In contrast, the frequency of events with moderate-top heights decreases. On days when it rains, the frequency of the daily rates of convective rainfall larger than 40 mm/day in June-July-August (JJA) and greater than 50 mm/day for December-January-February (DJF) increases. Generally, one finds a strong increase in the rain rate per convective event over most of the land areas on the summer hemispheres and in the inter-tropical convergence zone (ITCZ). Between 10 and 30°S there are decreases in rain rate per event over the ocean and parts of the continents.

Rajendran *et al.* (2002) found that the simulation of the monsoon precipitation and its intra-seasonal and interannual variations were sensitive to the cumulus parameterizations used in the National Center for Atmospheric Research (NCAR) Climate Community Model version 2 (CCM2). They attributed the changes to the differences in the mean moist static energy (MSE) simulated by different schemes. Changes to the cumulus scheme in the HadAM3 by incorporating the horizontal momentum by convection was found to improve the simulation of the Indian monsoon in the studies by Martin and Soman (1999) compared to the HadAM2b model. The inclusion of the convective momentum transport was found to weaken the flow at the upper levels and strengthen the monsoon circulation in the lower levels. 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. Romatschke and Houze (2011) conducted research on characteristics of precipitating convective and non-convective systems in the pre-monsoon season of south Asia**.** Their TRMM precipitation radar (PR) data showed that the precipitation is more convective in nature and more sensitive to synoptic forcing than during the monsoon.

The frequency of highest-reaching convective events increases, and the same holds for events with low cloud-top heights. In contrast, the frequency of events with moderate-top heights decreases. On days when it rains, the frequency of the daily rates of convective rainfall larger than 40 mm/day in JJA and greater than 50 mm/day for DJF increases. Generally, one finds a strong increase in the rain rate per convective event over most of the land areas on the summer hemispheres and in the inter-tropical convergence zone (ITCZ). Between 10 and 30°S there are decreases in rain rate per event over the ocean and parts of the continents. Changes to the cumulus scheme in the HadAM3 by incorporating the horizontal momentum by convection was found to improve the simulation of the Indian monsoon in the studies by Sujata *et al*., (1999) compared to the HadAM2b model. The inclusion of the convective momentum transport was found to weaken the flow at the upper levels and strengthen the monsoon circulation in the lower levels. 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.

Nesbitt and Zipser (2002) conducted research on the diurnal cycle of rainfall and convective 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. Romatschke and Houze (2001) conducted research on characteristics of precipitating convective and non-convective systems in the pre-monsoon season of south Asia**.** Their TRMM precipitation radar (PR) data showed that the precipitation is more convective in nature and more sensitive to synoptic forcing than during the monsoon.

Fihir (2018) has simulated the heavy rainfall events in the southeastern regions of Bangladesh during May 2013 using four different MPs i.e., Lin *et al*., WSM6, Thompson and WDM6 and four different cumulus parameterization (CP) schemes i.e., Kain-Fritsch (KF), Tiedtke (TD), Zhang-McFarlane (ZM) and Multi-Scale Kain-Fritsch (MSKF). In this research the impact of convective and non-convective rainfall have to be identified on total rainfall. Their research 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 WRF-ARW v3.5.1 model to simulate the heavy rainfall events in the southeastern regions of Bangladesh during 23-26 June, 23-26 July 2015 and 30 August –1 September 2015. In this research Kessler, Lin *et al.*, WSM3, Ferrier, WSM6, Thomson graupel, MYDM, MDM, CAM V5.12-Moment 5 class, SBU, WDM6 and NSSL2 microphysics schemes coupled with Kain-Fritsch cumulus parameterization scheme have been used to study the sensitivity of heavy rainfall events. In this research all Bangladesh stations rainfall averages suggests that among 12 MPs MDM, SBU, WDM6, MDM and TH schemes and 5 stations in the heavy rainfall region by Lin, WDM6 and SBU schemes respectively have simulated almost similar amount of rainfall.

Halder (2016) has simulated the station wise monsoon rainfall during 2010–2014 over Bangladesh using WRF-ARW V3.5.1 model. In this research the WSM6-class microphysics scheme coupling with KF cumulus parameterization scheme have been used. It has shown that the performance of the model for 24, 48 and 72 hours predictions are reasonably well except northeast and southeast hilly regions of Bangladesh. The distribution of 24 hours lead time predicted rainfall is almost similar all over the country except the higher rainfall area where model simulated rainfall is much more. It has found that where the rainfall is minimum the RMSE and MAE are also minimum.

Bhanu *et al.* (2012) conducted research on simulation of heavy rainfall events during retreat phase of summer monsoon season over parts of Andhra Pradesh. They noticed that, circulation features and rainfall quantities are validated with observed rainfall of IMD and satellite derived datasets of KALPANA–1. Ranadhur *et al.* (2009) conducted research on impacts of satellite–observed winds and total precipitable water on WRF short–range forecasts over the Indian region during the 2006 summer monsoon. The impacts of assimilating the different satellite dataset were measured in comparison to the control run, which does not assimilate any satellite data. They observed the assimilation of wind speeds resulted in a degradation of the temperature and humidity predictions at lower levels.

Karmakar and Khatun (1995) and Ahmed (1989) studied the probabilistic estimates of rainfall extremes in Bangladesh during the pre–monsoon season. Their studies were concentrated only on maximum rainfall events for a limited time period. The skill of the European Centre for Medium–Range Weather Forecasts (ECMWF) seasonal forecasting system (Anderson *et al.*, 2007) has been predicts 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. The area around Bangladesh, where a tremendous amount of rainfall occurs in summer, predominantly exhibits sub–monthly–scale intra–seasonal oscillation (ISO), but not 30–60 day ISO (Ohsawa *et al.*, 2000; Murata *et al.*, 2008; Fujinami *et al.*, 2011). The ISO feature allows the sub–monthly–scale ISO to modulate the total seasonal rainfall and the spatial patterns of circulation and convection around Bangladesh.

In the present study, the Weather Research and Forecast (WRF-ARWv3.8.1) model has been used to simulate the convective and non-convective rain of three different heavy rainfall events i.e. 3–5 July, 19–20 July and 23–24 July 2017 in the monsoon season over Bangladesh. The objectives of this study are to compare with the weather of high resolution WRF model is capable of simulating the observed features of heavy rainfall events. In this research twelve cumulus parameterization (CP) schemes i.e. Kain–Fritsch (KF) Scheme, Betts-Miller-Janjic (BMJ) scheme, Grell-Freitas (GF), Old simplified Arakawa-Schubert (OSAS), Grell-3 (G-3), Tiedtke Scheme (TD), Zhang–McFarlane (ZM) Scheme, Multi–scale Kain–Fritsch (MSKF) scheme, New SAS (NS), New Tiedtke (NTD), New SAS-HWRF (NSH) and Grell-Devenye (GD) and WDM6 microphysics (MP) scheme have been considered to study the rainfall events and try to identify the performance of the CP schemes. The primary objectives of this study are to examine which cumulus parameterization schemes are suitable for the prediction of convective and non-convective rain in the monsoon season. The results have been compared with the observed station rainfall of Bangladesh Meteorological Department (BMD). The model simulated results will be verified by using Threat Score (TS), Equitable Threat Score (ETS) and Bias Score (BS).

Chapter II
Literature Review

2.1 Monsoon

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

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

The Bay of Bengal (BoB) branch of south-west monsoon flows over the BoB heading towards North-Eastern India and Bengal, picking up more moisture from the BoB. Its hits the Eastern Himalaya and provides a huge amount of rain to the regions of North-Eastern India, Bangladesh and West Bengal. Cherrapunji situated on the southern slopes of the eastern Himalaya in Shillong, India is one of the wettest places on Earth.

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

The monsoon area has been defined by the following criteria:

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

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

2.1.1 Monsoon rainfall

The Indian summer monsoon is inter hemispheric circulation system, coupled with the land, atmosphere, and ocean, and contributes about 80% of the annual rainfall over India (Gadgil and Kumar, 2006). It is also a primary source of freshwater required for agriculture and industry. The interannual standard deviation of the Indian summer monsoon rainfall (ISMR) is about 10% of its climatological seasonal mean, which has a large impact on the agriculture and economy.

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

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

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

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

In the Himalayas, observations are extremely scanty, particularly from higher elevations where there is added difficulty of measuring snowfall. Rainfall measured in river valleys may not be representative of the hill slopes. Between the Great Himalayan Range and the plains, there is the PirPanjal, the Siwalikland the Mahabharat Ranges. Most of the available observations are from these ranges. Rainfall increases up to the slopes of these foothills, presumably decreases on their northern slopes and increase again on the Himalayan slopes. Annual rainfall at Chaunrikharka (2,700 m) is 2280 mm and at Namche Bazar (3,300 m) only 940 mm (Dhar and Narayanan, 1965). Both are in Nepal and the distance between the two is hardly 16 km. Therefore, we can tentatively conclude that above some elevation near 3 km, rainfall may decrease with height on the Himalayan range. In the eastern Himalayas, rainfall is more than in the western portions. In the east, annual rainfall of 4000 mm has been recorded but less than 2000 mm in the west.

2.1.2 Convective and Non-Convective rain

Convective rain is the rain which happens when the sun heats a water source to the point so that water turns into vapor and rises. By the time it reaches the condensation level, the vapor becomes cooled enough to turn back into water and fall in the form of rain. This type of precipitation occurs when large air masses rise diagonally as larger-scale atmospheric dynamics force them to move over each other. Convective rain is generally more intense, and of shorter duration and falls from active cumulus and cumulonimbus clouds. The convective rain fraction is about 18% (Deng *et al.,* 2014). Convective and stratiform rainfall differs in terms of rain rate, reflectivity, vertical velocity, and cloud microphysical process. Convective rainfall has a higher rain rate, stronger upward motions, and a larger horizontal reflectivity gradient than stratiform rainfall does. The accretion of cloud water by raindrops via collisions in strong updraft cores and the vapor deposition on ice particles are primary microphysical processes that account for the development of convective and stratiform rainfall, respectively (Houghton 1968).

Convective–stratiform rainfall separation has been largely based on magnitudes of convective signals such as radar reflectivity (Churchill and Houze, 1984) and surface rain rate (Tao *et al*., 1993). When the surface rain rate at model grid point is twice as large as the average taken over the surrounding four grid points, the model grid point and the grid point on either side or any grid point with a rain rate of higher than 20 mm h^{-1} are considered convective (Tao *et al.,* 1993). Convective rainfall is primarily associated with water vapor convergence (Cui and Li, 2006; Gao and Li, 2008; Shen *et al.,* 2011), and stratiform rainfall is mainly related to the transport of hydrometeor concentration from convective rainfall regions to stratiform rainfall regions. Convective and Non-Convective precipitation in mesoscale convective systems play different roles in the heating and mass transport (Gamache and

Houze 1983; Houze 1989; Johnson *et al.* 1999), both having important impacts on the global general circulation. Heating associated with convective rain is positive throughout the troposphere, while heating profiles in stratiform regions feature heating above the freezing level and cooling below. Convective rain forms mainly through collection of cloud particles in areas where vertical motion (ω>1ms^{-1}) is strong. In contrast, stratiform precipitation grows mainly by water vapor diffusion on the surface of ice particles that are detrained from the convective region and are characterized by a slower ascent (ω <1ms^{-1}). (Rutledge and Houze, 1987; Houze, 1989, 1997).

Weak horizontal gradients of reflectivity in stratiform precipitation region are distinct from sharp peaks of reflectivity core in the most vigorous convective regions (Steiner *et al*. 1995). Also, a pronounced layer of enhanced reflectivity and Doppler velocity in a shallow zone just below the $0^{O}C$ level (i.e., bright band), caused by melting aggregating ice particles, is an unambiguous indicator of the presence of stratiform precipitation (Houze 1997). The rest rainfalls which are not caused by this kind of process are called non-convective rain. Non-convective precipitation falls from nimbostratus clouds, the younger parts of the cumulonimbus clouds are 100% convective. Later, when convection decays, clouds become non-convective and co-exist with the embedded convective columns of rapid updraft.

2.1.3 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

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

2.2 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.

2.2.1 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 mixing ratio variables, and other quantities such as number concentrations. Four–dimensional arrays with three spatial indices and one species index are used to carry such scalars. Memory, i.e., the size of the fourth dimension in these arrays, is allocated depending on the needs of the scheme chosen, and advection of the species also applies to all these required by the microphysics options. 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 sub–steps, and this is done by saving the microphysical heating as an approximation for the next time step.

Currently, the sedimentation process is accounted for inside the individual microphysics modules, and, to prevent instability in the calculation of the vertical flux of precipitation, a smaller time step is allowed. The saturation adjustment is also included inside microphysics. In the future, however, it might be separated into an individual subroutine to enable the remaining microphysics to be called less frequently than the model’s advection step for efficiency.

2.2.1.1 WRF Double–Moment 6–class (WDM6) Scheme

The WRF double–moment 6–class microphysics scheme (WDM6) implements a double–moment bulk micro physical parameterization of clouds and precipitation and is applicable in mesoscale and general circulation models. The WDM6 scheme enables the investigation of the aerosol effects on cloud properties and precipitation processes with the prognostic variables of cloud condensation nuclei (CCN), cloud water and rain number concentrations. WDM6 extends the WRF single–moment 6–class microphysics scheme (WSM6) by incorporating the number concentrations for cloud and rainwater along with a prognostic variable of 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).

2.2.2 Cumulus Parameterization Schemes

These schemes are responsible for the sub–grid–scale effects of convective and/or shallow clouds. The schemes are intended to represent vertical fluxes due to unresolved updrafts and downdrafts 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 sub–grid–scale break down for finer grid sizes, sometimes these schemes have been found to be helpful in triggering convection in 5–10 km grid applications. Generally they should not be used when the model can resolve the convective eddies itself.

One of the main options which could potentially affect precipitation severely is the cumulus parameterization. It accounts for unresolved cloud formation. Depending on the grid resolution, convective clouds could be resolved by the explicit scheme, but with the resolution used (15 km) it still seems necessary to take into account the unresolved scales. 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. The KF scheme has demonstrated good performance on several situations and regions (Wang and Seaman, 1997). In the Alpine region, the Grell scheme was better than the KF scheme for some concrete events.

2.2.2.1 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 (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 sub–grid scheme using a mass flux approach with downdrafts and convective available potential energy (CAPE) removal time scale. Updraft generates condensate and dump condensate into environment downdraft evaporates condensate at a rate that depends on RH and depth of downdraft leftover condensate accumulates at surface as precipitation.

2.2.2.2 Betts-Miller-Janjic (BMJ) Scheme

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

Important vertical structures may be eliminated since the reference profiles are based on climatology. Convection only initiated for soundings with deep moisture profile. When convection is initiated the scheme often rains out to much water. This is because the reference profile is too dry for the forecast scenario or the transition to the reference profile was too rapid. This scheme does not account for the strength of CAPE inhibiting convective development and for any changes below the cloud base.

2.2.2.3 Grell-Freitas (GF) Scheme

The parameterization framework is a simple scheme that is based on a convective parameterization developed by (Grell, 1993).This scheme was expanded to allow for a series of different assumptions that are commonly used in convective parameterizations and that have proven to lead to large sensitivity in model simulations. The GF scheme was able to account of the small-scale processes that lead to the development of convection. The scheme initiated convection due to the presence of moderate CAPE and convection was sustained by employing a more complicated static control to represent updrafts. The static control was able to account for the advection of high θ_e air into the region and incorporate its contribution to the moisture field. The feedback from the scheme enhanced and preconditioned the environment, allowing for a relatively accurate representation of the isolated convective cells and their resulting precipitation.

2.2.2.4 Old Simplied Arakawa-Schubert (OSAS) Scheme

Arakawa and Schubert (1974) developed a cumulus parameterization scheme in a framework that conceptually divides the mutual interaction between the cumulus convection and large-scale disturbance into the categories of large-scale budget requirements and the quasi-equilibrium assumption of cloud work function. We have applied the Arakawa-Schubert scheme through a semi-prognostic approach to two different data sets: one is for an intense tropical cloud band event; the other is for tropical composite easterly wave disturbances. Both were observed in GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment (GATE). The cloud heating and drying effects predicted by the Arakawa-Schubert scheme are found to agree rather well with the observations. However, it is also found that the Arakawa-Schubert scheme underestimates both condensation and evaporation rates substantially when compared with the cumulus ensemble model results (Soong and Tao, 1980; Tao *et al.,* 1983). In order to examine how the Arakawa-Schubert scheme works in a fully prognostic problem, a simulation of the evolution and structure of the tropical cloud band mentioned above under the influence of an imposed large-scale, low level lifting was made by using a two-dimensional hydrostatic model with the inclusion of the Arakawa-Schubert scheme. Basically, the model result indicates that the mesoscale convective system is driven by the excess of the convective heating derived from the Arakawa-Schubert scheme over the adiabatic cooling due to the imposed large-scale lifting and induced mesoscale upward motion. 24-hour integration shows that the model is capable of simulating many important features, such as the life cycle, the intensity of circulation, and rainfall rat.

2.2.2.5 Grell-3 scheme

Grell 3D is an improved version of the GD scheme that may also be used on high resolution (in addition to coarser resolutions) if subsidence spreading (option cugd_avedx) is turned on (5). In this study, the call for the Grell-3 (G-3) scheme (Grell and Devenyi, 2002) is modified in the WRF-ARW model for the purpose of ensemble quantitative precipitation forecasts (QPFs). The potential of using the modified G-3 scheme in the ensemble QPFs is evaluated in a few case studies by using conventional skill metrics, such as bias scores, mean error, mean absolute error and root mean square error. The details of how to determine the ensemble mean can be found in Grell and Devenyi (2002). These ensemble members are chosen because statistically they give a large spread in terms of accumulated convective rainfall. In the effort to explore the potential of using the uncertainties in the convective parameterization schemes for ensemble QPFs, the G-3 scheme is modified such that it can be used as a single subroutine framework that can reduce to one of the individual parameterization schemes corresponding to those various closure assumptions. The reduction to individual parameterization schemes can also be refined based on the thickness of the capping inversion and the dependence of the downdraft on the precipitation efficiency, leading to more variability in the ensemble spread.

2.2.2.6 Tiedtke (TD) Scheme

The Tiedtke scheme considers a population of clouds where the cloud ensemble is described by a one dimensional bulk model as earlier applied by (Yanai, 1971) in a diagnostic study of tropical convection. Cumulus scale downdrafts are included. Various types of convection are represented, i.e., penetrative convection in connection with large–scale convergent flow, shallow convection in suppressed conditions like trade wind cumuli and midlevel convection like extra–tropical organized convection associated with potentially unstable air above the boundary layer and large–scale ascent. The closure assumptions for determining the bulk cloud mass flux are: penetrative convection and midlevel convection are maintained by large–scale moisture convergence and shallow convection by supply of moisture due to surface evaporation. In the Tiedtke scheme, convection is triggered if the parcel's temperature exceeds the environment temperature by a fixed temperature threshold of 0.50 K. This scheme performs well with 0.25 deg. grid resolution. The parameterization produces realistic fields of convective heating and appears to be in fair balance with real data for NWP as it does not initiate strong adjustment processes (spin–up) in global form.

2.2.2.7 Zhang–McFarlane (ZM) Scheme

The Zhang–McFarlane (1995) scheme is a simplified cumulus parameterization scheme, suitable for use in the general circulation models (GCMs). This parameterization is based on a plume ensemble concept similar to that originally proposed by (Arakawa and Schubert 1974). However, it employs three assumptions which significantly simplify the formulation and implementation of the scheme. The first assumption is that an ensemble of convective–scale updrafts with associated saturated downdrafts may exist when the atmosphere is locally conditionally unstable in the lower troposphere. However, the updraft ensemble is comprised only of those plumes which are sufficiently buoyant to penetrate through this unstable layer. The second assumption is that all such plumes have the same upward mass flux at the base of the convective layer. The third assumption is that moist convection, which occurs only when there is CAPE for reversible ascent of an undiluted parcel from the sub–cloud layer, acts to remove CAPE at an exponential rate with a specified adjustment time scale. The performance of the scheme and its sensitivity to choices of disposable parameters is illustrated by presenting results from a series of idealized single–column model tests. These tests demonstrate that the scheme permits establishment of quasi–equilibrium between large–scale forcing and convective response. However, it is also shown that the strength of convective downdrafts is an important factor in determining the nature of the equilibrium state. Relatively strong downdrafts give rise to an unsteady irregularly fluctuating state characterized by alternate periods of deep and shallow convection. The effect of using the scheme for GCM climate simulations is illustrated by presenting selected results of a multi–year simulation carried out with the Canadian Climate Centre GCM using the new parameterization. Comparison of these results with those for a climate simulation made with the standard model (McFarlane *et al.*, 1992) reveals the importance of other parameterized processes in determining the ultimate effect of introducing the new convective scheme. The radiative response to changes in the cloudiness regime is particularly important in this regard.

2.2.2.8 Multi–Scale Kain–Fritsch (MSKF) Scheme

The MSKF scheme is a mass flux parameterization scheme. It uses the Lagrangian parcel method (Kreitzberg and Perkey, 1976), including vertical momentum dynamics (Donner 1993), to estimate whether instability exists, whether any existing instability will become available for cloud growth, and what the properties of any convective clouds might be. Numerous modifications to the KF convective parameterization have been implemented over the last decade. Most modifications were inspired by feedback from users of the scheme (primarily numerical modelers) and interpreters of the model output (mainly operational forecasters). The specific formulation of the modifications evolved from an effort to produce desired effects in NWP while also rendering the scheme more faithful to observations and cloud–resolving modeling studies. The main task of the scheme is to identify potential source layers for convective clouds, that is, updraft source layers (USLs). Beginning at the surface, vertically adjacent layers in the host model are mixed until the depth of the mixture is at least 60 hPa. This combination of adjacent model layers composes the first potential USL. Convective downdrafts are fueled by evaporation of condensate that is generated within the updraft. A fraction of this total condensate is made available for evaporation within the downdraft, based on empirical formulas for precipitation efficiency as a function of vertical wind shear and cloud–base height (Zhang and Fritsch, 1986). Themethod by which the MSKF scheme satisfies its closure assumptions is described in Bechtold *et al.,* (2001). In fundamental terms, the MSKF scheme rearranges mass in a column using the updraft, downdraft, and environmental mass fluxes until at least 90% of the CAPE is removed.

2.2.2.9 New SAS (NS) scheme

The impact of revised simplified Arakawa-Schubert (RSAS) convective parameterization scheme in Climate Forecast System (CFS) version 2 (CFSv2) on the simulation of active and break phases of Indian summer monsoon (ISM) has been investigated. In spite of significant progress in understanding and predicting (Webster and Hoyos, 2004) Indian summer monsoon (ISM), still many of the monsoon features, namely, the intraseasonal oscillations (ISOs), diurnal variability remains a challenge.

Keeping the systematic bias of the climate forecast system model version 2 (CFSv2) in mind, an attempt is made to improve the Indian summer monsoon (ISM) rainfall variability in the model from diurnal through daily to seasonal scale. Experiments with default simplified Arakawa–Schubert (SAS) and a revised SAS schemes are carried out to make 15 years climate run (free run) to evaluate the model fidelity with revised SAS as compared to default SAS. It is clearly seen that the revised SAS is able to reduce some of the biases of CFSv2 with default SAS. Improvement is seen in the annual seasonal cycle, onset and withdrawal but most importantly the rainfall probability distribution function (PDF) has improved significantly. To understand the reason behind the PDF improvement, the diurnal rainfall simulation is analysed and it is found that the PDF of diurnal rainfall has significantly improved with respect to even a high resolution CFSv2 T382 version. In the diurnal run with revised SAS, the PDF of rainfall over central India has remarkably improved. The improvement of diurnal cycle of total rainfall has actually been contributed by the improvement of diurnal cycle of convection and associated convective rainfall. This is reflected in outgoing long wave radiation and high cloud diurnal cycle. This improvement of convective cycle has resolved a long standing problem of dry bias by CFSv2 over Indian land mass and wet bias over equatorial Indian Ocean. Besides the improvement, there are some areas where there are still scopes for further development. The cold tropospheric temperature bias, low cloud fractions need further improvement. To check the role of shallow convection, another free run is made with revised SAS along with shallow convection (SC). The major difference between the new and old SC schemes lies in the heating and cooling behavior in lower-atmospheric layers above the planetary boundary layer. However, the inclusion of revised SC scheme could not show much improvement as compared to revised SAS with deep convection. Thus, it seems that revised SAS with deep convection can be a potentially better parameterization scheme for CFSv2 in simulating ISM rainfall variability.

2.2.2.10 New Tiedtke (NTD) scheme

The New Tiedtke is improvement format of Tiedtke scheme. The New Tiedtke scheme considers amalgamate of clouds where the cloud ensemble is described by a three dimensional bulk model as earlier applied by (Yanai and Li, 1994) in a diagnostic study of tropical convection. Cumulus scale downdrafts are included. Various types of convection are represented, i.e., penetrative convection in connection with large–scale convergent flow, shallow convection in suppressed conditions like trade wind cumuli and midlevel convection like extra–tropical organized convection associated with potentially unstable air above the boundary layer and large–scale ascent. The closure assumptions for determining the bulk cloud mass flux are: penetrative convection and midlevel convection are maintained by large–scale moisture convergence and shallow convection by supply of moisture due to surface evaporation. The parameterization produces realistic fields of convective heating and appears to be in fair balance with real data for NWP as it does not initiate strong adjustment processes (spin–up) in global form.

2.2.2.11 New SAS-HWRF (NSH) scheme

The Hurricane Weather Research and Forecast (HWRF) system has been in operation at the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Prediction (NCEP) since 2007. This is new mass-flux scheme with deep and shallow components and momentum transport. This scheme (Cintineo *et al.,* 2014) is well tested for HWRF, used operationally at NCEP. This intensity bias is connected to the grid-scale convection. Generally speaking, explicit microphysics is prone to grid scale convection, and the grid scale convection can produce very strong small size storms. In HWRF model, the grid-scale convection is enhanced due to the moisture convergence from the second nest (where SAS scheme is used, and the storm size is larger compared to the third nest). In current HWRF model, sigma is small (due to small vertical velocity), and the meso-SAS scheme behaves similar to the current operational SAS. Three major problems identified: 1) some of the weak storms become too strong, 2) track and intensity forecasts are degraded for some strong storms and 3) Current meso SAS code may have computational problem when sigma is large.

2.2.2.12 Grell-Devenyi (GD) scheme

The GD scheme (Grell and Devenyi, 2002) is modified in the WRF-ARW model for the purpose of ensemble quantitative precipitation forecasts (QPFs). The potential of using the modified GD scheme in the ensemble QPFs is evaluated in a few case studies by using conventional skill metrics, such as bias scores, mean error, mean absolute error and root mean square error. The GD scheme is an expansion from the Grell convective parameterization to include several alternative closure assumptions that are commonly used in convective parameterizations. These assumptions, rooted in various considerations of convection initiation and development, represent a natural span of uncertainties in convective parameterization. The use of these assumptions in ensemble generation has been shown in multi-model ensemble experiments (Houtekamer, 1993; Stensrud and Skindlov, 1996) to be effective. The unique aspect of the GD scheme is that it uses 16 ensemble members derived from 5 popular closure assumptions to obtain an ensemble-mean realization at a time and location. The details of how to determine the ensemble mean can be found in Grell and Devenyi (2002). These ensemble members are chosen because statistically they give a large spread in terms of accumulated convective rainfall. In the effort to explore the potential of using the uncertainties in the convective parameterization schemes for ensemble QPFs, the GD scheme is modified such that it can be used as a single subroutine framework that can reduce to one of the individual parameterization schemes corresponding to those various closure assumptions. The reduction to individual parameterization schemes can also be refined based on the thickness of the capping inversion and the dependence of the downdraft on the precipitation efficiency, leading to more variability in the ensemble spread. The reduction is controlled by a flag parameter in the namelist input file.

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

2.2.3.1 Yonsei University (YSU) Scheme

The YSU PBL 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).

2.2.4 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.

2.2.4.1 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 lines loxodromes, as straight segments which conserve the angles with the meridians. While the linear scale is equal in all directions around any point, thus preserving the angles and the shapes of small objects, the Mercator projection distorts the size and shape of large objects, as the scale increases from the Equator to the poles, where it becomes infinite. Although the Mercator projection is still used commonly for navigation, due to its unique properties, cartographers agree that it is not suited to general reference world maps due to its distortion of land area. Mercator himself used the equal–area sinusoidal projection to show relative areas. As a result of these criticisms, modern atlases no longer use the Mercator projection for world maps or for areas distant from the equator, preferring other cylindrical projection or forms of equal–area projection. The Mercator projection is still commonly used for areas near the equator, however, where distortion is minimal.

2.2.4.2 Lambert Projection

A Lambert conformal conic projection (LCC) 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.

2.2.5 Arakawa Staggered C–grids

Arakawa and Schubert (1974), grid system depicts different ways to represent and compute orthogonal physical quantities on rectangular grids used for Earth system models for meteorology and oceanography. 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.

2.2.6 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. 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.

2.2.6.1 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. The flux of energy transported by outgoing longwave radiation is measured in W/m^2. In a different context, OLR values are often used as a proxy for convection in tropical and subtropical regions 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 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 GERB. Alternatively, the OLR can be indirectly inferred from narrowband radiance observations. The 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 EUMETSAT to support the derivation of climate–relevant parameters.

2.2.6.2 Downward Long wave Radiation

The downward longwave 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 longwave radiation from the atmosphere is difficult, even when the distributions of water vapor, carbon dioxide, cloudiness, and temperature are measured. Some satellite measurements like TOVS estimates downward longwave radiation. Little longwave radiation is reflected by the surface: natural surface emission is dominant. 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 3.8.1) model have been used to simulate the monsoon rainfall 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 MP and CP schemes options but in this research we have been used one microphysics and 12 cumulus parameterization schemes for the simulation of heavy rainfall events in the monsoon season. The 12 different CPs are KF, BMJ, and GF, OSAS, G-3, Tiedtke, ZM, MSKF, NS, NTD, NSH and GD schemes. The WDM6 scheme contains prognostic equations for cloud water, rainwater, cloud ice, snow, and graupel mixing ratio. The KF scheme includes convective available potential energy and shallow convection, BMJ scheme adjusts the sounding towards a pre-determined, post convective profile derived from climatology. This post convective profile has been defined by points at the cloud base, cloud top and freezing level. In this scheme there is no explicit updraft or downdraft and no cloud detrainment occur. OSAS scheme indicates that the mesoscale convective system is driven by the excess of the convective heating derived from the Arakawa-Schubert scheme over the adiabatic cooling due to the imposed large-scale lifting and induced mesoscale upward motion. G-3 schemes can be refined based on the thickness of the capping inversion and the dependence of the downdraft on the precipitation efficiency, leading to more variability in the ensemble spread. Tiedtke includes cumulus scale downdrafts and various types of convection, i.e., penetrative convection in connection with large–scale convergent flow, shallow convection in suppressed conditions like trade wind cumuli and midlevel convection like extra–tropical organized convection associated with potentially unstable air above the boundary layer and large–scale ascent. ZM includes convective–scale updrafts with associated saturated downdrafts, the same upward mass flux and moist convection and MSKF includes the updraft, downdraft, and environmental mass fluxes until at least 90% of the CAPE is removed. 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 PBL is treated with YSU. Dudhia (1989) scheme has been used for short wave radiation and Rapid Radiative Transfer Model (RRTM) for long wave (Mlawer *et al.,* 1997). The NS scheme used to cold tropospheric temperature bias, low cloud fractions needs further improvement. To check the role of shallow convection, another free run is made with revised SAS along with shallow convection (SC). NTD applied by a diagnostic study of tropical convection. Cumulus scale downdrafts are included. Various types of convection are represented, i.e., penetrative convection in connection with large–scale convergent flow, shallow convection in suppressed conditions like trade wind cumuli and midlevel convection. NSH Generally speaking, explicit microphysics is prone to grid scale convection, and the grid scale convection can produce very strong small size storms. In HWRF model, the grid-scale convection is enhanced due to the moisture convergence from the second nest. The potential of using the modified GD scheme in the ensemble QPFs is evaluated in a few case studies by using conventional skill metrics, such as bias scores, mean error, mean absolute error and root mean square error.

3.2 Model Domain and Configuration

The model has been configured in single domain, 6 km horizontal grid spacing with 161×183 grids in the east–west and north–south directions and 30 vertical levels. Time step of integration is set to 30 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 2:

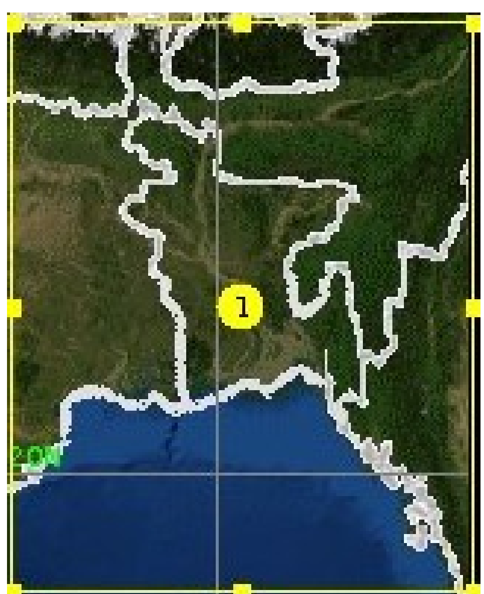

Figure 1: WRF Model Domain for the simulation of heavy rainfall in Bangladesh

Table 2: WRF Model and Domain Configurations

Dynamics	Non–hydrostatic
Number of domain	2
Central points of the domain	Central Lat.: 22.80°N, Central Lon.: 90.70°E
Horizontal grid distance	18 and 6 km
Integration time step	90 and 30 s
Number of grid points	X–direction 96×100 points, Y-direction 103×127 points
Map projection	Mercator
Horizontal grid distribution	Arakawa C–grid
Nesting	One way
Vertical co–ordinate	Terrain–following hydrostatic–pressure co–ordinate (30 sigma levels up to 100 hPa)
Time integration	3^{rd} order Runge–Kutta
Spatial differencing scheme	6^{th} order centered differencing
Initial conditions	Three–dimensional real–data (FNL: 1° × 1°)
Lateral boundary condition	Specified options for real–data
Top boundary condition	Gravity wave absorbing (diffusion or Rayleigh damping)
Bottom boundary condition	Physical or free–slip
Diffusion and Damping	Simple Diffusion
Microphysics	WDM6 Scheme
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	(1) Kain–Fritsch (KF) Scheme (2) Betts-Miller-Janjic (BMJ) scheme (3) Grell-Freitas (GF) (4) Old simplified Arakawa-Schubert (OSAS) (5) Grell-3 (G-3), (6) Tiedtke Scheme (TD) (7) Zhang–McFarlane (ZM) Scheme (8) Multi–scale Kain–Fritsch (MSKF) scheme (9) New SAS (NS), (10) New Tiedtke (NTD) (11) New SAS-HWRF (NSH) (12) Grell-Devenye (GD)
PBL parameterization	Yonsei University Scheme (YSU) (Hong *et al*., 2006)

3.3 Data and Methodology

Final Reanalysis (FNL) data ($1^o x 1^o$) collected from National Centre for Environment Prediction (NCEP) is used as initial and lateral boundary Conditions (LBCs) which is updated at six hours interval i.e. the model is initialized with 0000, 0600, 1200 and 1800 UTC initial field of corresponding date. The NCEP FNL data will be interpolated to the model horizontal and vertical grids.

Table 3: Heavy rainfall events and their BMD observed rainfall in the S–SE region of Bangladesh

3 – 5 July 2017		19–20July 2017		23-24 July 2017	
Stations	Observed Rain (mm)	Stations	Observed Rain (mm)	Stations	Observed Rain (mm)
Cox-Bazar	241	Sitakunda	347	Chittagong	223
Khepupara	195	Sandwip	248	Hatiya	218
Hatiya	152	Feni	186	Cox-Bazar	208
Chittagong	143	M.Court	136	Kutubdia	188
Sitakunda	142	Khulna	130	Sitakunda	185

In this research we have considered 3 heavy rainfall events those occurred in the southeastern region of Bangladesh. The events and amounts of heavy rainfall in different stations are presented in Table 3. In this research we have used twelve different CP schemes and single MP scheme. There is limited number of meteorological observation stations in the northeastern and southwestern regions of Bangladesh. For this reason we have added 8 more points in the Bangladesh to see the exact rainfall pattern on Bangladesh Map. In this research we have extracted total rain, convective and non–convective rainfall at 33 BMD station points with additional 8 points in the northeastern and southwestern regions of Bangladesh. From WRF Model run we made 3 hourly outputs during the study period. From this 3 hourly output of total rainfall, convective and non–convective rainfall data converted into daily total rainfall, convective and non–convective rainfall data of 3-5 July, 19-20 July and 23-24 July 2017. For collecting 24, 48 and 72 hour model rainfall data the WRF model has been run with those days with initial condition starting from 0000 UTC of each days. The model is generated 24 hours as day 1, 48 hours as day 2 and 72 hours as day 3 of model run. In this research we have calculated total rain on the basis of convective and non-convective rain. The convective and non-convective rains appear directly from the WRF-ARW model output. Txt format data from ctl file of WRF model output has been found using Grid Analysis and Display System (GrADS).These txt data have been converted into Microsoft Excel format and then plotted using SURFER Software. The daily rainfall data of 3 heavy rainfall events of

July 2017 have been plotted using 24, 48 and 72–hour lead time prediction. The model simulated results are verified by using three verification methods, i.e., Threat Score (TS), Equitable Threat Score (ETS) and Bias Score (BS).

3.4 Verification Methods

The quantitative precipitation forecasts (QPFs) and their improvements on a wide time–scale range, from hours to seasonal, are under heavy and constant demand from the general public and governments around the world. The verification of model QPFs is a key factor and the basis for improvement within this process (Olson *et al.* 1995). Thus, it is essential for the verification methods to reflect the model skill on QPFs as accurately as possible, especially for heavy rainfall on short time scales (within a few days) due to its hazardous nature. The most widely used objective verification methods for model QPFs are the threat score (TS), equitable threat score (ETS), and bias score (BS) (Wilks 1995; Ebert, 2001; Mason 2003).

The schematic of the model QPF verification (Gilleland *et al.,* 2009) at any specified threshold for a given accumulation time period in an area is shown in Figure 2. The observed rainfall area exceeding the threshold (dotted oval) is labeled O and the model forecast area (gray oval) has labeled F. The intersection of O and F is the hit area H, and the entire verification domain is N. The area of (O–H) is misses (occurred but not predicted), (F–H) is false alarms (predicted but did not happen) and [N–(F+O–H)] is correct negatives (correctly predicted to not occur). The dashed box (denoted by N_s) marks the conditions for a small verification area. The areas used here are calculated by their latitude–longitude. The area of a latitude–longitude rectangle is proportional to the difference in the longitudes. The area enclosed by latitude–longitude is given by the following formula,

$$A = \frac{2 \times \pi \times \mathrm{R}^2 |\sin(\mathrm{lat1}) - \sin(\mathrm{lat2})||\mathrm{lon1} - \mathrm{lon2}|}{360}$$
$$= \left(\frac{\pi \times \mathrm{R}^2}{180}\right) |\sin(\mathrm{lat1}) - \sin(\mathrm{lat2})||\mathrm{lon1} - \mathrm{lon2}| \qquad (1)$$

Where, R is defined as the radius of the earth having value of 6400 km.

We can define from Figure 2 at any given rainfall threshold over an accumulation period, the observed rain area exceeding the criterion is O and the model–predicted area is F. Their intersection (i.e., the hit area) is denoted by H, while the entire verification domain is N.

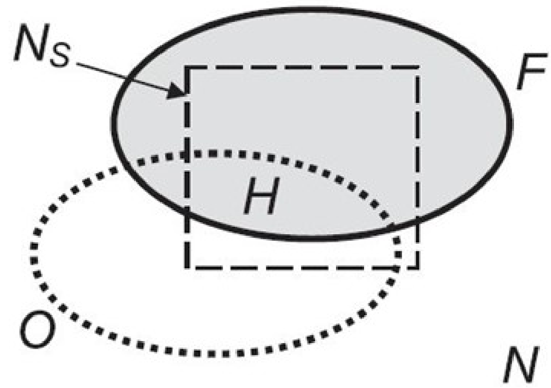

Figure 1.1: Schematic of the model QPF verification

3.4.1 Threat Score (TS)

The TS measures the fraction of observed and/or forecast events that were correctly predicted. It can be thought of as the accuracy when correct negatives have been removed from consideration, that is, TS is only concerned with forecasts that count. It is sensitive to hits and penalizes both misses and false alarms. It does not distinguish source of forecast error. Depends on climatological frequency of events (poorer scores for rarer events) since some hits can occur purely due to random chance. The TS has a value between 0 and 1 (as the hit area cannot be greater than the union of O and F), and a higher one represents better performance. The TS is defined as

$$TS = H / (O + F - H) \quad (2)$$

Where O = Observed heavy rain area; F = Model predicted heavy rain area; H = Intersected area between observed (O) and model predicted (F) heavy rain area. The TS is also called the critical success index.

3.4.2 Equitable Threat Score (ETS)

The ETS measures the fraction of observed and/or forecast events that were correctly predicted, adjusted for hits associated with random chance (for example, it is easier to correctly forecast rain occurrence in a wet climate than in a dry climate). The ETS is often used in the verification of rainfall in NWP models because its "equitability" allows scores to be compared more fairly across different regimes. It is sensitive to hits because it penalizes both misses and false alarms in the same way. It does not distinguish the source of forecast error. The ETS differs from the TS only in that a value of R is subtracted from both the denominator and numerator, as seen in Eq. (3), and thus can become negative but still capped by unity ($-1/3 \leq$ ETS≤ 1). Given in Eq. (4), R is the expected area for a random distribution of F to fall inside O just by chance (i.e., the random hit area). Due to this assumption of R being random and thus reflecting no model skill, it is excluded from the calculation of ETS and is therefore subtracted. Considered a fairer measure than the TS, the ETS is perhaps more widely used (Cartwright and Krishnamurti, 2007). The ETS is denoted as

$$ETS = (H - R) / (O + F - H - R) \tag{3}$$

Where, $$R = (O/N) * (F/N) * N = F * (O/N) = O * (F/N) \tag{4}$$

Where N = Entire verification domain. The ETS is also called the Gilbert skill score.

3.4.3 Bias Score (BS)

The BS is the ratio of the relative sizes of the rain areas in the forecast to the observations and, thus, can vary from 0 to infinity but ideal value is 1 (Wilks, 1995; Ebert, 2001). It measures the ratio of the frequency of forecast events to the frequency of observed events. It indicates whether the forecast system has a tendency to under forecast (BS<1) or over forecast (BS>1) events. It does not measure how well the forecast corresponds to the observations, only measures relative frequencies. In Figure 2, it is clear that the same TS or ETS can result from either an over forecast or an under forecast of rain by the model, and thus the BS often needs to be provided alongside to interpret the verification results more properly (Pasaric and Juras, 2011). The Bias Score is defined as,

$$BS = F/O \tag{5}$$

Chapter IV
Results and Discussion

4.1 Heavy rainfall event during 03-05 July 2017

4.1.1 Observed Daily Rainfall during 3-5 July 2017

The station wise BMD observed total rainfall during 3-5 July 2017 all over Bangladesh is presented in Figure 2(a-c). On this day very heavy rainfall (VHR) is observed in the southern and southeastern (SE), heavy rainfall (HR) in the western, northern and northwestern (NW), moderately heavy rainfall (MHR) in the eastern, moderate rainfall (MR) in the southwestern (SW) and light rainfall (LR) in the northeastern (NE) regions of Bangladesh respectively. Maximum total rainfall observed at Chittagong, Cox's Bazar, Hatiya, Khepupara, Rangamati, Sandwip and Sitakunda regions are 143, 151, 153, 195, 120, 113 and 142 mm respectively. The VHR is observed on 04 July (Figure 2b) in the SE and NE regions, HR in the southern and eastern regions, MHR and MR in the central and SW regions of Bangladesh respectively. Maximum total rainfall observed at Chittagong, Cumilla, Feni, Kutubdia, Patuakhali, Sitakunda, Sylhet and Teknaf regions are 91, 47, 67, 88, 80, 111, 95 and 112 mm respectively. The VHR is observed on 05 July (Figure 2c) in the SE regions, HR in the southern and Bogura regions, MHR in the central to western and Sylhet regions, MR in the SW regions of Bangladesh. Maximum total rainfall observed at Cox-Bazar, Teknaf, Kutubdia, Feni, Mongla and Bogura, regions are 241, 181 124, 79, 74 and 72 mm respectively.

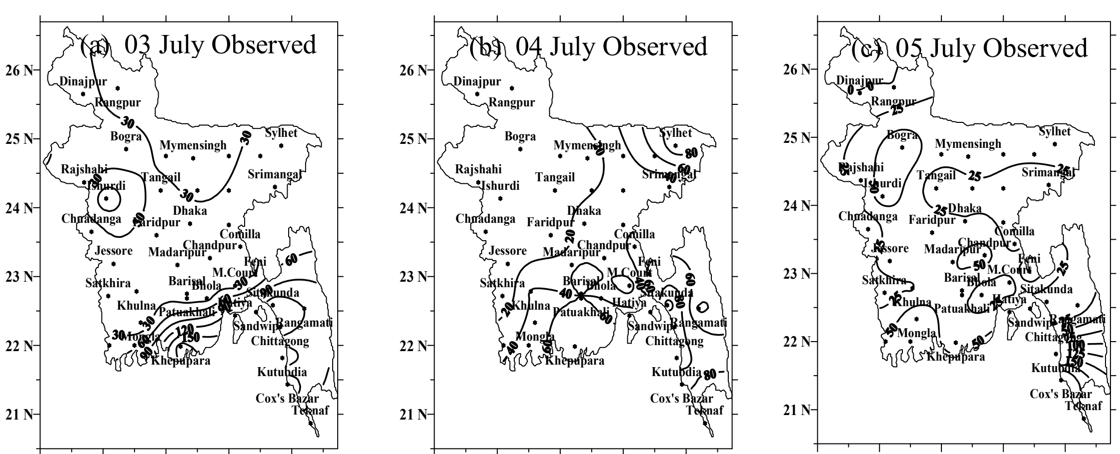

Figure 2: Distribution of observed daily total rainfall on a) 3, b) 4 and c) 5 July 2017 respectively all over Bangladesh.

4.1.2 Model simulated daily Total rainfalls on 03 July 2017

The daily model predicted total rainfall for different CP schemes in combination with WDM6 scheme on 03 July 2017 are presented in Figure 3(a-l) with the initial conditions of 0000 UTC of 03 July. The KF scheme has simulated VHR (Figure 3a) in the SE and NE region, HR in the northern, eastern and Bogura regions. The KF scheme has also simulated moderate to MHR in the NW regions and LR in the western and SW regions of Bangladesh. Maximum rain is simulated at Chittagong, Cox-Bazar, Kutubdia, Mymensingh, Sandwip, Sitakunda, Sylhet and Teknaf regions are 133, 131, 88, 89, 74, 108, 92 and 166 mm respectively. The KF scheme has simulated maximum total rainfall and its positions are found to match with the observed VHR in the SE regions and HR in the northern and NW regions but S-SW regions it would not match. The BMJ scheme has simulated HR (Figure 3b) in the northern, NW, NE and Teknaf regions, MR in the SE regions and LR all other regions of Bangladesh. Maximum total rainfall is found at Bogura, Rangpur, Sylhet, Tangail and Teknaf regions are 63, 65, 75, 61 and 63 mm respectively. VHR regions, which are situated in the S-SE regions of Bangladesh, are not simulated by BMJ scheme.

The GF scheme has simulated HR (Figure 3c) in the northern, southern, eastern and SE regions, MHR in the western, NW, NE regions and MR in the SW regions of Bangladesh. Maximum Total rainfall at Chittagong, Cox-Bazar, Hatiya, Mymensingh, Sandwip and Sitakunda regions are 71, 49, 88, 100, 75 and 75 mm respectively. The GF scheme has simulated higher rain in the northern regions and lower rain in the southern regions than that of observed total rainfall. The OSAS scheme has simulated HR (Figure 3d) at Bogura, Chandpur, Hatiya, and Kutubdia region, moderate to MHR all other of Bangladesh. Maximum total rainfall simulated at Bogura, Chandpur, Hatiya, and Kutubdia regions are 52, 64, 50 and 53 mm respectively. The simulated total rainfall by OSAS scheme is matched with observed HR in the NW regions but it would not match with the VHR in the south SE regions of Bangladesh. The G-3 scheme has simulated heavy to VHR (Figure 3e) in the S-SE and E-NE regions, MHR in all other regions of Bangladesh. Maximum rain is simulated at Kutubdia, Khepupara, Sylhet, Chittagong and Sitakunda regions are 139, 101, 90, 87 and 89 mm respectively. The G-3 scheme is found to match with observed HR in the SE regions but the amount is low. The Tiedtke scheme has simulated VHR (Figure 3f) in the northern region, MHR in the NE regions, MR in the western and NW regions of Bangladesh. Maximum total rainfall is simulated at Mymensingh is 95 mm. The TD scheme is matched with the observed HR in the northern regions but the amount of rain is high but it would not match in the VHR in the S-SE regions.

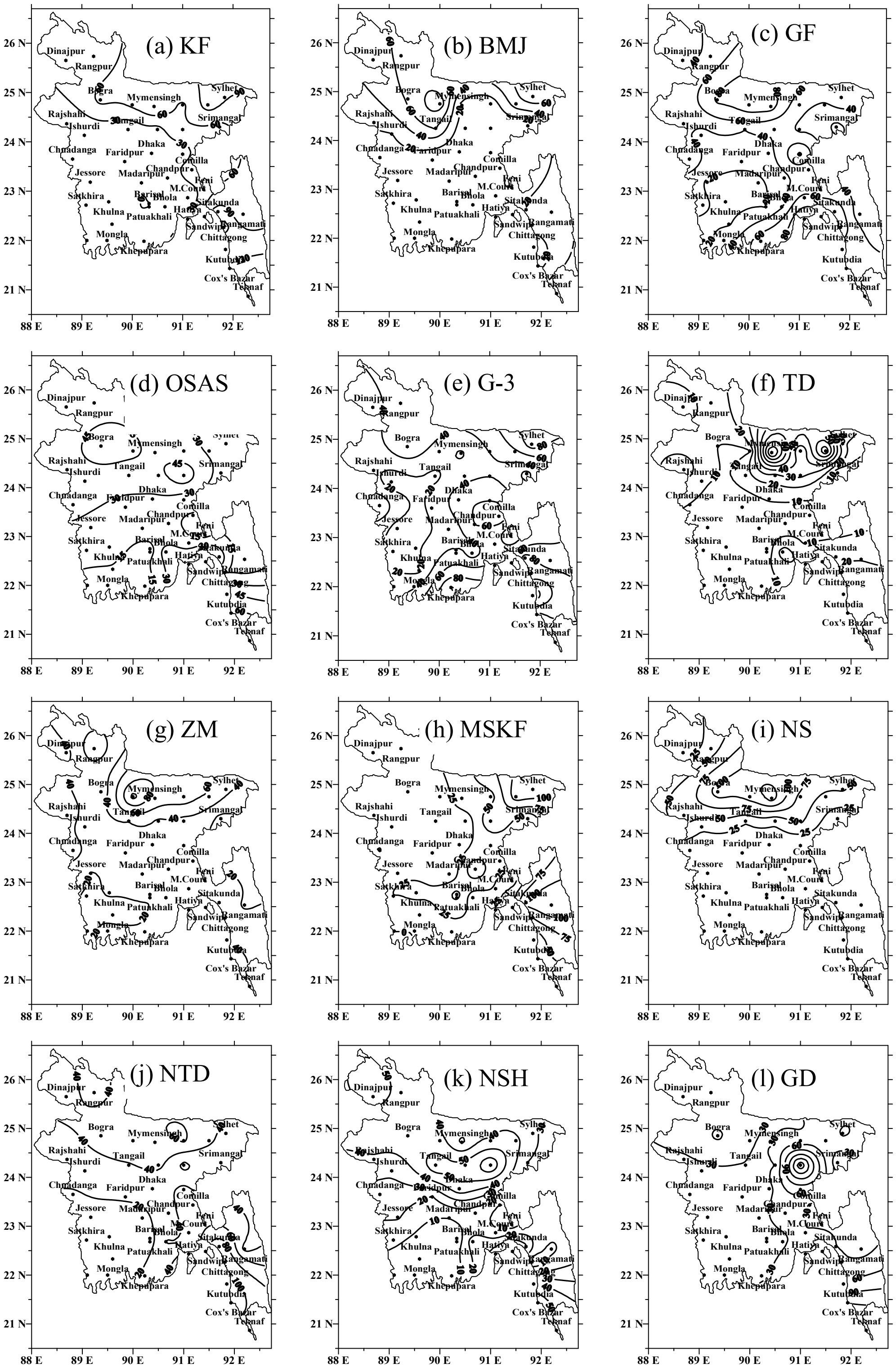

Figure 3: Spatial distribution of model simulated daily total rainfalls using different CPs in combination with WDM6 scheme on 03 July 2017 all over Bangladesh.

The ZM scheme has simulated HR (Figure 3g) in the NW to NE regions, moderate rain in the SW and SE regions and LR in other regions of Bangladesh. Maximum rain is simulated at Chuadanga, Dinajpur, Mymensingh and Rajshahi regions are 49, 46, 72, and 54 mm respectively. The ZM scheme is matched with the observed HR in the northern regions but it would not match in the VHR in the S-SE regions. The MSKF scheme has simulated VHR (Figure 3h) in the NE and SE regions, moderately heavy to HR in the central to eastern regions and LR in the W-NW regions of Bangladesh. Maximum total rainfall is simulated at Rangamati, Sitakunda and Sylhet regions are 124, 110 and 121 mm respectively. The position and amount of VHR is matched in the S-SE and NE regions. The NS scheme has simulated heavy to VHR (Figure 3i) in the N-NE and NW regions of Bangladesh. Maximum total rainfall is simulated at Bogura and Mymensingh regions are112and 137 respectively. The NS scheme is matched with observed HR in the northern regions but it would not match in the VHR regions.

The NTD scheme has simulated VHR and HR (Figure 3j) in the SE and northern regions, MHR in the western and NE regions of Bangladesh. Maximum rain is simulated at Chittagong, Cox-Bazar, Kutubdia, Sitakunda and Teknaf regions are 101, 110, 110, 99 and 92 mm respectively. The NTD scheme is matched with observed VHR and HR in the S-SE and northern regions. The NSH scheme has simulated HR at (Figure 3k) in the northern, NW and SE regions, MHR in the southern, eastern and SE regions, and moderate rain in the western regions of Bangladesh. Maximum rain is simulated at Cox-Bazar, Dinajpur, Sandwip and Tangail regions are 56, 52, 51, and 57 mm respectively. The NSH scheme is matched with observed HR in the northern regions but it would not match in the VHR regions.

The GD scheme has simulated VHR and HR (Figure 3l) in the NE and SE regions and MR in the southern regions of Bangladesh. Maximum rain is simulated at Bogura, Cox-Bazar, Kutubdia, Sandwip, and Teknaf regions are 65, 120, 61, 88, 158 mm respectively. The GD scheme is matched with the observed VHR and HR in the northern and SE regions.

4.1.3 Model simulated daily Total rainfalls on 04 July 2017

The daily model predicted total rainfall for different CP schemes in combination with WDM6 scheme on 04 July 2017 are presented in Figure 4(a-l) with the initial conditions of 0000 UTC of 04 July. The KF scheme has simulated VHR and HR (Figure4a) in the south to SE and NW to NE regions and moderate to MHR in the SW regions of Bangladesh. Maximum rain is simulated at Chittagong, Cox-Bazar, Feni, Kutubdia, Mymensingh, Srimangal and Teknaf regions are 54, 129, 65, 119, 82, 63 and 113 mm respectively. The simulated position and amount of HR by KF scheme are found to match with the observed heavy to VHR in the S-SE and NE regions. The BMJ scheme has simulated HR (Figure 4b) in the northern regions, MR and MHR in the SE, NW and NE regions of Bangladesh. Maximum total rainfall is found at Mymensingh and Rangpur regions are 59 and 49 mm respectively. The BMJ scheme has not simulated and matched with the observed HR regions all over Bangladesh. The GF scheme has simulated heavy to MHR (Figure 4c) in the northern and SW to SE regions of Maximum total rainfall is predicted at Cox-Bazar, Feni, Khulna, Kutubdia, Mongla, Sandwip and Sitakunda regions are 58, 60, 51, 59, 82, 44 and 46 mm respectively. The simulated total rainfall by GF scheme is matched with the observed rain in the SW regions but it could not match with the HR regions. The OSAS scheme has simulated HR (Figure 4d) in the SE region, LR in the NW and eastern regions, MHR and MR all other of Bangladesh. Maximum total rainfall is simulated at Cox-Bazar, Hatiya, Kutubdia, Sandwip and Teknaf regions are 62, 56, 61, 67 and 61 mm respectively.

The OSAS scheme is match with the observed HR in the SE regions. The G-3 scheme has simulated VHR and HR (Figure 4e) in the south to SE, eastern and north to NE regions, moderate to MHR in the west to SW regions of Bangladesh. Maximum total rainfall is simulated at Chittagong, Cox-Bazar, Faridpur, Feni, Sitakunda, and Teknaf regions are 67, 70, 90, 77, 105 and 86 mm respectively. The G-3 scheme has matched with the observed HR and VHR regions all over Bangladesh. The Tiedtke scheme has simulated MHR (Figure 4f) in the NW and SE region and MR in the NE regions of Bangladesh. Maximum rain is simulated at Kutubdia and Teknaf regions are43and 38 mm respectively. The TD scheme is not matched with the observed HR. The ZM (Figure 4g) and NS (Figure 4i) schemes have simulated HR in the NE regions of Bangladesh and maximum rain is found at Sylhet 74 and 106 mm respectively. The ZM and NS schemes are matched with the observed HR position in the NE regions and it would not match all other regions of Bangladesh. The MSKF scheme has simulated VHR and HR (Figure 4h) in the NE to NW and SE regions, LR at west to SW regions and MHR in the other regions of Bangladesh. Maximum total rainfall is found at Chittagong, Dinajpur, Sitakunda, Sylhet and Teknaf regions are 61, 77, 95, 125 and 66 mm respectively. The MSKF scheme is matched with observed HR and VHR position in the northern, NE and SE regions. The NTD scheme has simulated HR (Figure 4j) in the SE regions, LR in the western and SW regions and MR in other regions of Bangladesh. Maximum rain is found at Cox-Bazar, Kutubdia, Sandwip, Sylhet and Teknaf regions are 116, 82, 65, 56 and 94 mm respectively.

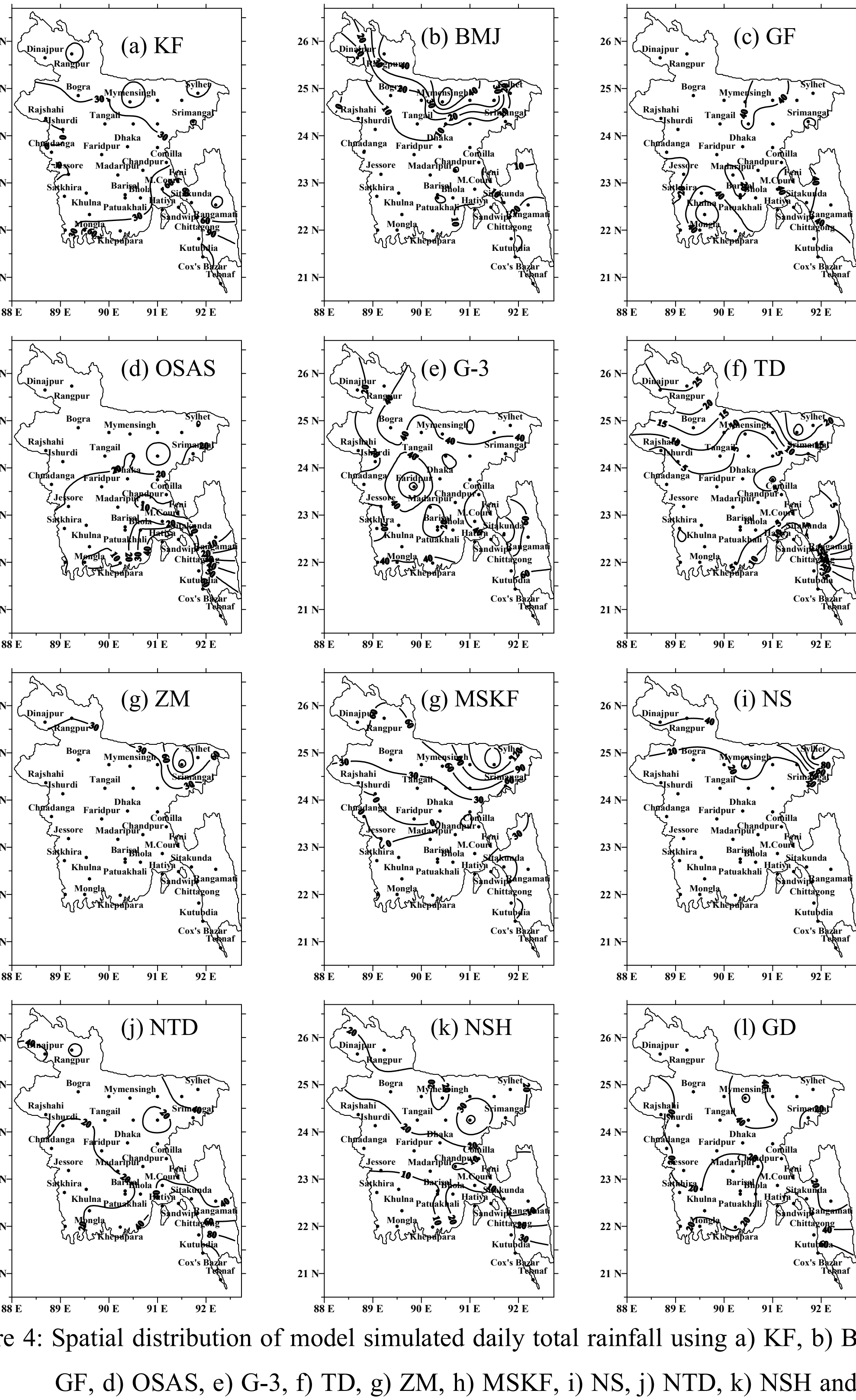

Figure 4: Spatial distribution of model simulated daily total rainfall using a) KF, b) BMJ, c) GF, d) OSAS, e) G-3, f) TD, g) ZM, h) MSKF, i) NS, j) NTD, k) NSH and l) GD schemes in combination with WDM6 scheme on 04 July 2017 all over Bangladesh.

The NTD scheme is matched with the observed HR position in the SE regions. The NSH scheme has simulated MHR (Figure 1k) in the NW to NE, south to SE and eastern regions of Bangladesh. Maximum total rainfall is not significant all over Bangladesh. The NSH scheme has not matched with the observed HR position. The GD scheme has simulated HR (Figure 1l) in the northern and SE regions and MR in other regions of Bangladesh. Maximum rain is simulated at Cox-Bazar, Mymensingh, Sandwip, and Teknaf regions are 78, 65, 59 and 74 mm respectively. The GD scheme is matched with the observed HR position in the SE region but not in the NE regions.

4.1.4 Model simulated daily Total rainfalls on 05 July 2017

The daily model simulated total rainfall on 05 July 2017 for different CP schemes in combination with WDM6 scheme with the initial conditions at 0000 UTC of 05 July are presented in Figure 5(a-l). The KF scheme has simulated HR (Figure 5a) in the SE and NE region, MHR in the southern and northern regions, MR in the NW regions and LR in other regions of Bangladesh. Maximum rain is simulated at Teknaf, Srimangal, Cox-Bazar and Mongla regions are 88, 50, 49 and 43 mm respectively. The KF scheme is found to match with observed HR in the SE regions but the simulated rain is almost one third than that of observed rain at Cox-Bazar station. The BMJ scheme has simulated HR (Figure 5b) in the NW and NE regions, MHR in the western regions and LR in other regions of Bangladesh. Maximum total rainfall is found at Sylhet, Rajshahi, Dinajpur and Teknaf regions are 86, 74, 59 and 55 mm respectively. BMJ scheme has simulated HR in different stations but could not match with the observed HR region.

The GF scheme has simulated HR (Figure 5c) Chandpur, Faridpur, Mymensingh and Rangpur regions, MR in the western to SW regions, MHR in all other regions of Bangladesh. Maximum Total rainfall is simulated at Chandpur, Mymensingh, Rangpur and Faridpur regions are 54, 55, 48 and 44 mm respectively. The GF scheme has not simulated VHR in any stations of Bangladesh. The OSAS scheme has simulated HR (Figure 5d) only at Hatiya region, MHR in the S-SE regions, LR in the eastern regions and MR all other regions of Bangladesh. Maximum total rainfall simulated at Hatiya and Teknaf regions are 44 and 37 mm respectively. The OSAS scheme has not simulated HR all over Bangladesh on 5 July. The G-3 scheme has simulated HR (Figure 5e) in the S-SE and NW regions, MHR and MR in the other regions of Bangladesh. Maximum total rainfall is simulated at Chittagong, Cox-Bazar, Khepupara, Rangpur, Sitakunda and Teknaf regions are 53, 46, 51, 51, 56 and 75 mm respectively.

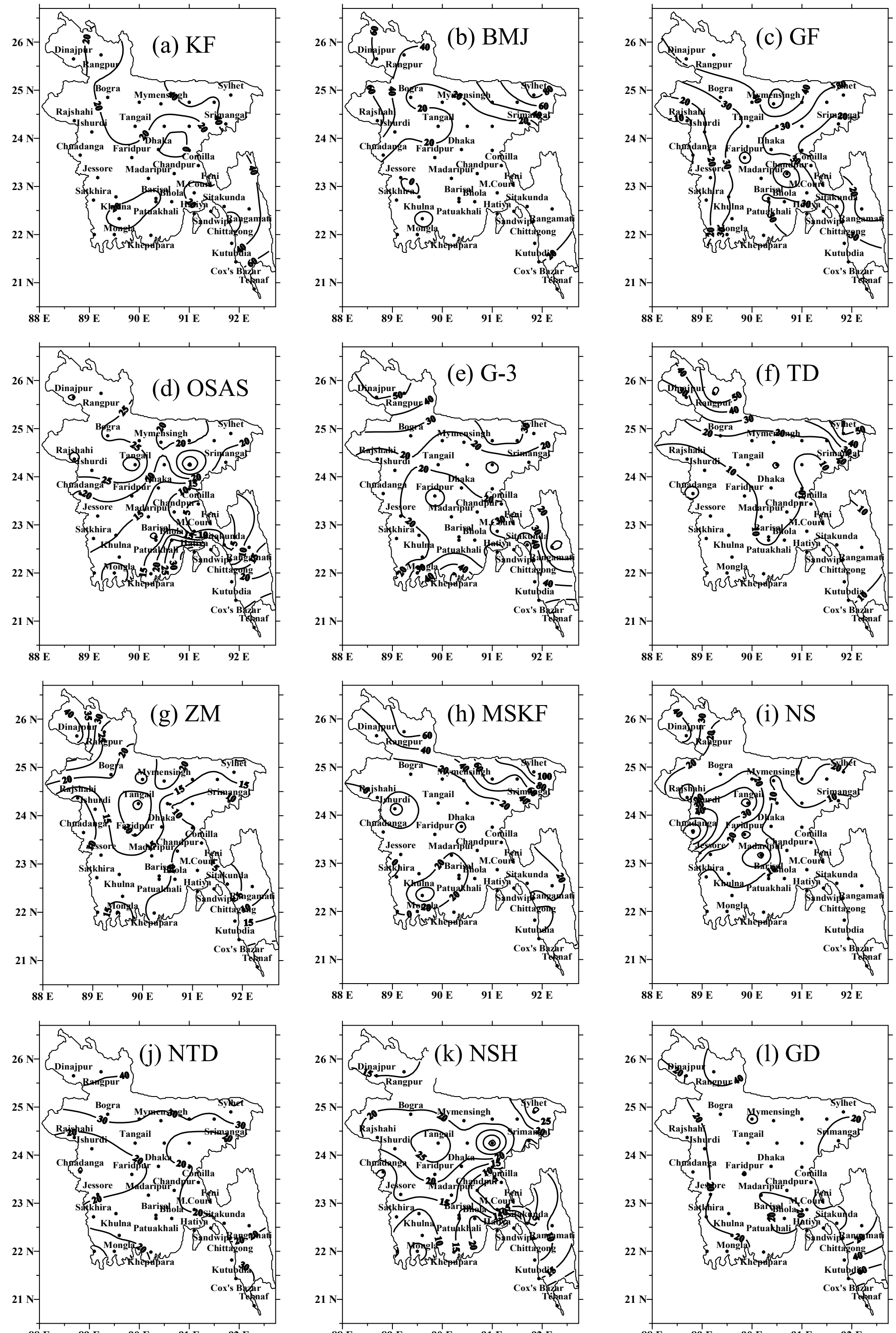

Figure 5: Spatial distribution of model simulated daily total rainfall using different CP schemes in combination with WDM6 scheme on 05 July 2017 all over Bangladesh.

The simulated HR region by G-3 scheme has matched with observed rain in the SE regions but the magnitude of total rainfall is not matched. The Tiedtke scheme has simulated HR

(Figure 5f) in the NW and NE region, MR in the northern regions and light rain in other regions of Bangladesh. Maximum total rainfall is simulated at Rangpur and Sylhet regions are 62 and 51 mm respectively. The simulated total rainfall by TD scheme has matched only at Sylhet regions. The ZM scheme has simulated HR (Figure 5g) in the NW regions, MHR in the northern and NE regions and MR in the southern, western and SE regions and LR in the other regions of Bangladesh. Maximum TR is simulated at Dinajpur, Mymensingh, Tangail and Teknaf regions are 45, 25, 27 and 25 mm respectively.

The MSKF scheme has simulated VHR (Figure 5h) in the NE, HR in the N-NW and western regions, and MHR in the SW regions and LR in other regions of Bangladesh. Maximum total rainfall is simulated at Ishwardi, Mongla, Rangpur and Sylhet regions are 52, 61, 69 and 112 mm respectively. The MSKF has matched with the observed total rainfall at Mongla and also significantly higher rain simulated than that of observed at Sylhet regions. The NS scheme has simulated HR and MHR (Figure 5i) in the western and NW region and LR in other regions of Bangladesh. Maximum total rainfall is simulated at Chuadanga regions is 74 mm. The NTD scheme has simulated HR (Figure 5j) at Dinajpur regions, MHR and MR in the other regions of Bangladesh. Maximum total rainfall at Dinajpur and Rangpur regions are 44 and 41 mm respectively. The NSH scheme has simulated HR (Figure 5k) at Sandwip regions, MHR in the western, NE and SE regions, and LR in the eastern and SW regions and MR in the other regions of Bangladesh. Maximum rain is simulated at Sandwip regions are 48 mm. The GD scheme has simulated VHR and HR (Figure 5l) in the SE and NW regions respectively, LR in the western regions, MHR and MR in the other regions of Bangladesh. Maximum rain at Teknaf, Cox-Bazar and Rangpur regions are 117, 63 and 50 mm respectively. The simulated HR by GD scheme has matched with the observed HR in the SE region.

4.1.5 Model simulated total rainfalls on 04 July with 03 July initial conditions

The daily model simulated total rainfall on 04 July 2017 for different CP schemes in combination with WDM6 scheme with the initial conditions of 0000 UTC of 03 July are presented in Figure 6(a-l). The KF scheme has simulated VHR (Figure 6a) in the eastern to SE, N-NW and NE regions and MHR in the western regions. Maximum rain is simulated at Cumilla, Cox-Bazar, Feni, Hatiya, Ishwardi, Kutubdia, Mymensingh, Rangpur, Sandwip, Sitakunda, Sylhet and Teknaf regions are 192, 156, 246, 116, 131, 148, 123, 130, 152, 159, 141 and 149 mm respectively. The KF scheme is found to match with observed VHR at Cox Bazar and Teknaf regions and other regions have simulated significant high amount of total rainfall those regions could not match. The BMJ scheme has simulated VHR (Figure 6b) in the SE regions, HR in the NE regions, MHR in the southern and eastern regions and LR in the other regions of Bangladesh. Maximum total rainfall is found at Chittagong, Hatiya, Kutubdia, Rangamati and Sitakunda regions are 206, 105, 95, 122 and 123 mm respectively. The total rainfall simulated by BMJ scheme is matched with observed total rainfall at Kutubdia and Sitakunda stations and all other stations have simulated higher or lower total rainfall than that of observed. The GF scheme has simulated VHR (Figure 6c) eastern and southern regions, HR in the western to SW regions, MHR in the SE and NW regions and MHR in all other regions of Bangladesh. Maximum Total rainfall is simulated at Chandpur, Feni, Khepupara, Mymensingh and Tangail regions are 91, 151, 90, 93 and 93 mm respectively. The GF scheme is found to match in the southern and SE regions, but the position of heavy rainfall region is shifted towards north-NW than that of observed.

The OSAS scheme has simulated MHR to HR (Figure 6d) all over Bangladesh except eastern region. Maximum rain is simulated at Cox-Bazar, Hatiya, Kutubdia, Sylhet, Tangail and Teknaf regions are 63, 49, 50, 47, 49 and 49 mm respectively. This position of simulated total rainfall by this scheme is found to match with the observed position in the SE and NE regions but the amount is not significant. The G-3 scheme has simulated VHR (Figure 6e) in the eastern and NE regions, HR in the SW to SE and NW regions and MR in the other regions of the country. Maximum rain is simulated at Chandpur, Cumilla, Patuakhali, Sitakunda and Teknaf regions are 103, 155, 96, 159 and 91 mm respectively. This position of simulated total rainfall by this scheme is found to match with the observed position of VHR and HR in the SE regions and it also shifted from Feni to Chandpur regions. The TD scheme has simulated VHR (Figure 6f) in the NE region, HR in the eastern and SE regions and light rain in the central to W-SW regions of Bangladesh. Maximum rain is simulated at Chittagong, Cox-Bazar, Hatiya, Kutubdia, Sitakunda and Sylhet regions are 62, 69, 59, 73, 66, 97 mm respectively. This position of simulated HR by TD scheme is found to match with the observed position in the NE and SE regions but it shifted from Teknaf to Cox- Bazar.

The ZM scheme has simulated HR (Figure 6g) in north of Dhaka and SE regions, MHR in the western and MR in the in other regions of Bangladesh. Maximum rain is simulated at Cox-Bazar, Feni, Sitakunda and Teknaf regions are 56, 62, 55 and 60 mm respectively. This position of simulated HR by ZM scheme is not match with the observed position. The MSKF scheme has simulated VHR (Figure 6h) all over Bangladesh except few regions. Maximum rain is simulated at Chandpur, Dinajpur, Jashore, Khepupara, Mymensingh, Sandwip and Sitakunda regions are 106, 102, 109, 105, 136, 151 and 126 mm respectively.

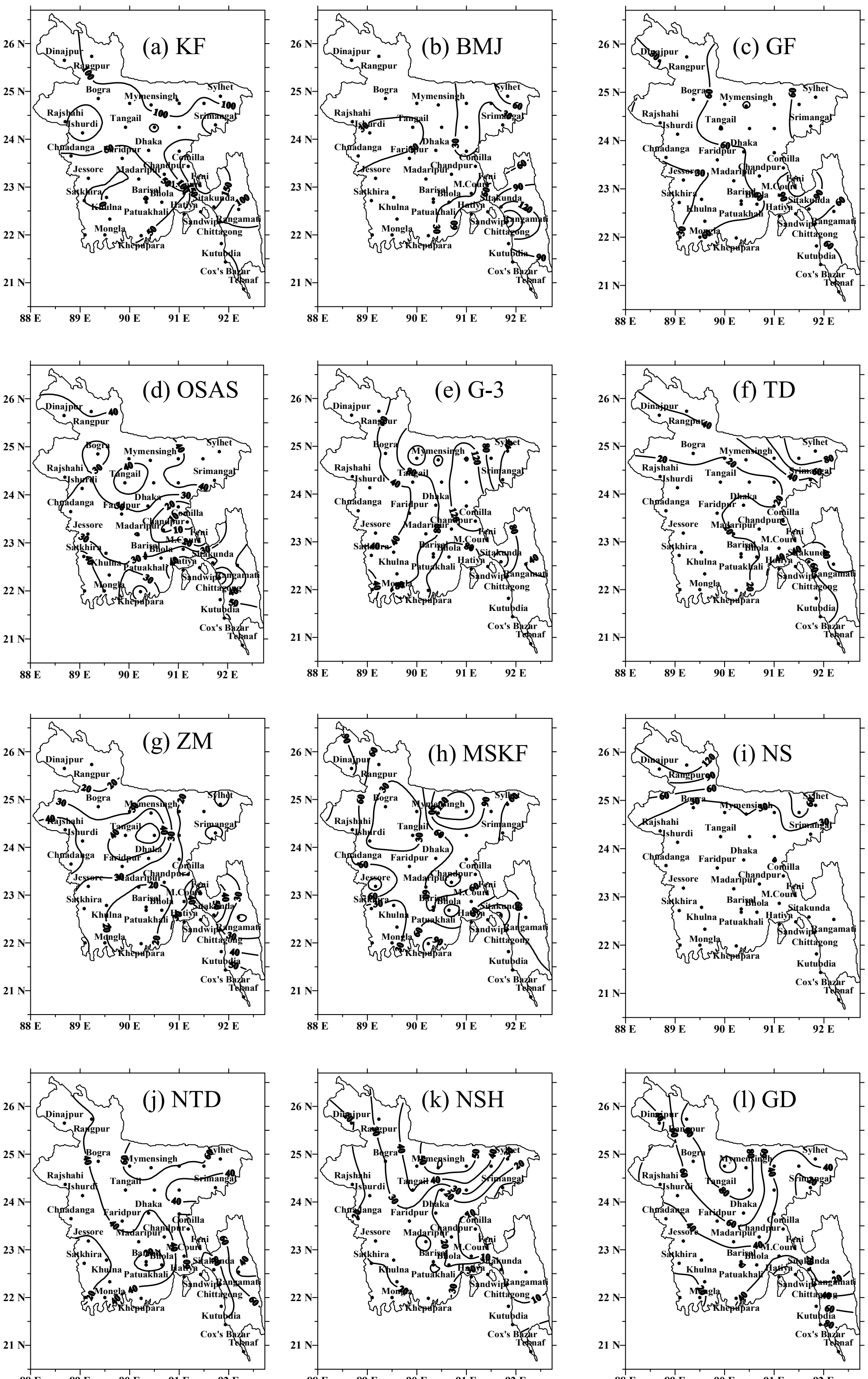

Figure 6: Spatial distribution of model simulated daily total rainfall using different CP schemes in combination with WDM6 scheme on 04 July with the initial conditions at 03 July 2017 all over Bangladesh.

The MSKF is found to match with observed HR at Sitakunda and in other regions the scheme has not matched. The NS scheme has simulated VHR (Figure 6i) in the NW region and HR in the NE regions and LR in all other regions of Bangladesh. Maximum total rainfall is simulated at Sylhet, Dinajpur and Rangpur regions are 50, 112 and 148 mm respectively. This position of simulated HR by NS scheme is not match with the observed position. The NTD scheme has simulated VHR (Figure 6j) in the SE regions, HR in the eastern, southern and north to NE regions and MHR in the other regions of Bangladesh. Maximum rain is simulated at Chittagong, Cumilla, Feni, Kutubdia, Sandwip, Sitakunda and Teknaf regions are 95, 77, 79, 95, 84, 96 and 72 mm respectively. This position of simulated HR by NTD scheme is found to match with the observed total rainfall position and also match with its amount.

The NSH scheme has simulated HR (Figure 6k) in the northern regions, MHR in the S-SE and W-NW and LR in the eastern regions and MR in the other regions of Bangladesh. Maximum rain is simulated at Hatiya, Mymensingh, Sandwip and Teknaf regions are 43, 61, 45 and 40 mm respectively. This scheme has not matched with the observed total rainfall. The GD scheme has simulated VHR (Figure 6l) in the N-NW and SE regions, HR in the southern, western and E-NE regions, and MHR in the other regions of Bangladesh. Maximum rain is simulated at Cox-Bazar, Dhaka, Hatiya, Mymensingh, Rangpur, Sandwip, Tangail and Teknaf regions are 85, 70, 74, 93, 91, 79, 78 and 95 mm respectively. The GD scheme is matched with the observed HR at Teknaf regions and all other regions it has not matched.

The model simulated maximum total rainfall and its position for different cumulus schemes are found to match with observed heavy to VHR in the S-SE and E-NE regions, Among these KF, G-3 and NTD scheme have shown better performance all over Bangladesh and BMJ, OSAS and TD schemes in the NE regions at 48 hour prediction.

4.1.6 Model simulated daily rain on 05 July with 04 July initial conditions

The spatial distribution of station wise BMD observed total rainfall on 05 July 2017 all over Bangladesh is presented in Figure 2(c).The VHR is observed (Figure2c) in the SE regions, HR at Bogura, Ishwardi and southern region, MHR in the central, western and northern regions and LR in the other regions of Bangladesh. Maximum total rainfall observed at Cox-Bazar, Teknaf, Kutubdia, Feni, Mongla and Bogura regions are 241, 181, 124, 79, 74 and 72mm respectively. The daily model simulated total rainfall on 05 July 2017 for different CP schemes in combination with WDM6 microphysics scheme with the initial conditions of 0000 UTC of 04 July are presented in Figure 7(a-l).

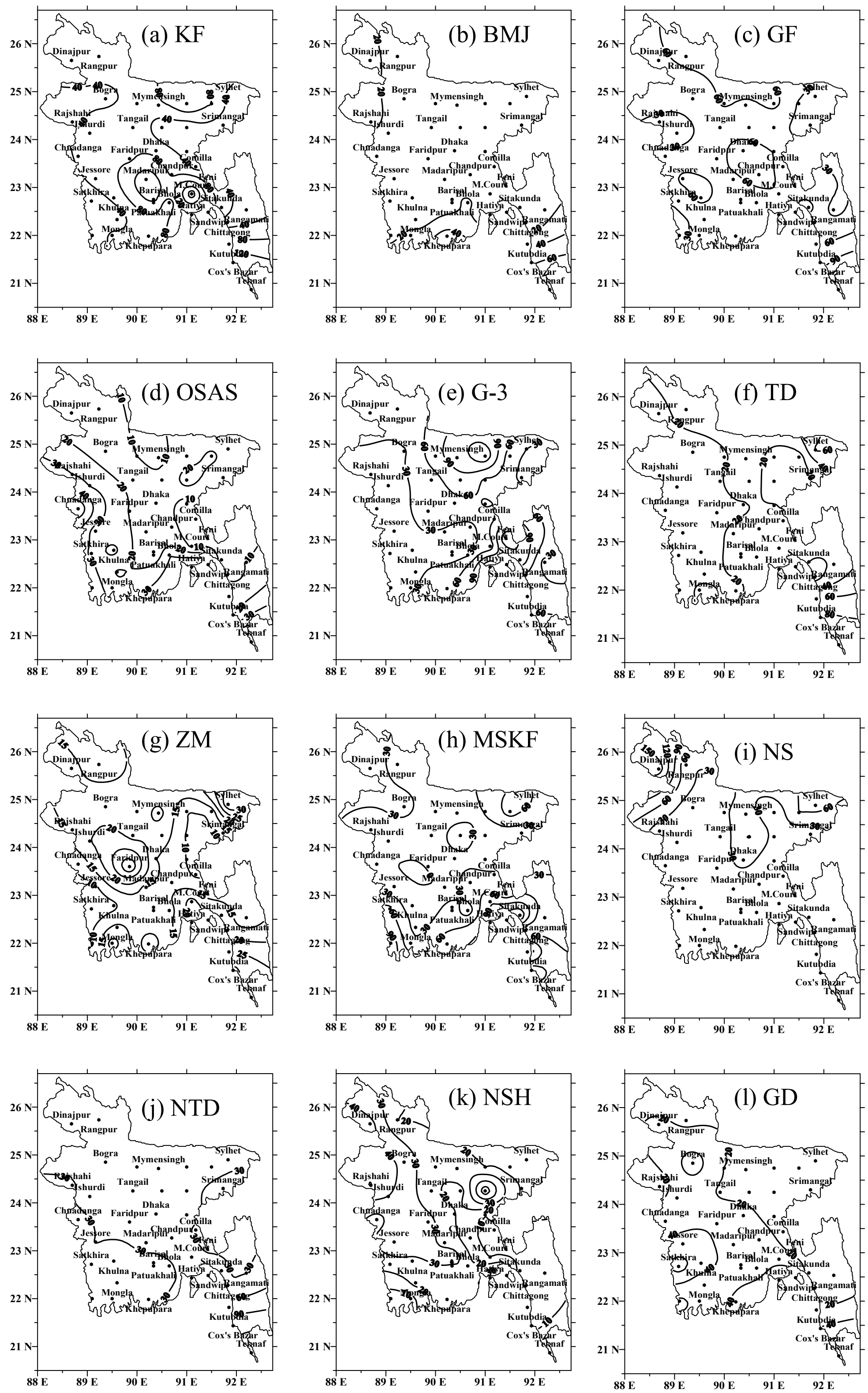

Figure 7: Spatial distribution of model simulated daily total rainfall using different CPs in combination with WDM6 scheme on 05 July with the initial condition at 04 July 2017 all over Bangladesh.

The KF scheme has simulated VHR to HR (Figure 7a) in the S-SE, N-NE and western region, LR in the SW regions, moderate to MHR in the other regions of Bangladesh. Maximum rain is simulated at M. Court, Teknaf, Madaripur, Cox-Bazar, Barishal, Hatiya, Patuakhali and Kutubdia regions are 229, 175, 154, 150, 137, 117, 106 and 99 mm respectively. KF scheme is matched with the observed HR in the SE regions and similar amount of total rainfall is simulated in the central region. The BMJ scheme has simulated total rainfall (Figure 7b) in the S-SE regions and western regions of Bangladesh. Maximum total rainfall is found at Cox-Bazar, Khepupara and Teknaf regions are 57, 50 and 102 mm respectively. BMJ scheme is matched only at Teknaf region and it would not match in other regions.

The GF scheme has simulated VHR (Figure 7c) in the SE regions, MHR in the N-NW regions and HR in the other regions of Bangladesh. Maximum total rainfall is simulated at Teknaf, Dhaka, Chandpur, Cox-Bazar, Khulna, Sitakunda and regions are 181, 89, 78, 73, 71 and 70 mm respectively. The observed and model simulated by using GF scheme are similar at Teknaf. The total rainfall simulated by GF scheme has not matched in all other regions of Bangladesh. The OSAS scheme has simulated MHR (Figure 7d) in the S-SE and western region, MR in the SW regions and LR in the northern and eastern regions of Bangladesh. Maximum total rainfall is simulated at Teknaf and Chuadanga regions are 63 and 59 mm respectively. The OSAS scheme has simulated moderate to moderately heavy rain all over but no heavy rain anywhere in the country.

The G-3 scheme has simulated VHR and HR (Figure 7e) in the S-SE and northern regions and MR in the W-SW to NW regions of Bangladesh. Maximum rain is simulated at Hatiya, Feni, Sitakunda, Mymensingh and Teknaf regions are 162, 148, 119, 106 and 92 mm respectively. The G-3 scheme is match with observed HR position in the S-SE region but the amount of total rainfall is not matched. The TD scheme has simulated HR (Figure 7f) in the NE and SE region, light rain in the W-SW and NW regions and MR in other regions of Bangladesh. Maximum rain is simulated at Teknaf, Cox-Bazar, Kutubdia and Sylhet regions are 93, 83, 68 and 62mm respectively. The simulated total rainfall by TD scheme is matched with the observed total rainfall in the SE and NE regions but the amount is not matched. The ZM scheme has simulated MR (Figure 7g) in the NE and SE regions and LR in the western and SW regions of Bangladesh. Maximum rain is simulated at Cox-Bazar, Faridpur, and Sylhet regions are 31, 35 and 35 mm respectively.

The MSKF scheme has simulated heavy to VHR (Figure 7h) in the S-SE, SW and NE regions, LR at western and northern regions and MR in other regions of Bangladesh. Maximum rain is simulated at Hatiya, Kutubdia, Sandwip, Sitakunda and Teknaf regions are

112, 159, 136, 149 and 98 mm respectively. The simulated heavy rainfall position and amount by MSKF scheme is almost matched with the observed rain in the S-SE regions.

The NS scheme has simulated heavy to VHR (Figure 7i) in the NW and NE region and LR in other regions of Bangladesh. Maximum total rainfall is simulated at Dinajpur and Sylhet are 169and 72 mm respectively. NS scheme has not matched with the observed heavy to VHR position and amount all over Bangladesh. The NTD scheme has simulated HR (Figure 7j) in the SE regions and MR in other regions of Bangladesh. Maximum total rainfall is simulated at Teknaf, Cox-Bazar, Kutubdia and Sandwip regions are 155, 103, 81 and 75mm respectively. The NTD scheme is matched with the observed rain in the SE regions but the amount of rain is not matched. The NSH scheme has simulated moderate to MHR (Figure 7k) in the central to western regions and light rain in other regions of Bangladesh. Maximum rain is simulated at Rajshahi and Sandwip regions are 50 and 48 mm respectively. The GD scheme has simulated MHR (Figure7l) in the SW and SE regions, LR in the central to NE and eastern regions and MR in other regions of Bangladesh. Maximum rain is simulated at Hatiya, Satkhira and Teknaf regions are 63, 70 and 87 mm respectively. The simulated total rainfall by GD scheme is not matched with the observed total rainfall.

The model simulated maximum total rainfall and its position for different cumulus schemes are found to match with observed heavy to VHR in the S-SE and NE regions, but amount is not match. Among these G-3 and MSKF scheme have shown better performance all over Bangladesh at 48 hour prediction.

4.1.7 Model simulated daily rain on 05 July with 03 July initial conditions

The daily model simulated total rainfall on 05 July 2017 for different CP schemes in combination with WDM6 microphysics scheme with the initial conditions of 0000 UTC of 03 July are presented in Figure 7(a-l).The KF scheme has simulated VHR (Figure 8a) in the central to eastern, northern, NE and SE regions, HR in the NW regions, moderate to MHR in the southern regions and LR in the western regions of Bangladesh. Maximum rain is simulated at Cumilla, Chandpur, Teknaf, Mymensingh, Dhaka and M.Court regions are 222, 190, 171, 139, 135 and 116 mm respectively. The simulated total rainfall by KF scheme has not matched with the observed heavy rainfall region. The BMJ scheme has simulated VHR (Figure 8b) in the NW regions and observed heavy rain is found in the SE region. Maximum total rainfall is simulated at Dinajpur regions are 118 mm. The GF scheme has simulated VHR (Figure 8c) in the SE regions, HR in the southern regions, MHR in the western, N-NW and NE regions and MR in all other regions of Bangladesh. Maximum Total rainfall at Cox-

Bazar, Teknaf, Dhaka, M.Court and Rangpur regions are 110, 93, 82, 77 and 63 mm respectively. The GF scheme is matched with the observed rain in the SE regions but the amount of total rainfall is not matched. The OSAS scheme has simulated MHR (Figure 8d) in the western region and LR in all other regions of Bangladesh. Maximum rain is found at Chuadanga, Hatiya, Jashore and Khulna regions are 46, 46, 44 and 44 mm respectively.

The G-3 scheme has simulated VHR (Figure 8e) in the central to northern, NW and NE regions, HR in the southern and eastern regions and MHR in the western and SW regions of Bangladesh. Maximum rain is found at Bogura, Cox-Bazar, M.Court, Mymensingh and Tangail regions are 192, 96, 174, 190 and 126 mm respectively. The observed VHR is found in the SE region but G-3 scheme is simulated in the northern regions. The TD scheme has simulated HR (Figure 8f) in the SE and NW region, MHR in the N-NE regions and LR in the SW regions of Bangladesh. Maximum rain is simulated at Cox-Bazar, Hatiya, Kutubdia, Rangpur and Teknaf regions are 77, 84, 61, 60, and 69 mm respectively. TD scheme is matched with the position of observed HR but amount is not matched in the SE regions and it also shifted from Bogura to Rangpur regions. The ZM scheme has simulated HR (Figure 8g) in the southern regions, MHR in the NW regions of Bangladesh. Maximum rain is simulated at Dinajpur and Mongla regions are 40 and 53 mm respectively. The MSKF scheme has simulated VHR (Figure 8h) in the western, southern and SE regions, HR in the E-NE regions and MHR in the other regions of Bangladesh.

Maximum rain is simulated at Jashore, Teknaf, Madaripur, Chuadanga, Sitakunda and M. Court regions are 189, 129, 107, 101, 101 and 99 mm respectively. The simulated HR by MSKF scheme is matched with observed total rainfall at Teknaf. The NS scheme has simulated heavy to VHR (Figure 8i) in the W-NW region and all other regions have no rain occurred. Maximum total rainfall is simulated at Rangpur, Dinajpur, Rajshahi and Bogura regions are 163, 127, 102 and 91 mm respectively. NS scheme is found to match with the observed HR in the NW region. The NTD scheme has simulated heavy to VHR (Figure 8j) in the S-SE and northern regions of Bangladesh. Maximum rain is found at Teknaf, Cox-Bazar, Kutubdia and Sandwip regions are 125, 83, 79 and 70 mm respectively. The simulated position of HR using NTD scheme is same as observed in the southern and SE regions but amount is not same. The NSH scheme has simulated MHR (Figure 8k) in the NW regions, MR in the southern regions and LR in the eastern regions of Bangladesh. Maximum rain is simulated at Bogura, Chuadanga, Dinajpur and Rajshahi regions are 40, 40, 45 and 50 mm respectively. The GD scheme has simulated HR (Figure 8l) in the central to southern, western and NW regions and MR in the eastern regions of Bangladesh.

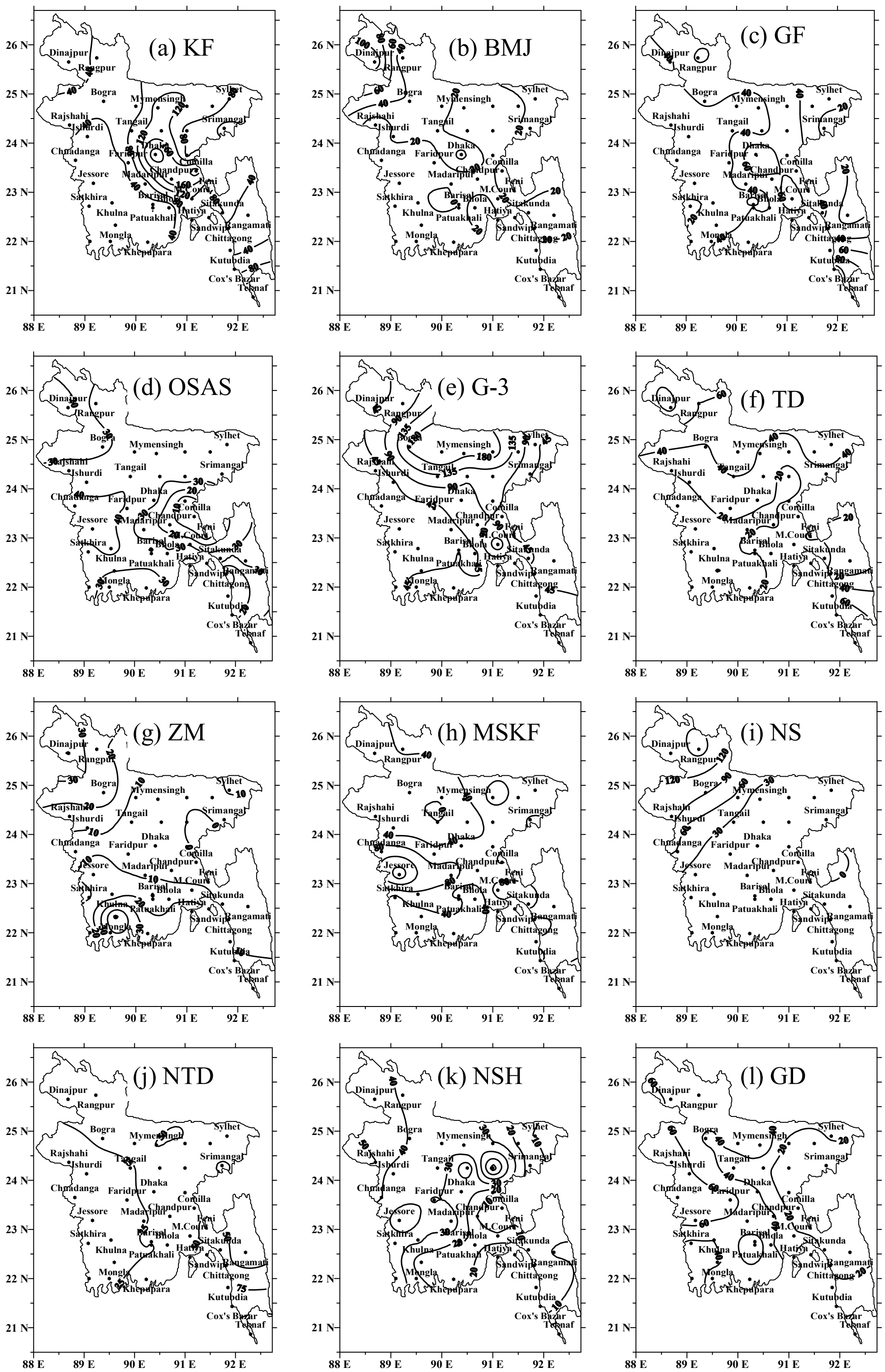

Figure 8: Spatial distribution of model simulated daily total rainfall using different CPs in combination with WDM6 scheme on 05 July with the initial conditions at 03 July 2017 all over Bangladesh.

Maximum rain is simulated at Barisal, Chuadanga, Faridpur, Patuakhali, Rajshahi, Sandwip and Teknaf regions are 70, 79, 70, 79, 76, 78 and 60 mm respectively. GD scheme is not matched with observed HR. The model simulated maximum total rainfall and its position for different cumulus schemes are found to match with observed heavy to VHR in the S-SE, E-NE and NW regions, Among these KF, GF, G-3, MSKF and GD scheme have shown better performance all over Bangladesh and BMJ, NS, NSH schemes in the NW regions, TD and NTD in the SE regions at 72 hour prediction.

4.1.8 Model simulated daily Convective rain on 03 July

The spatial distribution of model simulated daily convective rain (CR) on 03 July 2017 for different cumulus schemes with the initial conditions of 0000 UTC of 03 July is presented in Figure 9(a-l). The KF scheme has simulated very heavy convective rain (VHCR) (Figure 9a) in the SE regions, heavy convective rain (HCR) in the eastern and N-NE regions, moderately heavy convective rain (MHCR) in the NW regions of the country. Maximum CR is found at Chittagong, Cox-Bazar, Kutubdia, Sitakunda and Teknaf regions are 127, 128, 84, 104 and 135 mm respectively during 24 hour period. The maximum rain simulated by KF scheme in the SE and NE region of Bangladesh mainly convective.BMJ scheme has simulated LCR (Figure 9b) in the western and SW regions and no CR in all other regions of Bangladesh. The simulated maximum CR at Chuadanga, Ishwardi and Rajshahi regions are 10, 12 and 12 mm respectively. BMJ scheme has not simulated any CR in the SE region on 03 July, where VHR observed. The GF scheme has simulated MHCR (Figure 9c) in the southern and northern regions and MCR all other regions of Bangladesh. The simulated maximum CR at Bogura, Chittagong, Cox-Bazar, Hatiya, Khepupara, Mymensingh, Sandwip and Sitakunda regions are 54, 59, 53, 63, 56, 62 and 68 mm respectively. The CR have simulated all over Bangladesh. The maximum region of Bangladesh has simulated higher CR than that of observed rain but heavy rain region have simulated insignificant CR. The OSAS scheme has simulated HCR (Figure 9d) in the south to SE region and MCR in other regions of Bangladesh. Maximum CR is simulated at Cox-Bazar, Hatiya, Kutubdia, Sandwip and Teknaf regions are 62, 56, 61, 67 and 61 mm respectively. The G-3 scheme has simulated HCR (Figure 9e) in the southern, NE and S-SE regions, LCR in the western regions, MCR in the other regions of Bangladesh. Maximum CR is simulated at Chittagong, Cox-Bazar, Khepupara, Kutubdia, Sitakunda and Teknaf regions are 81, 69, 80, 78, 79 and 72 mm respectively. Maximum total rainfall observed at Chittagong, Cox's Bazar, Hatiya, Khepupara, Rangamati, Sandwip and Sitakunda regions are 143, 151, 153, 195, 120, 113 and 142 mm respectively.

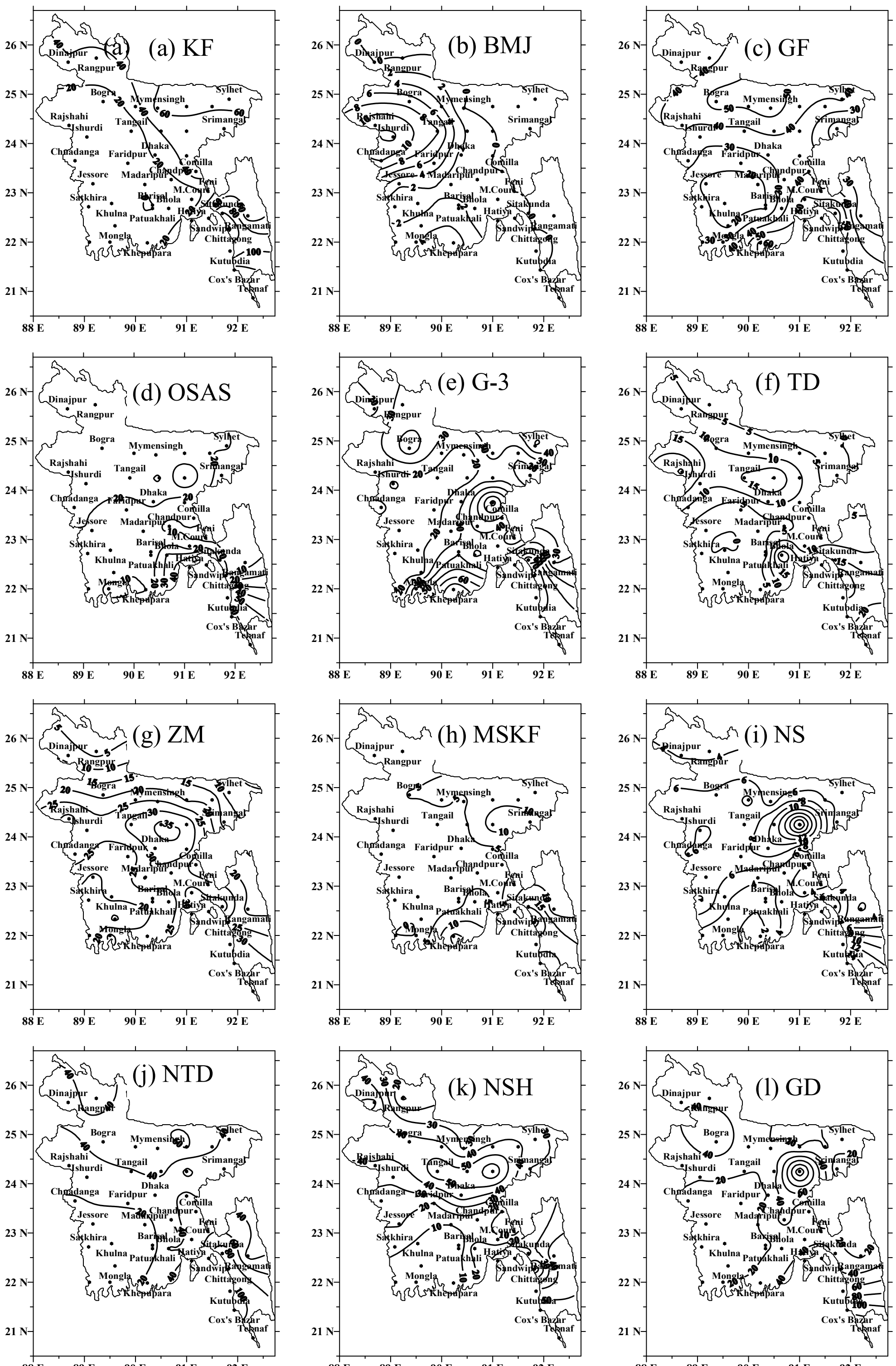

Figure 9: Spatial distribution of model simulated daily CR using different CP schemes in combination with WDM6 scheme on 03 July 2017 all over Bangladesh.

The TD scheme has simulated MCR (Figure 9f) in the S-SE and central to western regions and LCR in all other regions. Maximum CR at Bhola, Chittagong, Kutubdia, Rajshahi and

Teknaf regions are 25, 24, 20, 26 and 30 mm respectively. The simulated maximum CR is insignificant in comparison with the observed total rainfall. The ZM scheme has simulated light CR (Figure 9g) in the Dinajpur, Rangpur and Sylhet regions and rest of the regions have simulated MCR to MHCR. The maximum CR at Cox-Bazar, Hatiya, Kutubdia, Sandwip and Teknaf region is 33, 31, 36, 29 and 36 mm. The rain simulated by ZM scheme mainly convective in the central region but in the heavy rain area the rain is not convective. The MSKF scheme has simulated MCR at Chittagong and Cox's Bazar region, LCR (Figure 9h) in the S-SE and N-NE region and no CR in all other regions of Bangladesh. The simulated maximum CR at Chittagong and Cox-Bazar regions are 28 and 26 mm. The simulated maximum CR is insignificant in comparison with the observed total rainfall. The NS scheme has simulated MCR (Figure 9i) at Cox-Bazar, north east of Dhaka, Kutubdia, Sandwip and Teknaf regions and LCR in all other regions of Bangladesh. Maximum CR at Cox-Bazar, Dhaka, Kutubdia, Sandwip and Teknaf regions are 15, 10, 13, 11 and 14 mm respectively. The simulated maximum CR is insignificant in comparison with the observed total rainfall.

The NTD scheme has simulated VHCR (Figure 9j) in the SE regions and HCR in the eastern, N-NW regions, moderate to MHCR in the western, NE and southern regions and LCR in the SW regions of Bangladesh. Maximum CR is simulated at Chittagong, Cox-Bazar, Kutubdia, Sitakunda and Teknaf regions are 100, 108, 108, 99 and 91 mm respectively. The observed rain in the central and SE region mainly convective but in the southern region the rain is not convective. The NSH scheme has simulated HCR (Figure 9k) in the SE and NE of Dhaka, MHCR in the western, northern and NE regions, and light CR in the SW regions of Bangladesh. The simulated maximum CR at Bogura, Cox-Bazar, Dhaka, Dinajpur, Kutubdia, Sandwip and Teknaf regions are 44, 56, 47, 52, 44, 51, and 49 mm respectively. The observed rain in the central and Bogura region mainly convective but in the S-SE region the rain is not convective. The GD scheme has simulated VHCR (Figure 9l) in the SE and NE of Dhaka, HCR in the NW and eastern regions, light CR in the SW regions, MHCR and MCR in the other regions of Bangladesh. The maximum CR simulated at Bogura, Cox-Bazar, Hatiya, Kutubdia, Sandwip and Teknaf are 56, 117, 52, 60, 85 and 146 mm respectively. The observed rain in the central, Bogura and SE region mainly convective but in the southern region the rain is not convective.

4.1.9 Model simulated daily Convective rain on 04 July

The model simulated daily CR on 04 July 2017 for different cumulus schemes with the initial conditions of 0000 UTC of 04 July are presented in Figure 10(a-l). The KF scheme has simulated HCR (Figure 10a) in the SE regions, MHCR in the southern, N-NE regions, MCR in the NW regions and LCR in the western regions of the country. Maximum CR is simulated at Chittagong, Cox-Bazar, Kutubdia, M. Court, Mymensingh, Sandwip and Teknaf regions are 54, 125, 118, 63, 64, 61 and 112 mm respectively during 24 hour period. The BMJ scheme has simulated LCR (Figure 10b) all over Bangladesh. The simulated maximum CR at Hatiya is 14 mm. The GF scheme has simulated HCR (Figure 10c) in the southern, eastern to SE regions, MCR in the western to SW regions, MHCR in the other regions of Bangladesh. The simulated maximum CR at Cox-Bazar, Feni and Kutubdia regions is 56, 52 and 55 mm respectively. The OSAS scheme has simulated HCR (Figure 10d) in the SE region, MHCR in the southern and NE regions and LCR in the other regions of Bangladesh. Maximum CR is simulated at Cox-Bazar, Hatiya, Kutubdia, Sandwip and Teknaf regions are 62, 56, 61, 57 and 61 mm respectively. The G-3 scheme has simulated HCR (Figure 10e) in the southern to SE regions, MHCR in the N-NW and NE regions, moderate CR in the western to SW regions of Bangladesh. Maximum CR is simulated at Chittagong, Cox-Bazar, Faridpur, Feni, Kutubdia, Sitakunda and Teknaf regions are 61, 67, 50, 63, 52, 80 and 77 mm respectively.

The TD scheme has simulated MHCR (Figure 10f) in the NW and SE regions, MCR in the NE regions and no CR in the central to SW regions of Bangladesh. Maximum CR at Kutubdia regions is 43 mm. The ZM scheme has simulated MCR (Figure 10g) all over Bangladesh. The maximum CR at Teknaf is 34 mm. The MSKF scheme has simulated MCR (Figure 10h) in the SE regions, light CR in the NE regions and no CR in the maximum regions of Bangladesh. The simulated maximum CR at Teknaf regions is 30 mm. The NS scheme has simulated MCR (Figure 10i) all over Bangladesh except SW regions, where no CR is simulated. Maximum but insignificant CR at Cox-Bazar regions is 17 mm. The NTD scheme has simulated VHCR and HCR (Figure 10j) in the southern and SE regions and MCR and in the western to SW regions and MHCR in the other regions of Bangladesh. Maximum CR is simulated at Chittagong, Hatiya, M. Court, Sandwip, Sitakunda, Sylhet and Teknaf regions are 114, 82, 65, 50, 56 and 91 mm respectively. The NSH scheme has simulated MHCR (Figure 10k) in the NE and SE regions, MCR in the southern, N-NW regions and LCR in the western to SW regions of Bangladesh. The simulated maximum CR at Cox-Bazar, Sandwip and Teknaf regions are 37, 37 and 44 mm respectively.

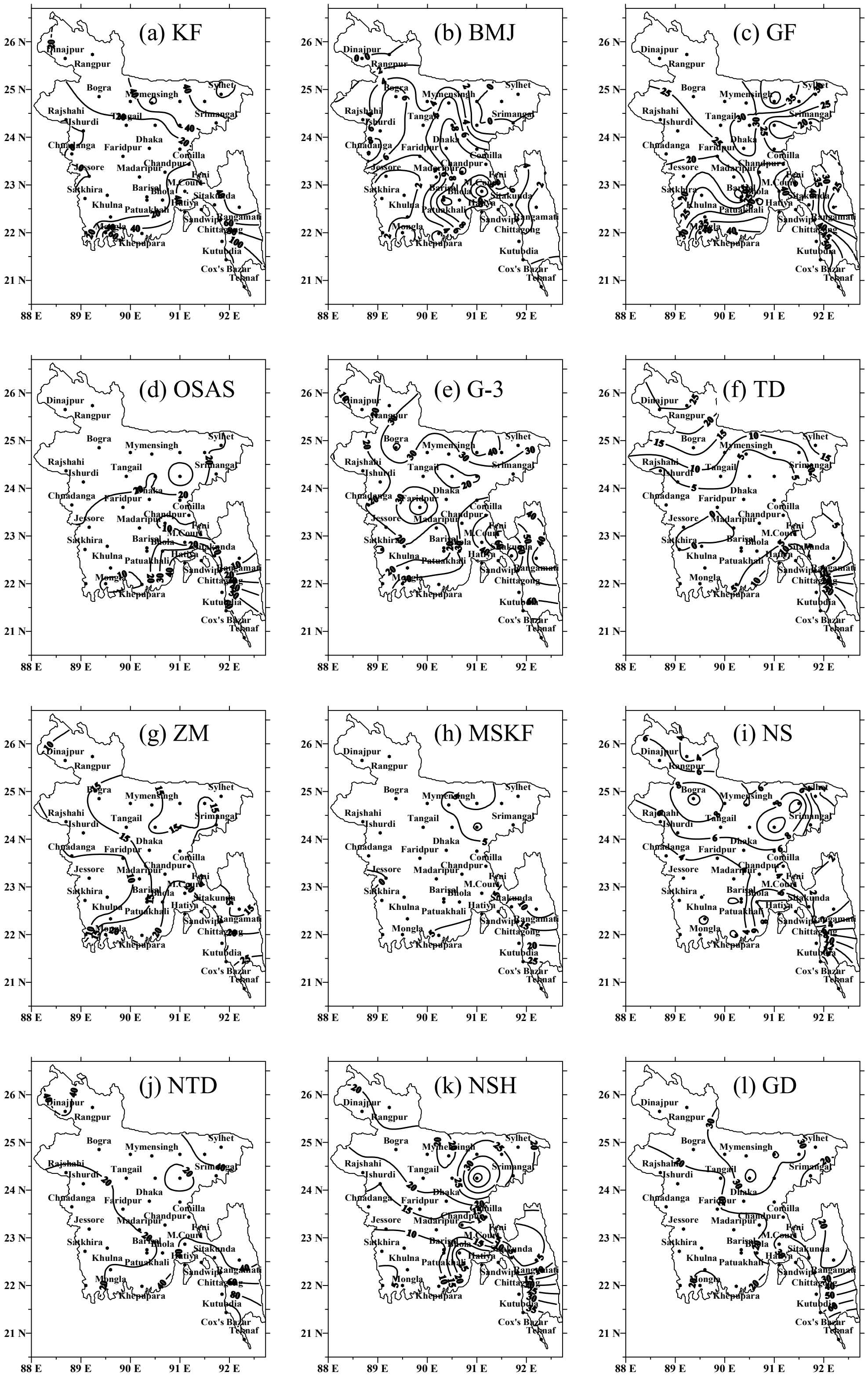

Figure 10: Spatial distribution of model simulated daily CR using a) KF, b) BMJ, c) GF, d) OSAS, e) G-3, f) TD, g) ZM, h) MSKF, i) NS, j) NTD, k) NSH and l) GD schemes in combination with WDM6 scheme on 04 July 2017.

The GD scheme has simulated HCR (Figure 10l) in the SE regions, MHCR in the northern to NW and NE regions, MCR in the other regions of Bangladesh. The maximum CR is simulated in the Kutubdia, Mymensingh, Sandwip and Teknaf are 58, 43, 51 and 108 mm respectively.

4.1.10 Model simulated daily Convective rain on 05 July

The spatial distribution of model simulated daily CR on 05 July 2017 for different cumulus schemes with the initial conditions of 0000 UTC of 05 July is presented in Figure 11(a-l). The KF scheme has simulated HCR (Figure 11a) in the SE and NE regions, MCR in the western and eastern regions, no CR in the SW and NW regions. The distribution pattern also gives the information that it increased continuously from center towards NE and SE regions Maximum CR is found at Cox-Bazar, Srimangal, Tangail and Teknaf regions are 45, 50, 40 and 88 mm respectively during 24 hour period. The rain simulated by KF scheme mainly convective from central N-NE regions of Bangladesh. The BMJ scheme has simulated LCR (Figure 11b) all over Bangladesh. The amount of CR is insignificant in comparison with the observed total rainfall. The GF scheme has simulated moderate to MHCR (Figure 11c) all over Bangladesh. The CR is simulated maximum at Cox-Bazar, Kutubdia, Mymensingh, Sitakunda and Teknaf regions are 36, 36, 40, 37 and 43 mm respectively. The rainfall simulated by GF scheme mainly convective all over the country but it could not simulate heavy to VHR in different regions of the country.

The OSAS scheme has simulated moderate to MHCR (Figure 11d) all over Bangladesh. Maximum CR is simulated at Hatiya, Rangpur, Sandwip, Tangail and Teknaf regions are 44, 30, 33, 33 and 37 mm respectively. The rainfall simulated by OSAS scheme mainly convective all over the country but it could not simulate heavy to VHR in different regions of the country. The G-3 scheme has simulated moderate to MHCR (Figure 11e) all over Bangladesh. Maximum CR at Chittagong, Cox-Bazar, Khepupara, Sitakunda and Teknaf regions are 40, 46, 48, 49, and 75 mm respectively. The rainfall simulated by G-3 scheme mainly convective all over the country but it could not simulate heavy to VHR in different regions of the country. The TD scheme has simulated MCR (Figure 11f) in the N-NW regions and LCR in other regions of Bangladesh. Maximum CR at Barishal, Bogura, Dhaka, Srimangal and Teknaf regions are 15, 17, 17, 16 and 23 mm respectively. The rainfall simulated by TD scheme mainly convective in the central region but it could not simulate heavy to VHR in different regions of the country.

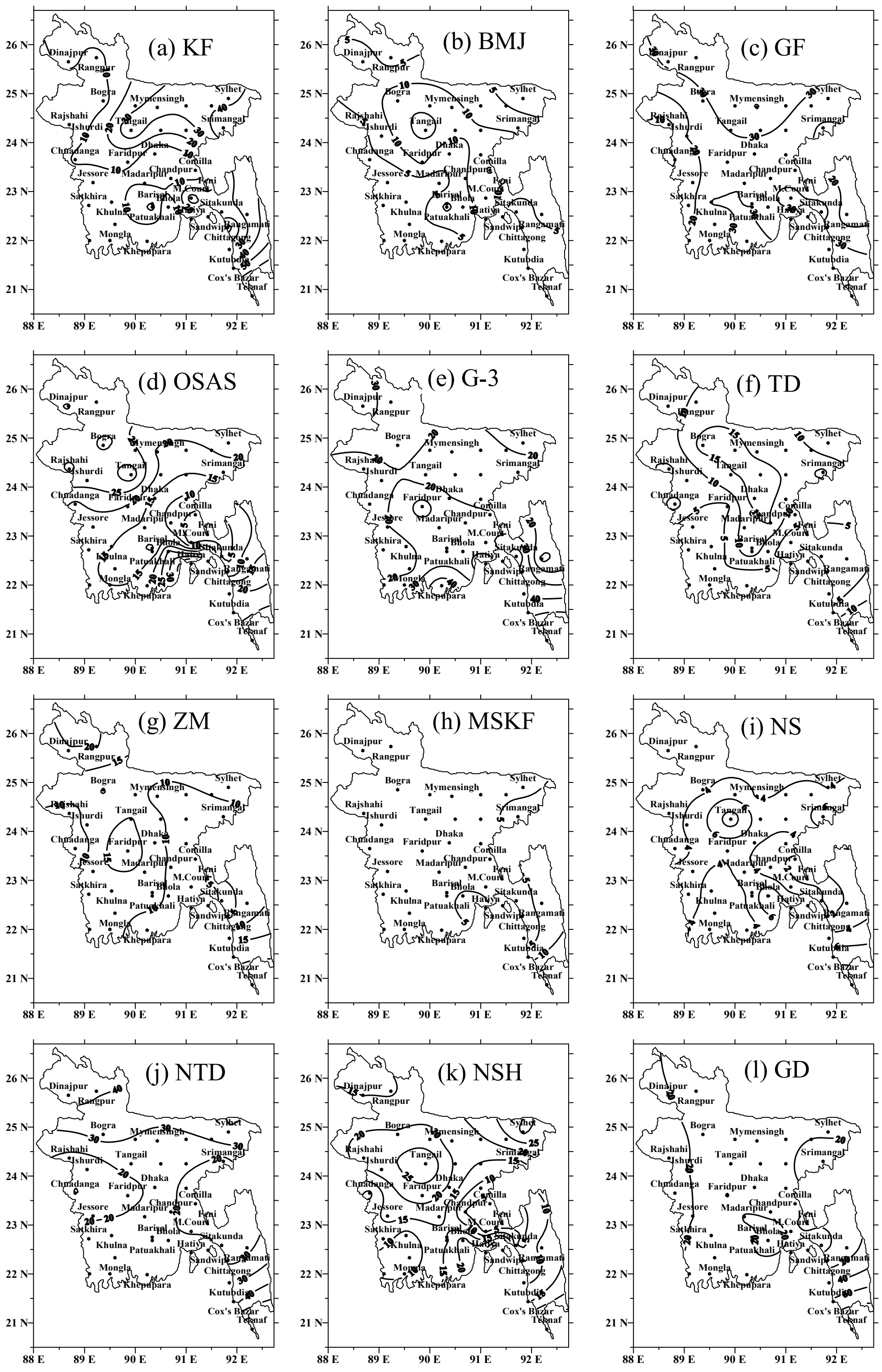

Figure 11: Spatial distribution of model simulated daily CR using different CP schemes in combination with WDM6 scheme on 05 July 2017 all over Bangladesh.

Faridpur, Rangpur and Teknaf region are 18, 20, 19, 20 and 25 mm. The MSKF scheme has simulated LCR (Figure 11h) only in the SE region of Bangladesh and maximum at Teknaf is

21 mm. The NS scheme has simulated LCR (Figure 11i) all over Bangladesh and which is insignificant in comparison with observed rain. The NTD scheme has simulated MHCR (Figure 11j) all over Bangladesh.

Maximum CR is simulated at Dinajpur, Rangpur, Sylhet and Teknaf regions are 44, 41, 40 and 73 mm respectively. The rainfall simulated by NTD scheme mainly convective in the central to NW and NE region but it could not simulate heavy to VHR in SE regions of the country. The ZM scheme has simulated MCR (Figure 11g) in the S-SE and central to NW regions and LCR in the other regions of Bangladesh. The NSH scheme has simulated moderate to MHCR (Figure 11k) all over Bangladesh. The CR is simulated maximum at Sandwip, Sylhet, Tangail and Teknaf regions are 48, 31, 30 and 33 mm respectively. The rainfall simulated by NSH scheme mainly convective in the central to NE region but it could not simulate heavy to VHR in the SE regions of the country. The GD scheme has simulated heavy to VHCR (Figure 11l) in the SE regions and MCR in other regions of Bangladesh. The maximum CR simulated at Cox-Bazar, Faridpur, Kutubdia and Teknaf are 63, 41, 42 and 117 mm respectively. The rainfall simulated by GD scheme mainly convective in the central to NE and SE regions but it could not simulate heavy to VHR in the SE regions of the country.

4.1.11 Model simulated daily Non-Convective rain on 03 July

The spatial distribution of model simulated daily NCR on 03 July 2017 for different cumulus schemes with the initial conditions of 0000 UTC of 03 July is presented in Figure 12(a-l).The KF scheme has simulated HNCR (Figure 12a) at Bogura regions, MNCR at SE and NE regions and no NCR in the central S-SW and eastern regions of Bangladesh. Maximum NCR at Bogura and Teknaf regions are 60and 31 mm respectively. The rainfall simulated by KF scheme mainly non-convective at Bogura region and other region it is convective. The BMJ scheme has simulated moderate to MHNCR (Figure 12b) in the N-NW, NE and SE regions and no NCR in other regions of Bangladesh. The simulated maximum NCR at Bogura, Dinajpur, Rangpur, Sylhet, Tangail and Teknaf regions are 56, 48, 65, 75, 53 and 65 mm respectively. The rainfall simulated by BMJ scheme mainly non-convective all over the country. The GF scheme has simulated MNCR (Figure 12c) in the N-NE, NW and Hatiya-Sitakunda regions and no NCR all other regions of Bangladesh. The simulated maximum NCR at Mymensingh region is 32 mm. The OSAS scheme has simulated little NCR (Figure 12d) only at Rangpur region and no NCR have found in other regions.

The G-3 scheme has simulated moderately heavy to HNCR (Figure 12e) in the SE region, MNCR in the E-NE and NW regions and LNCR in the northern regions of Bangladesh. The simulated maximum NCR at Chuadanga, Hatiya, Kutubdia, Rangamati and Sylhet regions are 38, 34, 61, 40 and 39 mm respectively.

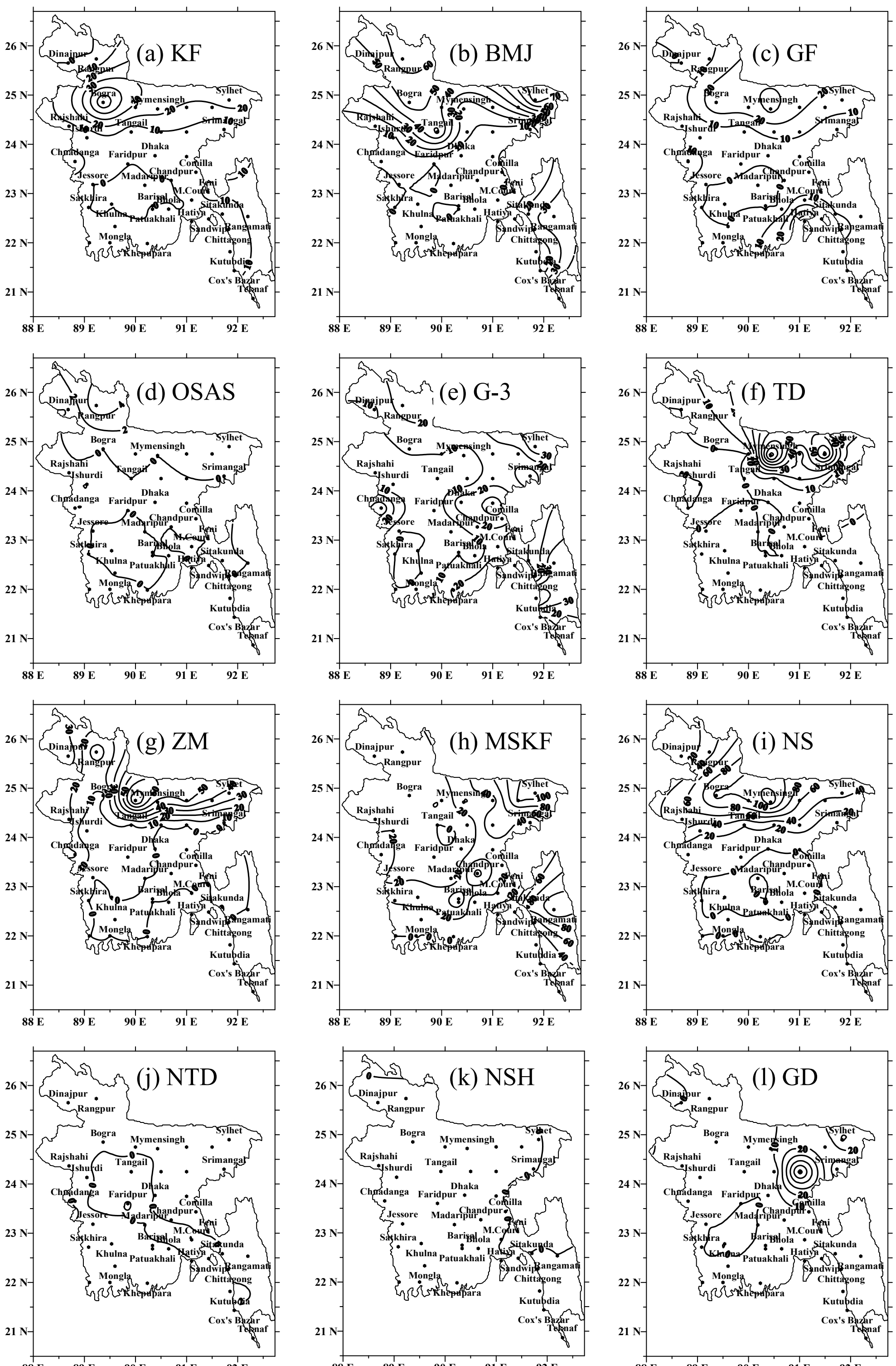

Figure 12: Spatial distribution of model simulated daily NCR using different CP schemes in combination with WDM6 scheme on 03 July 2017 all over Bangladesh.

The TD scheme has simulated moderate to MHNCR (Figure 12f) in the N-NE regions and no NCR in the maximum regions of Bangladesh. The simulated maximum NCR at Mymensingh and Sylhet regions are 87 and 23 mm respectively. The simulated rain in the N-NE regions mainly non-conductive and NCR have not simulated in the observed rain region by TD scheme. The ZM scheme has simulated moderately heavy to HNCR (Figure 12g) in the N-NW and NE regions of the country and no NCR in the central to S-SE and SW regions of Bangladesh. The simulated maximum NCR at Dinajpur, Mymensingh and Sylhet regions are 38, 46 and 38 mm respectively. The simulated rain in the N-NE and NW regions mainly non-conductive and NCR have not simulated in the observed heavy rain region by ZM scheme. The MSKF scheme has simulated heavy to VHNCR (Figure 12h) in the E-NE and SE regions, MNCR in the northern and western regions and LNCR in the central to NW region of Bangladesh.

The simulated maximum NCR at Chandpur, Rangamati, Sitakunda and Sylhet regions are 69, 117, 90, and 113 mm respectively. The rain simulated in the NE and SE regions mainly non-conductive. The NS scheme has simulated heavy to VHNCR (Figure 12i) in the N-NW and NE regions and no NCR in the other regions of Bangladesh. The simulated maximum NCR at Bogura, Mymensingh, Rajshahi and Sylhet regions are 106, 132, 58 and 47mm respectively. The rain simulated in the N-NE and NW regions mainly non-conductive. The NTD (Figure 12j) and NSH (Figure 12k) schemes have not simulated any NCR all over Bangladesh. The GD scheme has simulated MNCR (Figure 12l) in the NE region and no NCR in all other regions of Bangladesh. Maximum amount of NCR is simulated at Sylhet region 32 mm.

4.1.12 Model simulated daily Non-Convective rain on 04 July

The spatial distribution of model simulated daily NCR on 04 July 2017 for different cumulus schemes with the initial conditions of 0000 UTC of 04 July is presented in Figure 13(a-l).The KF scheme has simulated MNCR (Figure13a) in the N-NW and eastern regions, LNCR in the SE and NE regions and no NCR in the central to S-SW regions of Bangladesh. KF scheme has not simulated NCR in the SE regions of Bangladesh. The BMJ scheme has simulated HNCR (Figure 13b) in the N-NW regions, LNCR in the eastern and NE regions and no NCR in the central to S-SW and western regions of Bangladesh. The simulated maximum NCR at Mymensingh, and Rangpur regions are 51 and 49 mm respectively. The rainfall simulated by BMJ scheme mainly non-convective. The GF scheme has simulated HNCR (Figure 13c) at Mongla regions, LNCR in the eastern and northern regions and no NCR in the other regions.

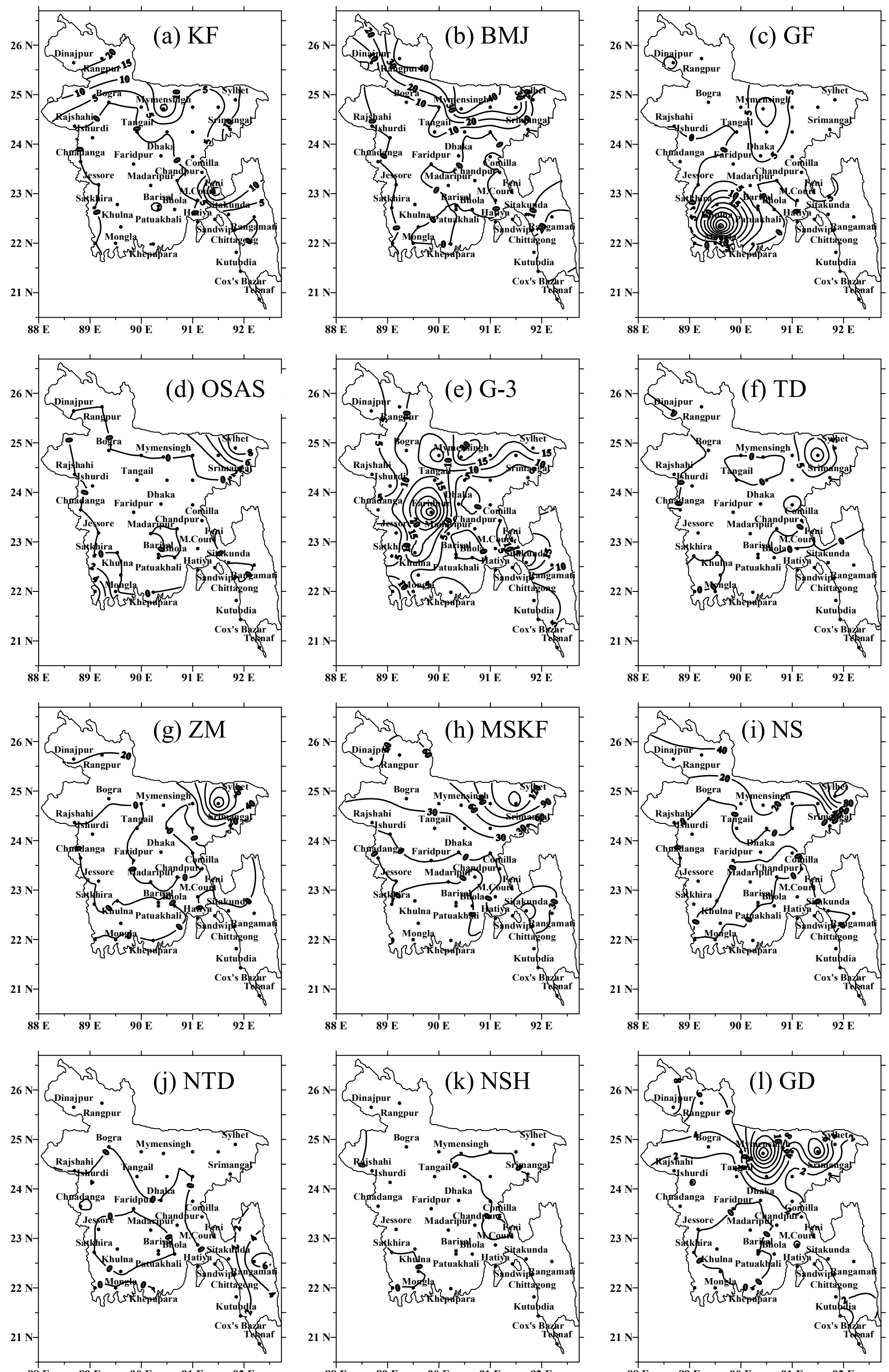

Figure 13: Spatial distribution of model simulated daily NCR using different CP schemes in combination with WDM6 scheme on 04 July 2017 all over Bangladesh.

The simulated maximum NCR at Mongla region is 50 mm. The rain simulated by GF scheme mainly non-convective in the SW region and convective in the SE and NE regions. The

OSAS scheme has simulated LNCR (Figure 13d) only at Sylhet regions and no NCR all over the country. The G-3 scheme has simulated MHNCR (Figure 13e) in the central and northern region, MNCR in the E-NE, W-NW and SW region and LNCR in the SE regions of Bangladesh. Maximum NCR is simulated at Faridpur regions are 40mm. The TD scheme has simulated LNCR (Figure 13f) in the NE and SE regions only. The ZM scheme has simulated moderate to HNCR (Figure 13g) in the NE and NW regions and no NCR all other regions of Bangladesh. The simulated maximum NCR at Dinajpur and Sylhet regions are 22and 60 mm respectively. The rainfall simulated by ZM scheme mainly non-convective. The MSKF scheme has simulated VHNCR (Figure 13h) in the NE regions and HNCR in the NW regions, moderate to MHNCR in the northern and SE and no NCR in the central to W-SW and eastern regions of Bangladesh. The simulated maximum NCR at Dinajpur, Sitakunda, Sylhet and Teknaf regions are 74, 81, 117 and 37 mm respectively. The rainfall simulated by MSKF scheme mainly non-convective. The NS scheme has simulated HNCR (Figure 13i) at Sylhet region, MHNCR northern and NW region and no NCR in all other regions of Bangladesh. The simulated maximum NCR at Dinajpur, Mymensingh, Rangpur and Sylhet regions are 35, 41, 37, and 103 mm. The rainfall simulated by NS scheme mainly non-convective. The NTD scheme has simulated LNCR (Figure 13j) in the SE regions and no NCR in all other regions of Bangladesh. The NSH scheme has simulated (Figure 13k) no NCR all over Bangladesh. The GD scheme has simulated MNCR (Figure 13l) in the northern region, LNCR in western, NW and NE regions and no NCR in the other regions of Bangladesh.

4.1.13 Model simulated daily Non-Convective rain on 05 July

The spatial distribution of model simulated daily NCR on 05 July 2017 for different cumulus schemes with the initial conditions of 0000 UTC of 05 July is presented in Figure 14(a-l). The KF scheme has simulated MHNCR (Figure14a) at Mongla regions, MNCR at Bogura and Dinajpur regions. KF scheme has also simulated LNCR at Barishal and no NCR in other regions of the country. Maximum NCR is found at Mongla region 37 mm. The rainfall simulated by KF scheme mainly non-convective at Mongla and Bogura region and in other region the simulated rain mainly convective. The BMJ scheme has simulated HNCR (Figure 14b) in the W-NW and NE regions, MNCR in the SW and SE regions and no NCR in other regions of Bangladesh. The maximum NCR is simulated at Dinajpur, Rajshahi, Sylhet and Teknaf regions are 52, 70, 86 and 50 mm respectively. The rainfall simulated by BMJ scheme mainly non-convective all over Bangladesh.

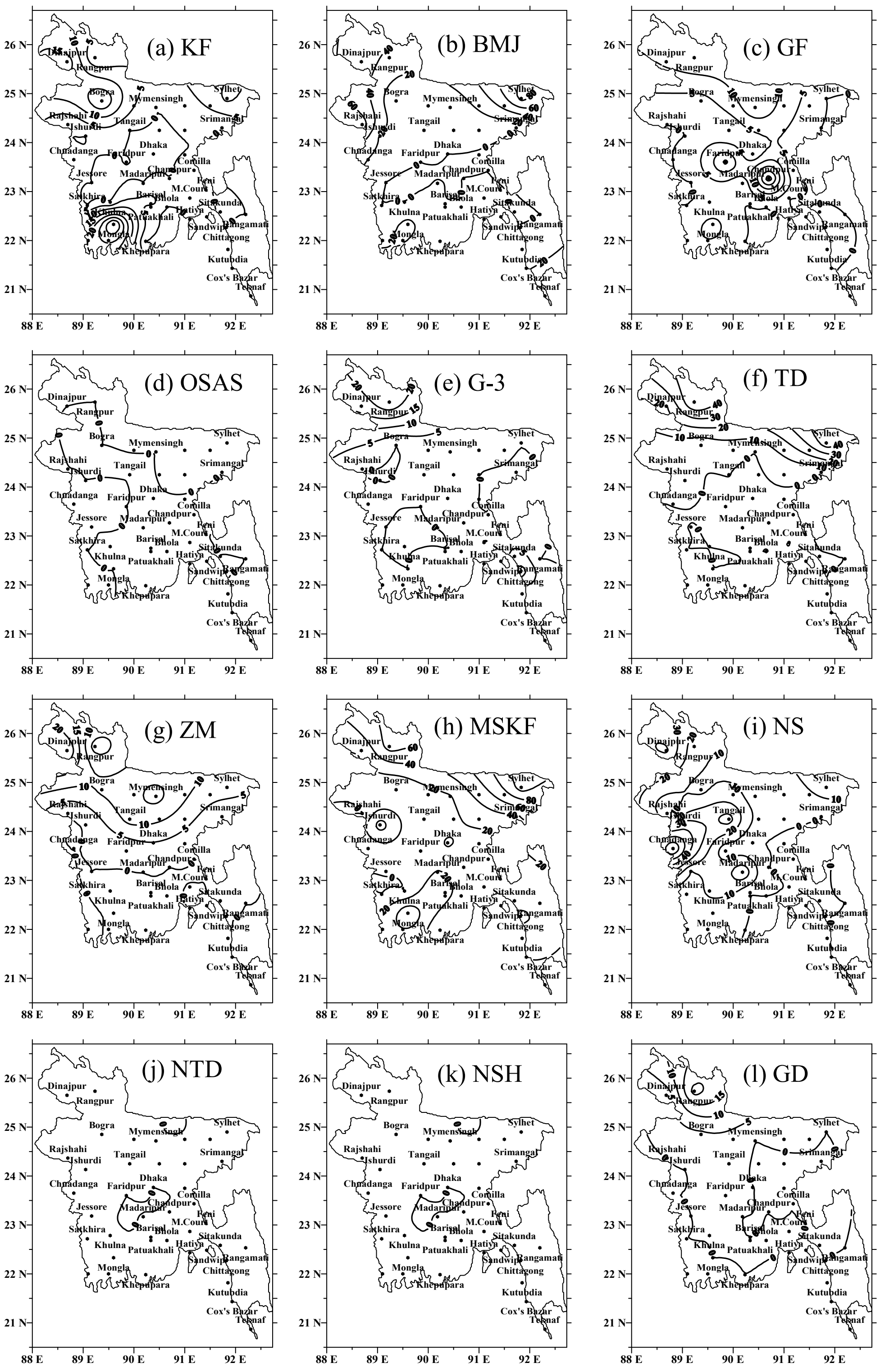

Figure 14: Spatial distribution of model simulated daily NCR using different CP schemes in combination with WDM6 scheme on 05 July 2017 all over Bangladesh.

The GF scheme has simulated MHNCR (Figure 14c) at Chandpur regions, MNCR in the NW regions and no NCR in other regions of Bangladesh. The simulated maximum NCR at Chandpur region is 29mm. The OSAS scheme has not simulated any NCR (Figure 17d) all over Bangladesh. The G-3 scheme has simulated MNCR (Figure 14e) at Rangpur, Chittagong and Dinajpur regions and no NCR in the maximum regions of Bangladesh. Maximum NCR at Rangpur region is 25 mm. The rainfall simulated by G-3 scheme mainly convective all over Bangladesh. The TD scheme has simulated HNCR (Figure 14f) in the NW and NE regions and LNCR at Ishwardi and Teknaf regions and no NCR in other regions of Bangladesh. Maximum NCR is simulated at Rangpur and Sylhet regions are 51 and 46 mm respectively. The rainfall simulated by TD scheme mainly non-convective in the NW and NE regions and in other regions it is convective.

The ZM scheme has simulated moderate to MHNCR (Figure 14g) at Dinajpur, Bogura, Mymensingh and Tangail regions and light NCR at Dhaka, Faridpur, Rangpur and Sylhet regions of Bangladesh. The maximum NCR at Dinajpur region is 25 mm. The MSKF scheme has simulated VHNCR (Figure 14h) in the NE regions, HNCR in the southern, western and NW, MHNCR in the eastern and SE regions and LNCR in other regions of Bangladesh. The simulated maximum NCR at Ishwardi, Mongla, Rangpur and Sylhet regions are 50, 59, 68 and 109 mm respectively. The rainfall simulated by MSKF scheme mainly non-convective all over Bangladesh. The NS scheme has simulated HNCR (Figure 14i) at Chuadanga regions, MHNCR at Dinajpur, Ishwardi, Madaripur and Tangail regions, MNCR in the SW Regions and no NCR in other regions of Bangladesh. Maximum NCR at Chuadanga and Dinajpur regions are 71 and 42mm respectively. The rainfall simulated by NS scheme mainly non-convective all over Bangladesh. The NTD (Figure 14j) and NSH (Figure 14j) schemes have not simulated any NCR all over the country. The GD scheme has simulated light to MNCR (Figure 14k) in the NW regions of Bangladesh. The maximum NCR simulated at Rangpur is 22 mm.

4.2 Heavy rainfall event during 19-20 July 2017

4.2.1 Observed daily total rainfall during 19-20 July 2017

The station wise BMD observed daily total rainfall during19-20 July 2017 all over Bangladesh is presented in Figure 15(a-b). The VHR is observed (Figure 15a) in the eastern to SE regions, HR in the southern and central to northern regions, MR in the western to SW regions and LR in the NW regions of Bangladesh. Maximum total rainfall observed at Sitakunda, Sandwip, Feni, Kutubdia, Teknaf, Cox-Bazar, M. Court and Chittagong regions are 176, 154, 149, 118, 115, 105, 100 and 95 mm respectively. The heavy to VHR is observed (Figure 15b) in the E-SE and SW regions, MHR in the western and NE regions, MR in the central regions and LR in the N-NW regions of Bangladesh. Maximum total rainfall observed at Sitakunda, Sandwip, Feni, M. Court, Khulna, Hatiya, Patuakhali and Chandpur regions 347, 248, 186, 136, 130, 118, 97 and 92 mm respectively.

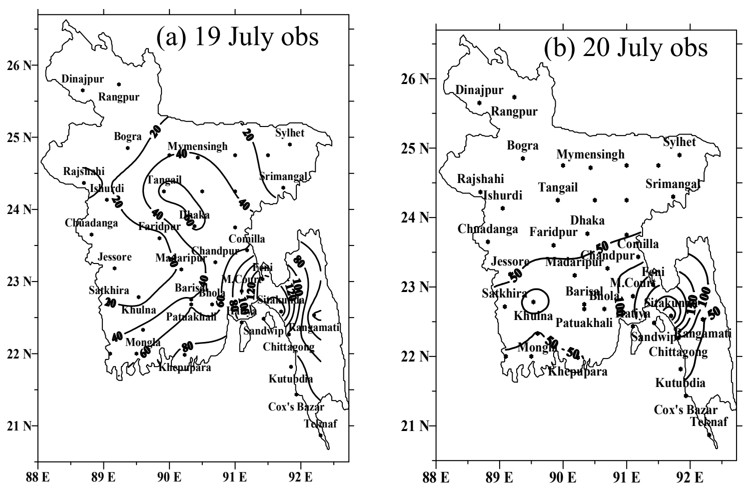

Figure 15: Distribution of (a-b) Observed daily total rainfall during 19-20 July 2017 all over Bangladesh.

4.2.2 Model simulated daily total rainfalls on 19 July

The model simulated daily total rainfall on 19 July 2017 for different CP schemes in combination with WDM6 microphysics scheme with the initial conditions of 0000 UTC of 19 July are presented in Figure 16(a-l).The KF scheme has simulated VHR (Figure 16a) at Chandpur and Teknaf region, HR at eastern to SE, Mymensingh and Satkhira regions, moderate to MHR at Jashore-Khulna-Barishal-Khepupara, Dhaka-Tangail and Sylhet regions and LR in the W-NW regions of Bangladesh. Maximum rain is simulated at Chandpur, Sandwip, Satkhira and Teknaf regions are 83, 72, 63 and 95 mm respectively. The simulated position of HR by KF scheme is matched with its positions in the SE regions but the amounts of total rainfall are not matched and the observed HR in the central regions could not simulate by this scheme. The BMJ scheme has simulated HR (Figure 16b) at eastern to SE regions, MR at south to SW regions and LR in the NE to northwestern (NW) regions of Bangladesh. Maximum total rainfall is found at Chandpur, Cox-Bazar, Hatiya, Kutubdia and Teknaf regions are 44, 47, 65, 72 and 58 mm respectively. The simulated position of HR by BMJ scheme is matched with its positions in the SE regions but the amounts of total rainfall are insignificant in comparison with observed and the observed HR in the central and S-SW regions could not simulate by this scheme. The GF scheme has simulated HR (Figure 16c) at Chandpur, Hatiya, M.Court and Teknaf regions, MHR in the central regions and LR at all other regions of Bangladesh. Maximum rain is found at Chandpur, Hatiya, M.Court, and Teknaf regions are 44, 47, 69, and 48 mm respectively. The GF scheme could not simulate the HR event.

The OSAS scheme has simulated MHR (Figure 16d) at Hatiya, Sandwip, and Teknaf region, MR at Bhola, Cox-Bazar, Sitakunda and Srimangal regions, LR at all other regions of Bangladesh. Maximum TR at Hatiya, Sandwip and Teknaf regions are 59, 58 and 68 mm respectively. The GF scheme could simulate the HR event in the SE regions but the amount is insignificant. The G-3 scheme has simulated VHR (Figure 16e) at M. Court, Sandwip, and Teknaf regions, HR at Cumilla, Cox-Bazar, Hatiya, Kutubdia and Khepupara regions, MHR in the central to eastern and SW regions and MR in other regions of Bangladesh. Maximum rain is simulated at Kutubdia, M. Court, Sandwip and Teknaf regions are 75, 132, 88 and 107 mm respectively. The G-3 is matched with the observed HR in the SE regions.The TD scheme has simulated VHR (Figure 16f) at Cox-Bazar and Kutubdia region, HR at SE and Jashore-Satkhira regions, MR in the southern and eastern regions and light rain in the northern and NW regions of Bangladesh. Maximum rain is simulated at Cox-Bazar, Jashore, Kutubdia and Teknaf regions are 93, 87, 103 and 77 mm respectively. The TD is matched with the observed HR in the SE regions but not in other regions.

The ZM scheme has simulated MHR (Figure 16g) at Sandwip and Teknaf regions, moderate rain in the eastern and western regions and LR in the NW regions of Bangladesh. Maximum rain is simulated in Sandwip and Teknaf regions are 49 and 55 mm respectively. The ZM scheme could not simulate the observed HR in different regions. The MSKF scheme has simulated HR (Figure 16h) at southern, eastern to SE regions, MHR at Cox-Bazar, Dhaka, Hatiya, Sandwip and Srimangal regions, MR at Jashore, Khulna and Mymensingh regions and LR at NW regions of Bangladesh. Maximum rain is simulated at Barishal, Chittagong, Faridpur and Patuakhali are 76, 89, 75 and 74 mm respectively.

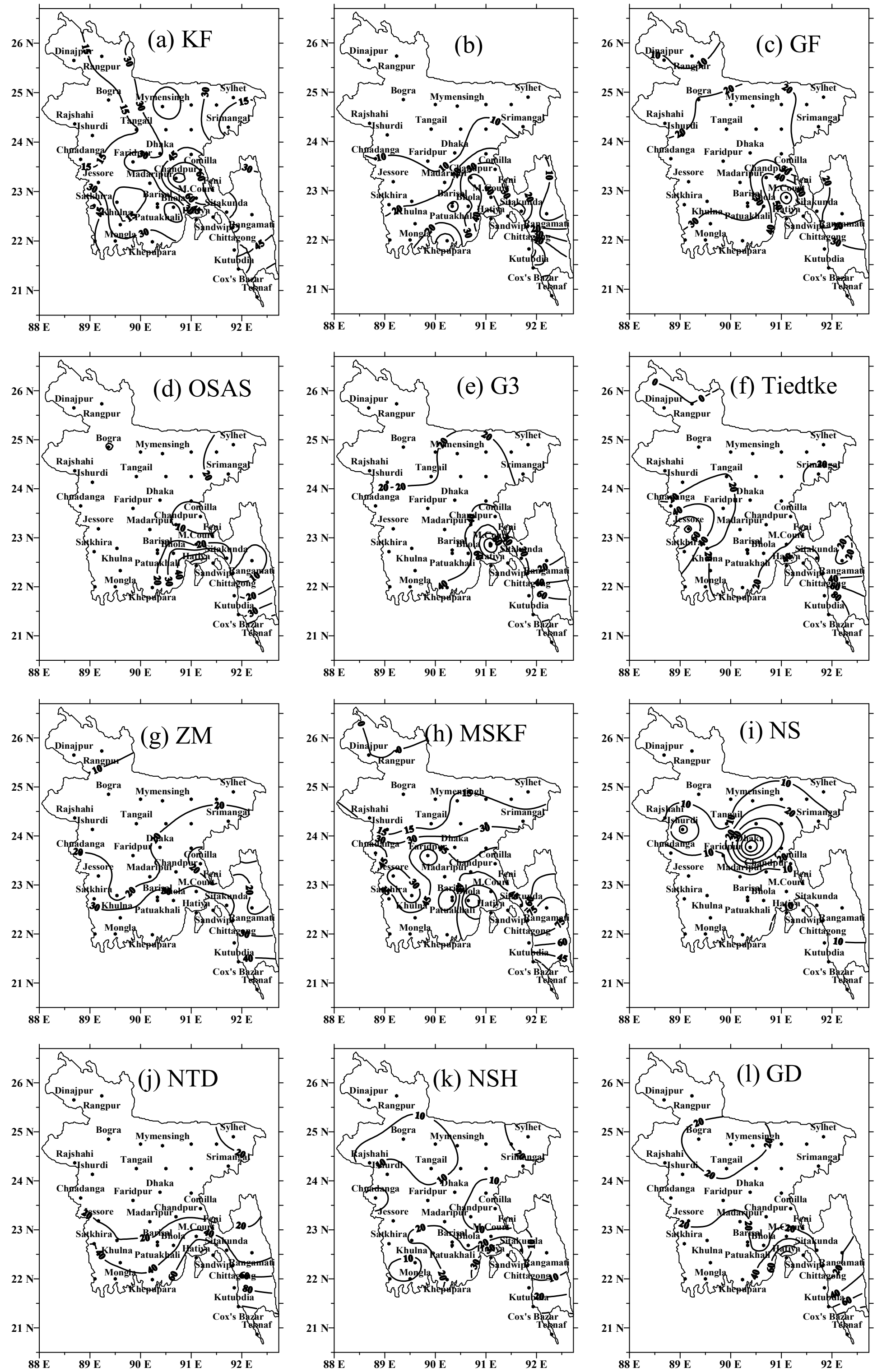

Figure 16: Spatial distribution of model simulated daily total rainfall using different CPs in combination with WDM6 scheme on 19 July 2017 all over Bangladesh.

The MSKF scheme could simulate the HR event in the SE regions and shifted from Dhaka to Faridpur regions. The NS scheme has simulated HR (Figure 16i) at Dhaka region only, MR at

Ishwardi and Mymensingh regions and LR in other regions of Bangladesh. Maximum total rainfall is simulated at Dhaka at 73 mm. The NS scheme could simulate the HR event at Dhaka regions and it could not simulate any rain in the SE regions. The NTD scheme has simulated heavy to VHR (Figure16j) in the S-SE regions, MHR at Satkhira regions and LR at other regions of Bangladesh. Maximum total rainfall is simulated at Cox-Bazar, Kutubdia, Sandwip and Teknaf regions are 101, 85, 98 and 124 mm respectively. The NTD scheme could simulate the HR event in the SE regions and it could not simulate HR in any other regions. The NSH scheme has simulated HR at (Figure16k) Sandwip and Teknaf regions, MR in the S-SE, N-NE regions and LR in regions of Bangladesh. Maximum total rainfall is simulated at Sandwip and Teknaf regions are 51and 49 mm respectively. The GD scheme has simulated heavy to VHR (Figure 16l) in the SE regions, MHR in the southern and Bogura regions and MR in other regions of Bangladesh. Maximum total rainfall is simulated at Cox-Bazar, Hatiya, Sandwip and Teknaf regions are 56, 106, 58, and 131 mm respectively. The GD scheme could simulate the HR event in the SE regions and it could not simulate HR in any other regions.

4.2.3 Model simulated daily total rainfalls on 20 July

The model simulated daily total rainfalls on 20 July 2017 for different CP schemes in combination with WDM6 microphysics scheme with the initial conditions of 0000 UTC of 20 July are presented in Figure 17(a-l). The KF scheme has simulated VHR (Figure 17a) at Chittagong, Hatiya, M.Court and Sandwip regions, HR at Cumilla, Cox-Bazar, Kutubdia, Rangamati and Sitakunda regions, MHR in the western and SE regions, LR in the northern and NW regions of Bangladesh. Maximum total rainfall is simulated at Sandwip, Hatiya, Chittagong and M. Court regions are 180, 170, 122 and 103mm respectively. The KF scheme is match with observed HR position in the eastern and SE regions. The simulated position of HR by KF scheme is matched with its positions in the SE regions but the amounts of total rainfall are not matched and the observed HR in the SW regions could not simulate by this scheme. The BMJ scheme has simulated VHR (Figure 17b) in the SE regions, MHR in the southern and eastern regions and LR in the W-NW and N-NE regions of Bangladesh. Maximum total rainfall is simulated at Sitakunda, Cox-Bazar, Sandwip and Kutubdia regions are 251, 180, 162 and 106 mm respectively. The simulated VHR by BMJ scheme is almost matched in the SE regions.

The GF scheme has simulated HR (Figure 17c) in the SE and SW regions, moderate to MHR in the southern and LR in the central to W-NW and NE regions of Bangladesh. Maximum total rainfall is simulated at Bhola, Kutubdia, Khulna and Sandwip are 54, 72, 64 and 60 mm respectively. The simulated position of HR by GF scheme is matched with its positions at Khulna and in the SE regions but the amounts of total rainfall is not matched. The OSAS scheme has simulated heavy to MHR (Figure 17d) in the S-SE regions, MR in the SW regions and LR in the W-NW and NE regions of Bangladesh. Maximum total rainfall is simulated at Hatiya and Sandwip regions are 79 and 53 mm respectively. The simulated position of HR by OSAS scheme is matched with its positions in the SE regions but the amounts of total rainfall are not matched and the observed HR in the SW regions could not simulate by this scheme.

The G-3 scheme has simulated VHR (Figure 17e) at M. Court regions, heavy to MHR in the S-SW and SE regions, MR in the NW region and LR in the N-NE regions of Bangladesh. Maximum total rainfall is simulated at M.Court, Hatiya, Sandwip and Mongla regions are 105, 79, 70 and 51 mm respectively. The G-3 scheme is match with observed position in the southern and eastern regions. The simulated position of HR by G-3 scheme is matched with its positions in the SE regions but the amounts of total rainfall are not matched. The TD scheme has simulated HR (Figure 17f) at Cox-Bazar, Hatiya, Rajshahi and Sandwip regions, MR in the eastern region and LR in the W-SW and NW regions of Bangladesh. Maximum total rainfall is simulated at Hatiya, Rajshahi and Sandwip regions are 55, 50 and 84 mm respectively. The simulated position of HR by TD scheme is matched with its positions in the SE regions but the amounts of total rainfall are not matched. The ZM scheme has simulated MHR (Figure 17g) in the S-SE and eastern regions, MR in the W-NW and N-NE regions and LR in the SW regions of Bangladesh. Maximum total rainfall is simulated at Hatiya and Sandwip regions are 54 and 50 mm respectively. The simulated position of HR by ZM scheme is matched with its positions in the SE regions but the amounts of total rainfall are not matched. The MSKF scheme has simulated heavy to VHR (Figure 17h) in the S-SE and SW regions, MR in the NE regions and LR in the W-NW regions of Bangladesh. Maximum total rainfall is simulated at and Sitakunda, Sandwip, Hatiya, Khepupara, Chittagong and Rangamati regions are 328, 302, 241, 228, 226 and 169 mm respectively. The MSKF scheme is Match with observed in the southern, SE and eastern regions. The simulated amount and position of HR by MSKF scheme is matched with its positions in the SE and SW regions. The NS scheme has simulated MHR (Figure 17i) in the SE and NW regions and LR in other regions of Bangladesh. Maximum total rainfall is simulated at Dinajpur, Kutubdia, Sitakunda and Teknaf regions are 64, 65, 59 and 70 mm respectively. The simulated position of HR by NS scheme is matched with its positions in the SE regions but the amounts of total rainfall

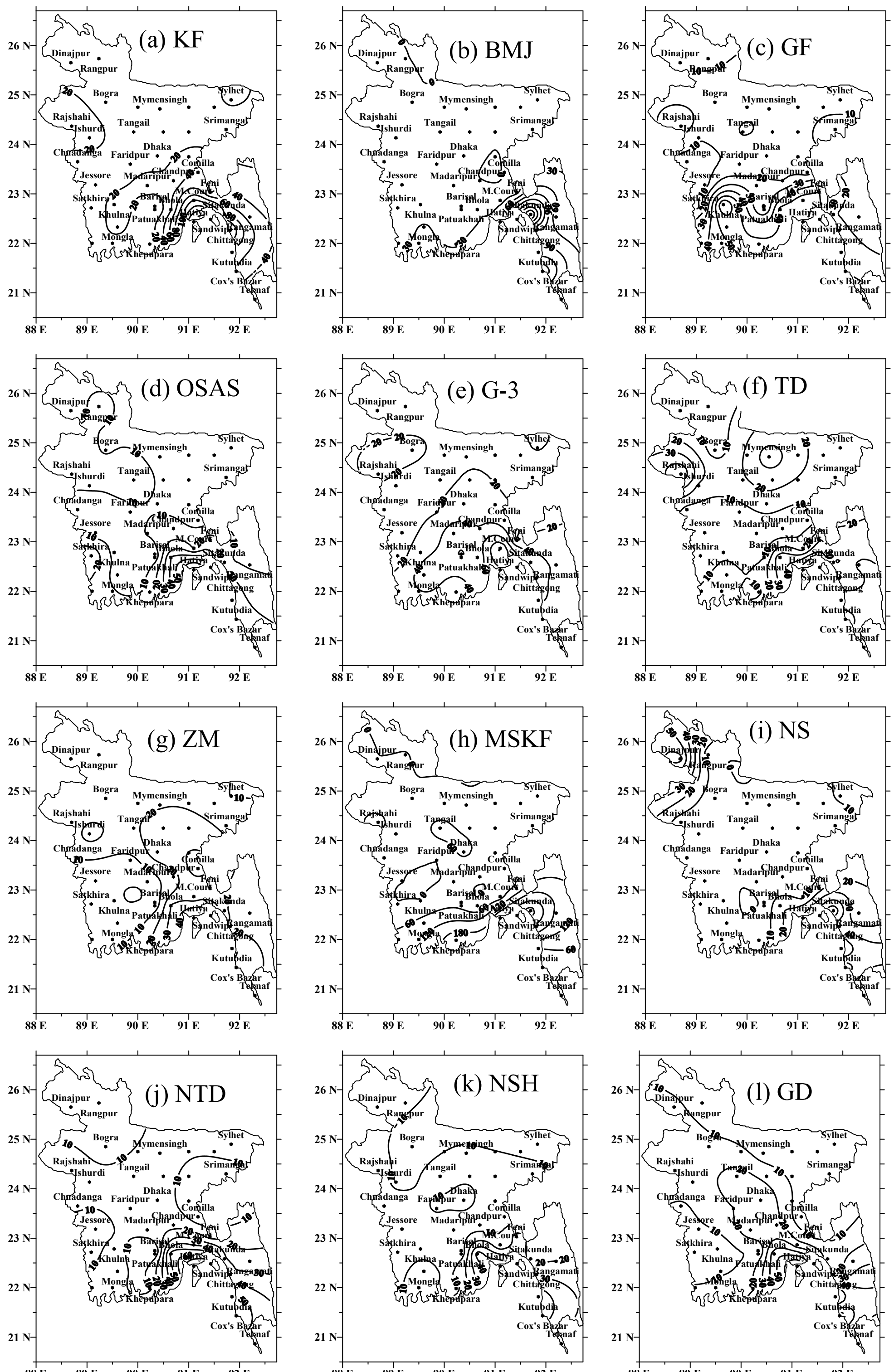

Figure 17: Spatial distribution of model simulated daily total rainfall using different CP schemes in combination with WDM6 scheme on 20 July 2017 all over Bangladesh.

are not matched. The NTD scheme has simulated MHR (Figure 17j) in the S-SE regions, MR in the W-SW and NE regions and LR in the NW regions of Bangladesh. Maximum total rainfall is simulated at Bhola, Cox-Bazar, Kutubdia, Hatiya and Sandwip regions are 54, 59, 81, 54 and 81 mm respectively. The simulated position of HR by NTD scheme is matched with its positions in the SE regions but the amounts of total rainfall are not matched. The NSH scheme has simulated MHR (Figure 17k) in the S-SE regions, MR at Bogura, Dhaka, Faridpur and Sylhet regions and LR in the W-NW and SW regions of Bangladesh. Maximum total rainfall is simulated at Bhola, Cox-Bazar, Hatiya and Kutubdia regions are 45, 45, 50 and 47 mm respectively. The simulated position of HR by NSH scheme is matched with its positions in the SE regions but the amounts of total rainfall are not matched. The GD scheme has simulated HR (Figure 17l) in the SE regions, moderate to MHR in the southern, eastern and NW regions and LR in the W-SW and NE regions of Bangladesh. Maximum total rainfall is simulated at Bhola, Hatiya, Kutubdia and Teknaf regions are 46, 76, 68 and 71 mm respectively. The simulated position of HR by GD scheme is matched with its positions in the SE regions but the amounts of total rainfall are not matched.

4.2.4 48 hourly prediction of rain on 20 July

The model simulated daily total rainfall on 20 July 2017 for different CP schemes in combination with WDM6 microphysics scheme with the initial conditions of 0000 UTC of 19 July are presented in Figure 18(a-l). The KF scheme has simulated VHR (Figure 18a) in the E-SE and SW region, HR in the southern and western regions moderate to MHR in the N-NE regions of Bangladesh. Maximum rain is simulated at Teknaf, Hatiya, M.Court, Satkhira, Sandwip, Madaripur, Patuakhali and Cox-Bazar regions are 190, 139, 139, 110, 101, 96, 94 and 89 mm respectively. The simulated position of HR by KF scheme is matched with its positions in the SE regions but the amounts of total rainfall are not matched and the observed HR in the SW regions could not simulate by this scheme. The BMJ scheme has simulated heavy to VHR (Figure 18b) in the SE and W-SW regions, MR in the northern and NE regions and LR in the NW regions of Bangladesh. Maximum total rainfall is found at Hatiya, Jashore, M.Court and Teknaf regions are 104, 96 115 and 77mm respectively. The simulated position of HR by BMJ scheme is matched with its positions in the SE regions but the amounts of total rainfall are not matched and the observed HR shifted from Khulna to Jashore region. The GF scheme has simulated VHR (Figure 18c) in the W-SW regions, HR in the S-SE and eastern region, MHR in the NE, MR in the northern and light rain in the NW regions of Bangladesh. Maximum total rainfall is found at Hatiya, Jashore, Khulna, M.Court, Sandwip and Satkhira regions are 77, 104, 90, 101, 98 and 121 mm respectively. The simulated position of HR by GF scheme is matched with its positions in the SE regions but the amounts of total rainfall are not matched and the observed HR and its position in the SW region matched.

The OSAS scheme has simulated HR (Figure 18d) in the southern and W-SW region, LR in the eastern and NW regions and all other regions of Bangladesh have simulated MR. Maximum total rainfall is found at Faridpur, Jashore, Khepupara, Khulna, Madaripur and Mongla regions are 51, 63, 49, 65, 56 and 52 mm respectively. The simulated position and amount of HR by OSAS scheme is not matched in the SE regions but the position in the SW region are matched and the observed HR. The G-3 scheme has simulated VHR (Figure 18e) in the west and S-SW regions, HR in the E-SE regions, LR in the NW region and MR in other regions of Bangladesh. Maximum rain is simulated at Faridpur, Hatiya, Jashore, Khepupara, Khulna, Madaripur, M.Court and Mongla regions are 92, 114, 91, 90, 95, 94, 197 and 95 mm respectively. The simulated position and amounts of HR by G-3 scheme is matched with its positions in the SW regions but it could not simulate in the SE region. The TD scheme has simulated MHR (Figure 18f) in the W-SW and southern region, LR in the NW regions and MR in other regions of Bangladesh. Maximum total rainfall is simulated at Kutubdia, Sandwip, Satkhira, and Sitakunda regions are 62, 52, 49 and 56 mm respectively. The TD scheme has not simulated HR in different region of Bangladesh.

The ZM scheme has simulated heavy to VHR (Figure 18g) in the S-SW regions, LR in the E-NE and NW regions and MR in the all other regions of Bangladesh. Maximum rain is simulated at Barishal, Bhola, Khepupara, Khulna, Mongla and Patuakhali regions are 110, 70, 70, 115, 116 and 108 mm respectively. The simulated position and amounts of HR by ZM scheme is matched with its positions in the SW regions but it could not simulate heavy to VHR in the SE region. The MSKF scheme has simulated VHR (Figure 18h) in the S-SW and SE regions, LR in the N-NE regions and no rain in the NW regions of Bangladesh. Maximum rain is simulated at Barishal, Bhola, Chittagong, Cumilla, Hatiya, Jashore, Khepupara, Khulna, M.Court, Mongla, Patuakhali, Sandwip, Satkhira and Sitakunda regions are 185, 113, 115, 125, 113, 128, 241, 235, 241, 208, 153, 99, 198 and 119 mm respectively. The simulated position and amounts of HR by MSKF scheme is matched with its positions in the SE and SW regions of Bangladesh. The NS scheme has simulated HR (Figure 18i) at Barishal, Patuakhali and Chuadanga region, MHR in the northern and SE region, MR in the southern and E-NE regions and LR in other regions of Bangladesh. Maximum at Barishal, Chuadanga, Ishwardi and Patuakhali regions are 57, 75, 45 and 61 mm.

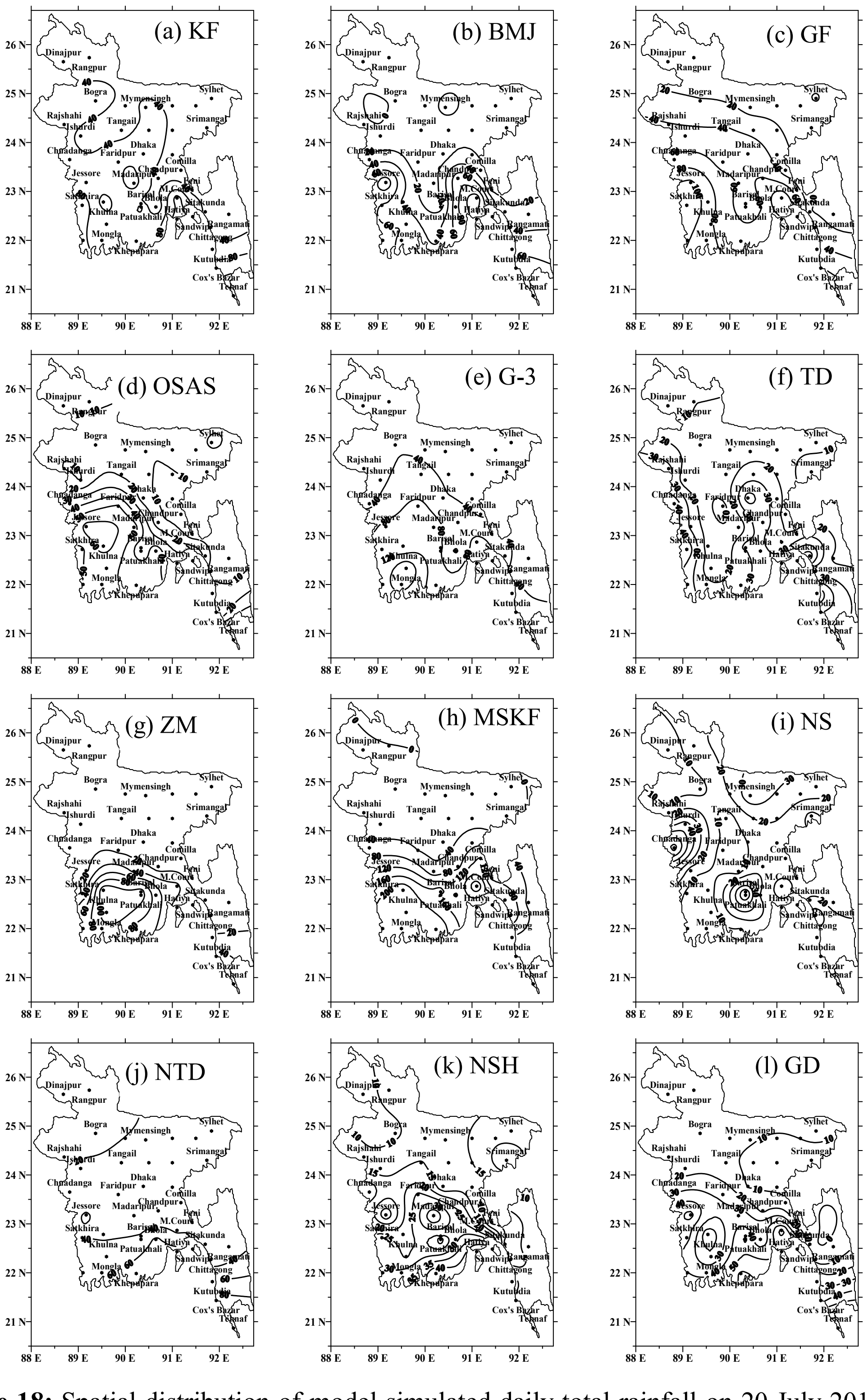

Figure 18: Spatial distribution of model simulated daily total rainfall on 20 July 2017 using different CP schemes in combination with WDM6 scheme with the initial condition at 0000 UTC of 19 July all over Bangladesh.

The total rainfall is simulated NTD scheme has simulated VHR (Figure 18j) in the SE regions, HR in the southern regions, LR in the NW regions and MR in other regions of Bangladesh. Maximum total rainfall is simulated at Cox-Bazar, Hatiya, Kutubdia, Sandwip and Teknaf regions are 88, 65, 66, 65 and 110 mm respectively. The NSH scheme has simulated HR (Figure 18k) in the southern regions, LR in the eastern and W-NW regions, moderate to MHR in other regions of Bangladesh. Maximum total rainfall is simulated at Hatiya, Khepupara and Sandwip regions are 46, 45 and 45 mm respectively. The GD scheme has simulated HR (Figure 18l) in the S-SW and SE regions, LR in the NW and NE regions and moderate to MHR in other regions of Bangladesh. Maximum total rainfall is simulated at Hatiya, Jashore, Khepupara, M.Court, Patuakhali, Sandwip and Teknaf regions are 50, 54, 62, 65, 52, 70 and 88 mm respectively.

4.2.5 Model simulated daily convective rain on 19 July

The model simulated daily CR on 19 July 2017 for different cumulus schemes with the initial conditions of 0000 UTC of 19 July is presented in Figure 19(a-l). The KF scheme has simulated heavy CR (Figure 19a) at Kutubdia, Chandpur and M.Court region and very heavy convective rain (VHCR) at Teknaf regions. KF scheme has also simulated moderate CR in the southern, SW and north to NE regions and light CR at western and northwestern regions of the country. Maximum CR is found at Chandpur, Kutubdia, M.Court and Teknaf regions are 77, 53, 71 and 95 mm respectively during 24 hour period. The BMJ scheme has simulated heavy CR at Teknaf (Figure 19b) region, moderate CR in the SE region and LCR in all other regions of Bangladesh. The simulated maximum CR at Cox-Bazar and Teknaf regions are 39 and 56 mm respectively. The GF scheme has simulated heavy CR (Figure19c) at M.Court and Teknaf region, light CR in the NE and NW regions and moderate CR all other regions of Bangladesh. The simulated maximum CR at M.Court and Teknaf regions are 52 and 48 mm.

The OSAS scheme has simulated heavy CR (Figure 19d) in the SE region, moderate CR at Bhola, Kutubdia, Sitakunda and Srimangal regions and light CR in other regions of Bangladesh. Maximum CR is simulated at Hatiya; Sandwip and Teknaf regions are 59, 58 and 68 mm respectively.

The G-3 scheme has simulated VHCR at Teknaf region (Figure 19e), heavy CR at M.Court, Sandwip, Hatiya, Cox-Bazar and Kutubdia regions and moderate CR in the southern and SW regions and light CR in other regions of Bangladesh. Maximum CR at Cox-Bazar, Hatiya, Kutubdia, M.Court, Sandwip, and Teknaf regions are 65, 51, 61, 79, 78 and 102 mm respectively.

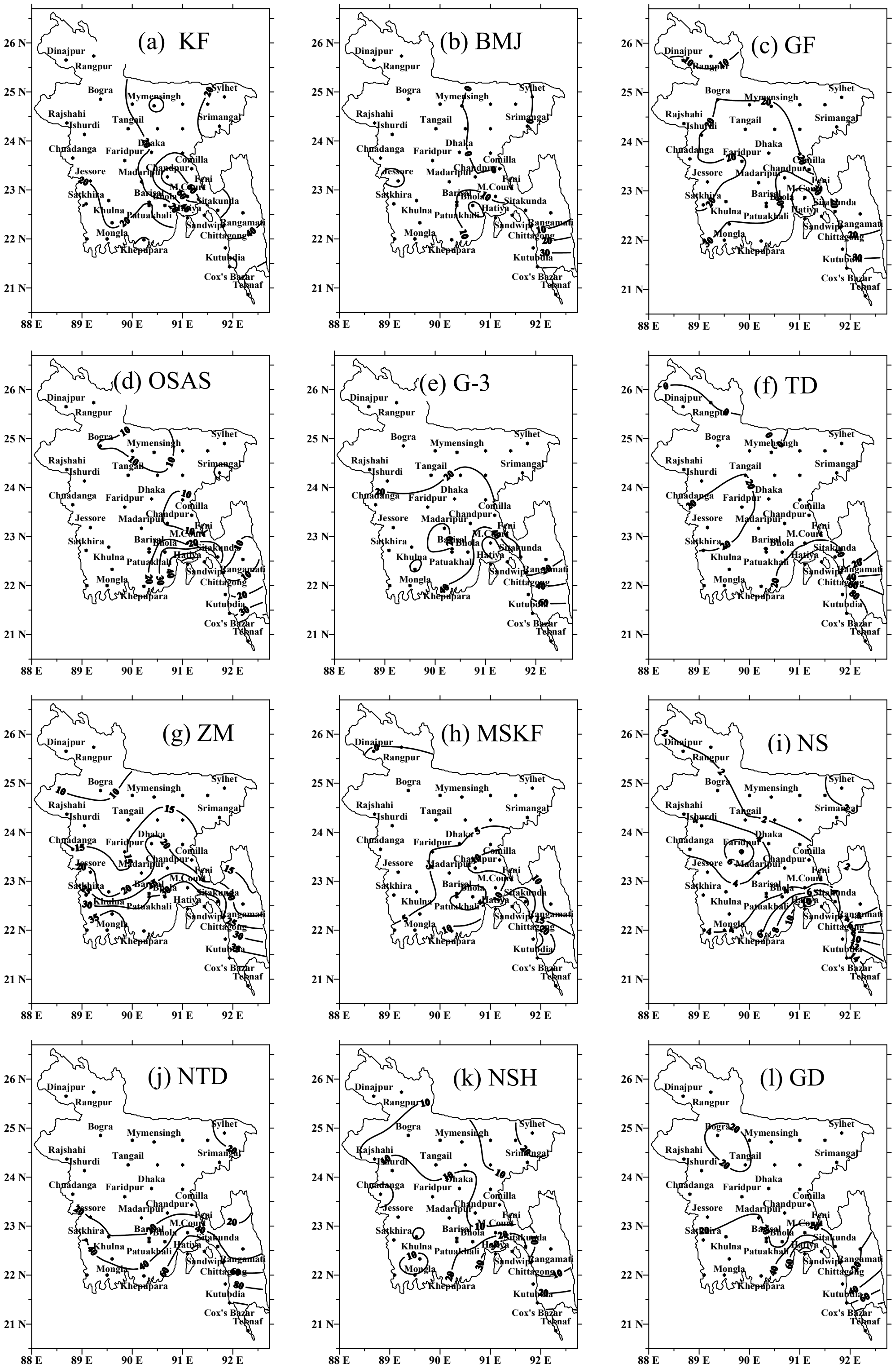

Figure 19: Spatial distribution of model simulated daily convective rainfall using different CP schemes in combination with WDM6 scheme on 19 July 2017 all over Bangladesh.

The TD scheme has simulated VHCR (Figure 19f) at Cox-Bazar, Kutubdia and Teknaf regions, HCR at Sandwip region, moderate CR at Faridpur, Jashore and Sitakunda regions and light CR in the northern, NW and NE regions of Bangladesh. Maximum CR at Cox-Bazar, Kutubdia, Hatiya, Sandwip and Teknaf regions are 93, 103, 52, 69 and 77 mm respectively. The ZM scheme has simulated HCR (Figure 19g) at Teknaf region, light CR in the northern, western, NE and NW regions and moderate CR in other regions of Bangladesh. The maximum CR at Teknaf region is 47 mm. The MSKF scheme has simulated moderate CR (Figure 19h) at Kutubdia, Sandwip, Sitakunda and Teknaf regions and light CR all the other regions of Bangladesh. The simulated maximum CR at Kutubdia is 33 mm. The NS scheme has simulated light CR (Figure 19i) all over Bangladesh and maximum CR at Teknafis15 mm. The NTD scheme has simulated VHCR (Figure 19j) at Cox-Bazar, Hatiya, Kutubdia, Sandwip and Teknaf regions and heavy CR at Chittagong, Khepupara, M.Court and Sitakunda regions of Bangladesh. Maximum simulated CR at Cox-Bazar, Kutubdia, Sandwip and Teknaf are 101, 85, 98 and 124 mm respectively. The NSH scheme has simulated heavy CR(Figure 19k) at Sandwip and Teknaf regions, moderate CR at Chuadanga, Cox-Bazar, Hatiya, Kutubdia and Sylhet regions and light CR all other regions of Bangladesh. The simulated maximum CR at Sandwip and Teknaf regions are 51 and mm respectively. The GD scheme has simulated VHCR (Figure 19l) at Hatiya and Teknaf regions, HCR at Cox-Bazar and Sandwip regions, light CR in the SW, Western and NE regions and moderate CR simulated in other regions of Bangladesh. The maximum CR simulated at Cox-Bazar, Hatiya, Sandwip and Teknaf are 56,106, 57 and 131mm respectively.

4.2.6 Model simulated daily convective rain on 20 July

The model simulated daily CR on 20 July 2017 for different cumulus schemes with the initial conditions of 0000 UTC of 20 July is presented in Figure 20(a-l). The KF scheme has simulated HCR (Figure 20a) in the SE regions, MCR in the western region and LCR in other regions of the country. Maximum CR is found at Hatiya, M.Court, Kutubdia and Cox-Bazar regions are 139, 72, 60, and 54 mm respectively during 24 hour period. The rainfall simulated by KF scheme mainly convective at Hatiya, M. Court and Kutubdia regions of the country. The BMJ scheme has simulated MCR (Figure 20b) in the southern regions and LCR in other regions of Bangladesh. The simulated maximum CR at Bhola, Cox-Bazar and Hatiya regions are 30, 12 and 15 mm respectively. BMJ scheme have simulated maximum CR at Bhola. The GF scheme has simulated HCR (Figure 20c) in the SE to SW regions, MCR in the eastern

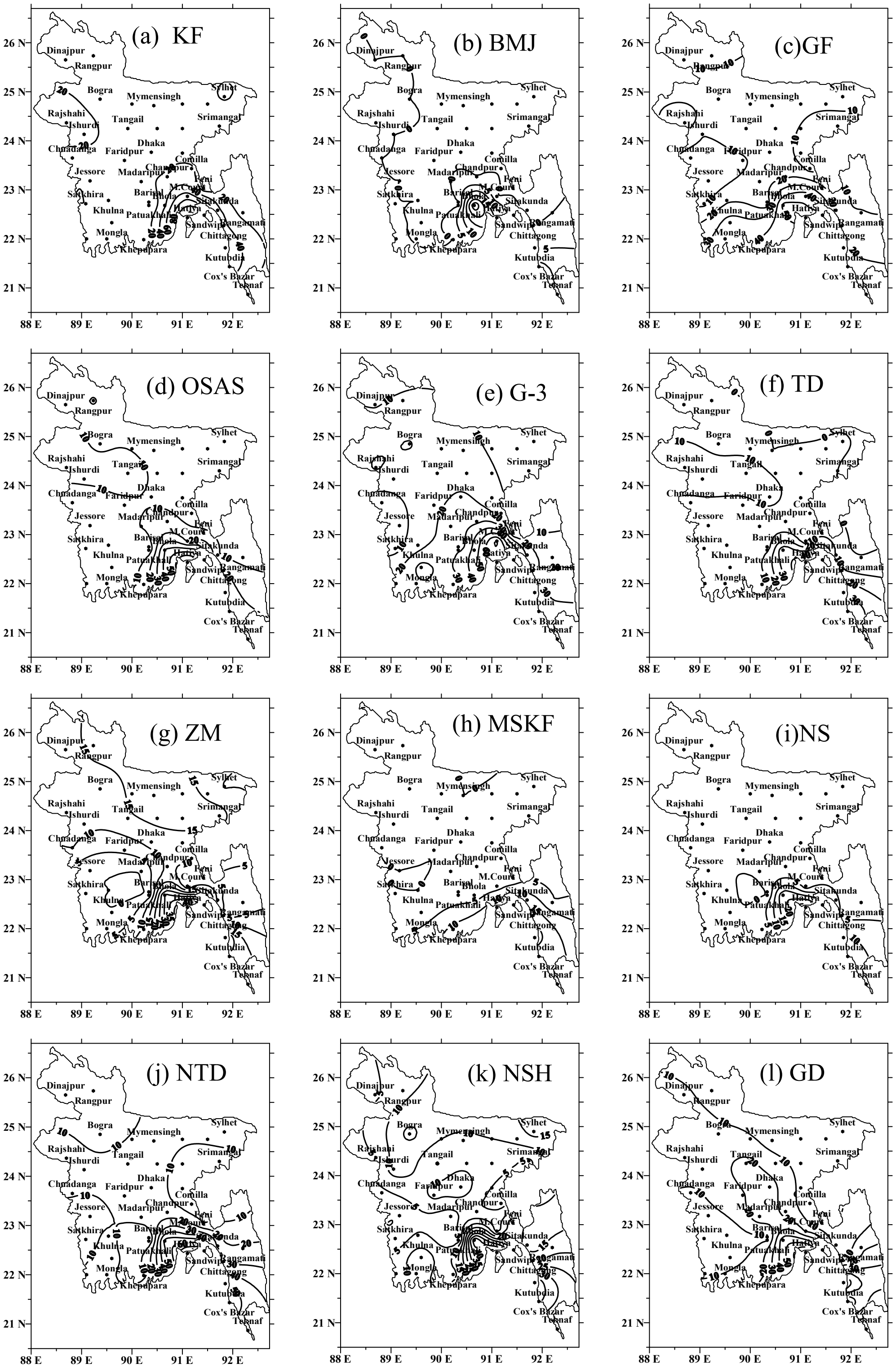

Figure 20: Spatial distribution of model simulated daily CR using a) KF, b) BMJ, c) GF, d) OSAS, e) G-3, f) TD, g) ZM, h) MSKF, i) NS, j) NTD, k) NSH and l) GD schemes in combination with WDM6 scheme on 20 July 2017.

and western regions and light CR in other regions of Bangladesh. The simulated maximum CR at Bhola, Sandwip, Hatiya and M. Court regions are 53, 53, 50, and 46 mm respectively. The CR have simulated all over Bangladesh. The rainfall simulated by GF scheme mainly convective in the SE to SW regions of the country. The OSAS scheme has simulated MHCR to HCR (Figure 20d) in the S-SE region, MCR in the central to western regions and light CR in other regions of Bangladesh. Maximum CR is simulated at Hatiya, Sandwip, Bhola and Cox-Bazar regions are 79, 53, 41 and 24 mm respectively. The rainfall simulated by OSAS scheme mainly convective in the S-SE regions of the country. The G-3 scheme has simulated MHCR to HCR in the S-SE regions (Figure 20e) and moderate CR in the western and eastern regions and light CR in other regions of Bangladesh. Maximum CR is simulated at M. Court, Hatiya, Mongla and Khepupara, regions are 73, 67, 34 and 24mm respectively. The rainfall simulated by G-3 scheme mainly convective in the SE regions of the country. The TD scheme has simulated MHCR to HCR (Figure 20f) in the S-SE regions and LCR in other regions of Bangladesh. Maximum CR is simulated at Sandwip, Hatiya and Cox-Bazar regions are 61, 51 and 40 mm respectively. The rainfall simulated by TD scheme convective in the SE regions. The ZM scheme has simulated HCR (Figure 20g) at Hatiya region, MHCR and MCR in the S-SE and eastern regions LCR in the SW regions of Bangladesh. The maximum CR is simulated at Hatiya, Sandwip and Kutubdia regions are 53, 43 and 27 mm. The rainfall simulated by ZM scheme mainly convective in the SE regions. The MSKF scheme has simulated MCR (Figure 20h) in the S-SE regions and LCR all the other regions of Bangladesh. The simulated maximum CR at Kutubdia, Chittagong and Sandwip regions are 23, 19 and 18 mm.

The NS scheme has simulated MCR in S-SE regions and LCR (Figure 20i) all other regions of Bangladesh. The NTD scheme has simulated HCR (Figure 20j) in the SE regions and MCR to MHCR in the S-SW and E-NE regions and LCR in other regions of Bangladesh. Maximum CR is simulated at Hatiya, Sandwip, Cox-Bazar, Bhola and Kutubdia regions are 81, 80, 57, 54, and 53mm respectively. The rainfall simulated by NTD scheme mainly convective all over the country but it could not simulate heavy to VHR. The NSH scheme has simulated HCR to MHCR (Figure 20k) in the SE regions, moderate CR in the S-SW and E-NE and light CR in other regions of Bangladesh. The simulated maximum CR at Hatiya, Kutubdia, Bhola, Cox-Bazar and Sandwip regions are 50, 40, 45, 36, and 29 mm respectively. The rainfall simulated by NSH scheme mainly convective all over the country but it could not simulate heavy to VHR. The GD scheme has simulated MHCR to HCR (Figure 20l) in the south and SE regions, MCR in the eastern, western and NW regions and light CR in the SW and NE regions of Bangladesh. The maximum CR simulated at Hatiya, Kutubdia, Teknaf and Bhola regions are 74, 65, 65 and 46mm respectively. The rainfall simulated by GD scheme mainly convective all over the country but it could not simulate heavy to VHR.

4.2.7 Model simulated daily Non-Convective rain on 19 July

The model simulated daily NCR using different CP schemes on 19 July 2017 have presented in Figures 21(a–l) for the initial conditions at 0000 UTC of 19 July 2017.The KF scheme has simulated moderately heavy NCR (Figure21a) at Faridpur region, moderate NCR at Cumilla, Mymensingh, Rangpur and Satkhira regions, light NCR in the NE regions and no NCR in all other regions of Bangladesh. Maximum NCR has simulated at Faridpur and Satkhira regions are 26 and 22 mm respectively. The NCR is simulated by KF scheme all over the country but the amount is not significant. The BMJ scheme has simulated HNCR(Figure 21b) at Chandpur, Kutubdia and Hatiya regions, MHNCR at Cumilla, M-Court, Mongla, Patuakhali and Sitakunda regions, MNCR at Barishal, Feni, Khulna and Satkhira regions and LNCR in the western, SE and NE regions of Bangladesh. The maximum NCR is simulated at Hatiya, Kutubdia Chandpur, M.Court and Cumilla regions are 45, 44, 43, 36 and 33 mm respectively. The rainfall simulated by BMJ scheme mainly non-convective in the eastern and SE regions of the country. The GF scheme has simulated MNCR (Figure 21c) in the eastern regions and LNCR in other regions of the country. The NCR simulated by GF scheme is insignificant. The OSAS scheme has simulated light NCR (Figure 21d) north to NE regions and no NCR all other regions of Bangladesh. The NCR simulated by OSAS scheme is insignificant. The G-3 scheme has simulated HNCR (Figure 21e) at M.Court region, MHNCR at Cumilla region and LNCR in all other regions of Bangladesh. Maximum NCR is simulated at M.Court regions are 53 mm.The rainfall simulated by G-3 scheme mainly NC at M.Court regions. The TD scheme has simulated HNCR (Figure 21f) in Jashore region, MHNCR at Satkhira region, MNCR at Feni, Sitakunda and Srimangal regions and no NCR in SE and NW regions of Bangladesh. The simulated maximum NCR at Jashore and Satkhira regions are 46 and 37 mm respectively. The rainfall simulated by TD scheme mainly NC all over the country. The ZM scheme has simulated LNCR (Figure 21g) all over the country. The NCR simulated by ZM scheme is insignificant. The MSKF scheme has simulated HNCR (Figure 21h)S-SW and E-SE regions and MHNCR Chandpur, Dhaka, Hatiya, Kutubdia and Madaripur regions, MNCR in the northern and NE regions and light NCR in the NW region of Bangladesh.

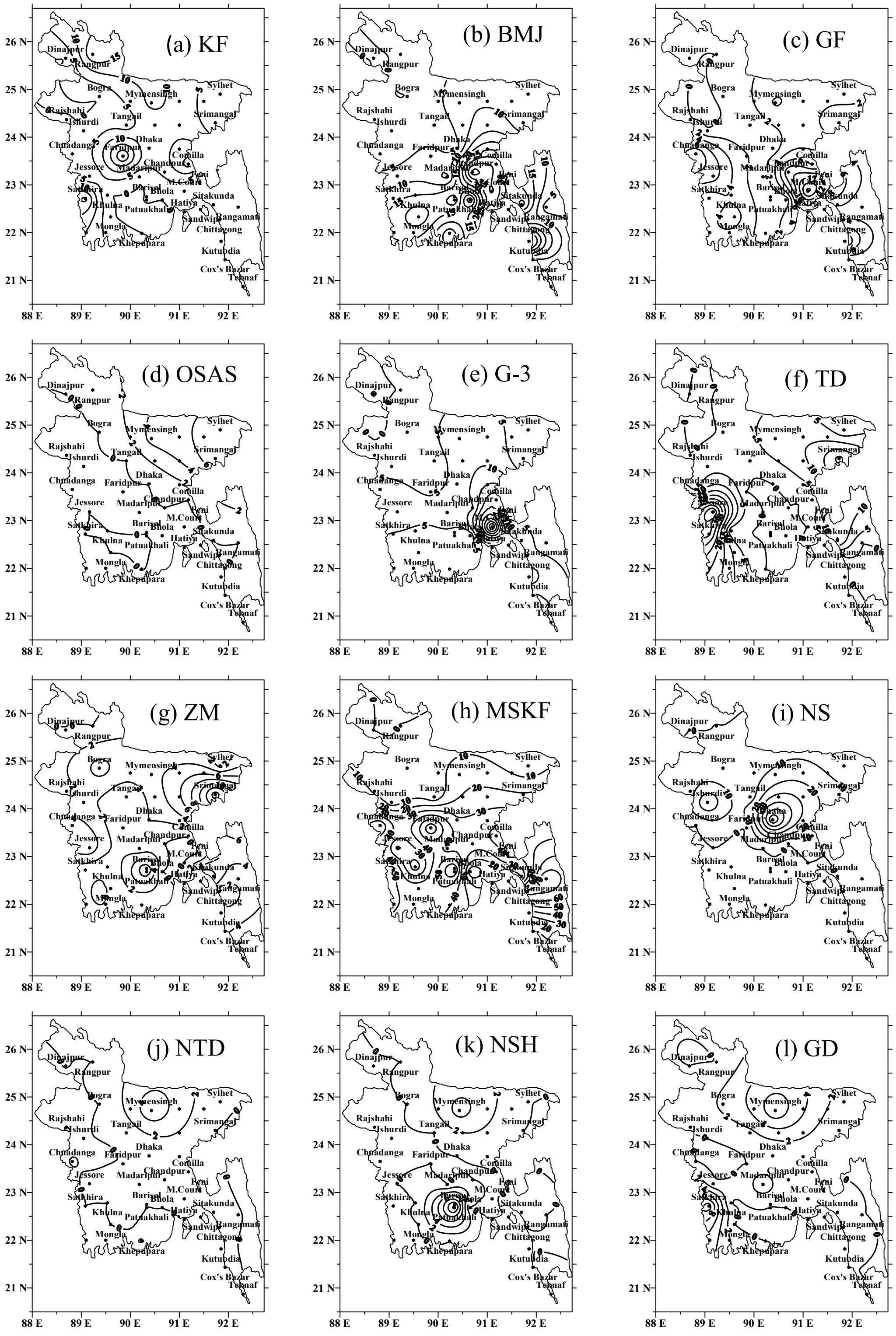

Figure 21: Spatial distribution of model simulated daily NCR using a) KF, b) BMJ, c) GF, d) OSAS, e) G-3, f) TD, g) ZM, h) MSKF, i) NS, j) NTD, k) NSH and l) GD schemes in combination with WDM6 scheme on 19 July 2017.

The simulated maximum NCR at Rangamati, Chuadanga, Barishal, Faridpur and Chittagong regions are 79, 74, 70, 70, 60, and mm respectively. The rainfall simulated by MSKF scheme mainly NC all over the country. The NS scheme has simulated HNCR (Figure 21i) at Dhaka region, MNCR at Cumilla, Ishwardi, Mymensingh and Srimangal regions and LNCR at other regions of Bangladesh. The simulated maximum NCR at Dhaka is 70 mm. The rainfall simulated by NS scheme mainly non-convective in the central to eastern regions. The NTD scheme has simulated light NCR (Figure 21j) at maximum regions of the country. The NCR simulated by NTD scheme is insignificant. The NSH scheme has simulated MNCR (Figure 21k) at Barishal and Patuakhali regions, LNCR at Mymensingh and Sitakunda regions and no NCR all other regions of Bangladesh. The NCR simulated by NSH scheme is insignificant. The GD scheme has simulated LNCR (Figure 21l) LNCR all over the country. The NCR simulated by GD scheme is insignificant.

4.2.8 Model simulated daily Non-Convective rain on 20 July

The model simulated daily NCR on 20 July 2017 for different cumulus schemes with the initial conditions of 0000 UTC of 20 July is presented in Figure 22(a-l). The KF scheme has simulated MHNCR to HNCR (Figure 22a) in the SE regions and LNCR in other regions of the country. Maximum NCR is found at Chittagong, Sandwip, Sitakunda, Feni and Hatiya regions are 77, 67, 35, 31 and 31 mm respectively during 24 hour period. The rainfall simulated by KF scheme mainly non-convective at Chittagong, Sandwip and Rangamati regions of the country. The BMJ scheme has simulated VHNCR (Figure 22b) in the SE regions and LNCR in other regions of the country. The regions and their rainfalls are Sitakunda, Cox-Bazar, Sandwip, Kutubdia, and Chittagong, regions are 251, 169, 161, 102, and 90 mm respectively. The rainfall simulated by BMJ scheme mainly non-convective in the SE regions of the country. The GF scheme has simulated HNCR (Figure 22c) at Khulna and Feni region and LNCR in the other regions of Bangladesh. The simulated maximum NCR at Khulna, Feni, and Mongla regions are 53, 28 and 19 mm respectively. The rainfall simulated by GF scheme non-convective at Khulna and Feni regions.

The OSAS scheme has simulated MNCR (Figure 22d) at Satkhira and light NCR at Feni, regions and no NCR all other regions of Bangladesh. The rainfall simulated by OSAS scheme mainly NC at Satkhira regions. The G-3 scheme has simulated MNCR to MHNCR (Figure 22e) in the central to S-SE regions and LNCR all other regions of Bangladesh. Maximum NCR is simulated at Chittagong, Madaripur, M.Court and Sitakunda regions are 22, 25, 32 and 27 mm.

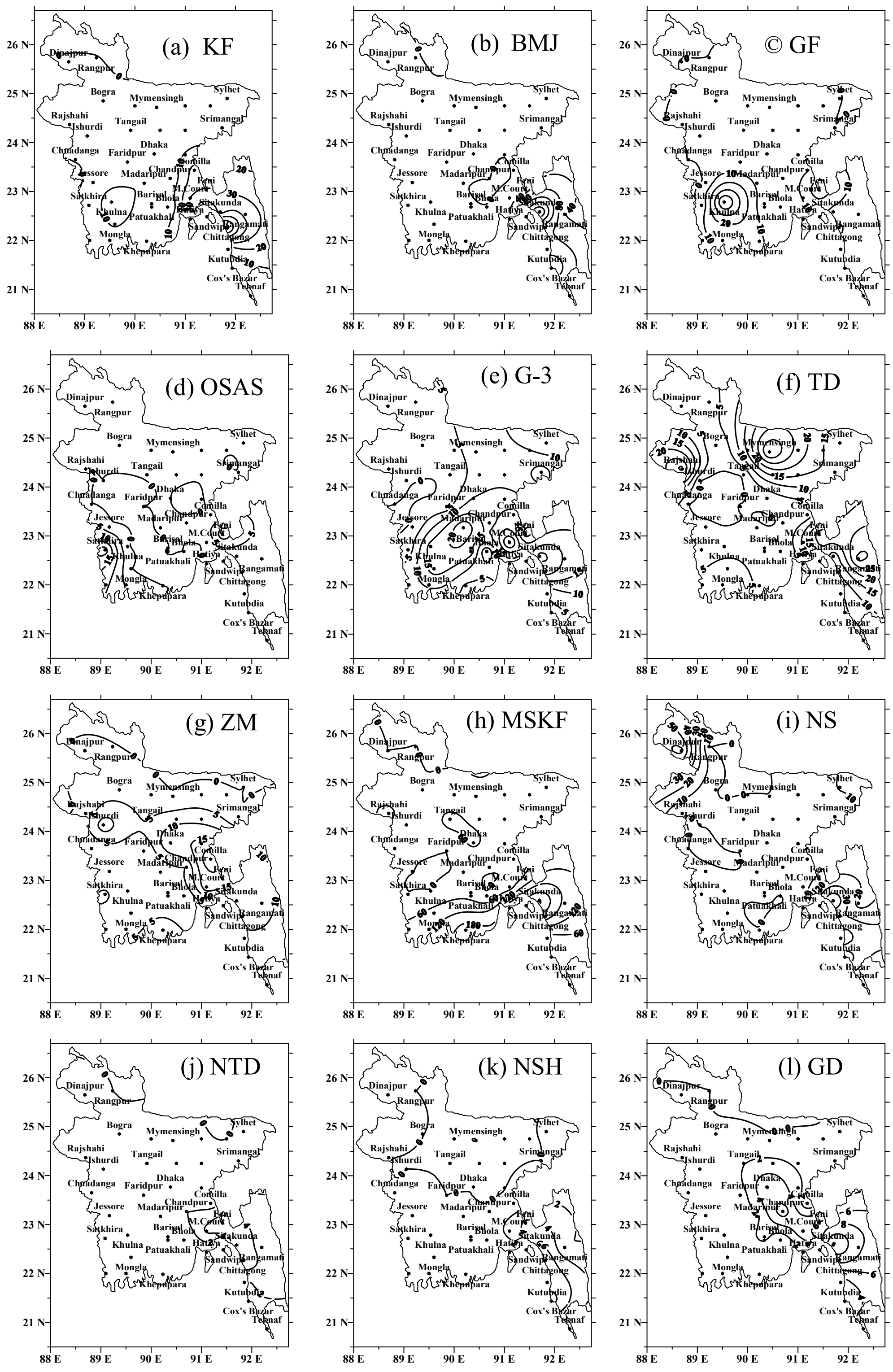

Figure 22: Spatial distribution of model simulated daily NCR using a) KF, b) BMJ, c) GF, d) OSAS, e) G-3, f) TD, g) ZM, h) MSKF, i) NS, j) NTD, k) NSH and l) GD schemes in combination with WDM6 scheme on 20 July 2017 all over Bangladesh

The TD scheme has simulated MNCR to MHNCR (Figure 22f) in the western, northern and SE regions and LNCR in other regions of Bangladesh. The maximum NCR is simulated at Mymensingh, Rajshahi, Rangpur and Sandwip regions are 36, 32, 32 and 23 mm respectively. The simulated rainfall mainly non-convective in the western and northern regions and mixed in the SE regions. The ZM scheme has simulated MNCR (Figure 22g) in the eastern and S-SE regions and LNCR all other regions of Bangladesh. The simulated maximum NCR at Chittagong, Cumilla, Feni and M.Court regions are 15, 25, 16 and 19 mm respectively. The MSKF scheme has simulated VHNCR to HNCR (Figure 22h) in the southern, eastern, SE and SW regions and MNCR to MHNCR in the western and NE regions and light NCR in the northern and NW region of Bangladesh. The simulated maximum NCR at Sitakunda, Sandwip, Hatiya, Khepupara, Chittagong and Rangamati regions are 314, 284, 227, 216, 207, and 163 mm respectively. The rainfall simulated by MSKF scheme mainly non-convective in the southern and SE regions of the country. The NS scheme has simulated HNCR (Figure 22i) in the NW and SE region, MNCR in the NE region and LNCR other regions of Bangladesh. The simulated maximum NCR at Dinajpur, Teknaf, Sitakunda and Kutubdia regions are 63, 60, 53 and 52 mm respectively. The rainfall simulated by NS scheme mainly non-convective in the NW and SE regions of the country. The NTD (Figure 22j), NSH (Figure 22k) and GD (Figure 22l) schemes have simulated light NCR only in the SE region of Bangladesh.

4.3 Heavy rainfall event during 23-24 July 2017

4.3.1 Observed daily total rainfalls during 23-24 July 2017

Heavy to very heavy rainfall observed on23 July in the S-SE and SW regions and on 24 July 2017all over Bangladesh. The spatial distribution of observed total rainfall all over Bangladesh during 23-24 July 2017 is presented in Figure 23(a-b). The VHR is observed on 23 July (Figure 23a) in the SE regions, HR in the southern and SW regions, MHR in the eastern and NW regions, MR in the western and northern regions of Bangladesh. Maximum total rainfall observed at Kutubdia, Cox-Bazar, Chittagong, Mongla, Rangamati and Satkhira regions are 188, 155, 132, 93, 92 and 75 mm respectively. The VHR is observed on 24 July (Figure 23b) in the S-SE and central regions, HR in the western and northern regions of Bangladesh. Maximum total rainfall observed at Chittagong, Hatiya, Cox-Bazar, Bhola, Sitakunda, Kutubdia, Tangail, Rangamati, Sandwip, Cumilla, Patuakhali and Faridpur regions are 223, 218, 208, 185,178, 175, 172,170, 122, 120, 118 and 104 mm respectively.

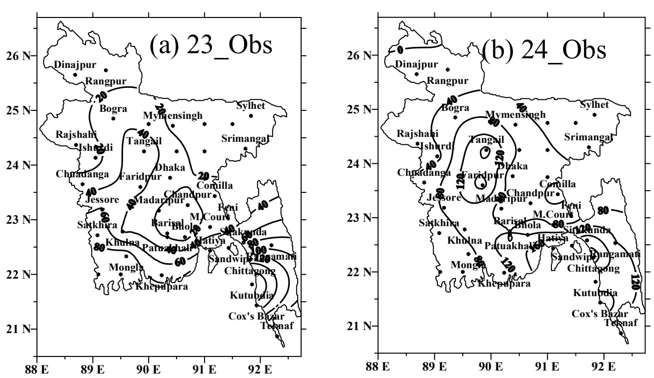

Figure 23: Spatial distribution of observed total rainfall during (a) 23 and (b) 24 July 2017 all over Bangladesh.

4.3.2 Model simulated daily total rainfalls on 23 July

The model predicted daily total rainfall for different CP schemes in combination with WDM6 scheme on 23 July 2017 are presented in Figure 24(a-l) with the initial conditions of 0000 UTC of 23 July. The KF scheme has simulated VHR (Figure 24a) in the S-SE regions, HR to MHR in the eastern to NE and SW regions and LR N-NW and western regions of Bangladesh. Maximum total rainfall is simulated at Rangamati, Chittagong, Kutubdia, Khepupara, Hatiya and Mongla regions are 243, 235, 235, 194, 120 and 106mm respectively. The simulated total rainfall by KF scheme is matched with the observed heavy to VHR position and amounts all over the country. The BMJ scheme has simulated heavy to VHR (Figure 24b) in the S-SE regions, MHR in the SW regions and LR in W-NW and N-NE regions of Bangladesh. Maximum total rainfall is simulated at Chittagong, Teknaf, Rangamati, Sitakunda, Kutubdia and Cox-Bazar regions are 288, 199, 166, 151, 151 and 148 mm respectively. The BMJ scheme is matched with the observed rain in the SE regions. The GF scheme has simulated heavy to VHR (Figure 24c) in the central to S-SW-SE and E-NE, MR in the NW regions and LR in the western regions of Bangladesh. Maximum total rainfall is simulated at Chittagong, Kutubdia, Rangamati, Feni, Mongla, Hatiya and Khepupara regions are 269, 250, 192, 159, 147, 145 and 128 mm respectively. This scheme is almost matched with the amount of observed heavy to VHR and their position also. The OSAS scheme has simulated heavy to VHR (Figure 24d) in the S-SE and E-NE regions, MR in the central to northern and western and LR in the NW regions of Bangladesh. Maximum total rainfall is simulated at Chittagong, Rangamati, Hatiya, Feni and Khepupara regions are 205, 186, 139, 119 and107 mm respectively. This scheme is almost matched with the amount of observed heavy to VHR and their position also. The G-3 scheme has simulated heavy to VHR (Figure 24e) in the central to S-SE and SW regions, MR in the NE region and LR in the northern and NW regions of Bangladesh. Maximum total rainfall is simulated at Chittagong, Mongla, Rangamati Feni, Khepupara, Kutubdia, Cox-Bazar, M.Court and Barishal regions are 304, 173, 171, 141, 141, 133, 120, 108 and 104, mm respectively. The simulated total rainfall by G-3 scheme is almost matched with the observed heavy to VHR position and amounts all over the country. The TD scheme has simulated heavy to VHR (Figure 24f) in the central to S-SE and SW regions, MR in the NE regions and LR in the western and NW regions of Bangladesh. Maximum total rainfall is simulated at Kutubdia, Rangamati, Khepupara, Chittagong, Sitakunda, Mongla, Sandwip, Patuakhali, Barishal, Cox-Bazaar, Hatiya, Madaripur and Khulna regions are 369, 254, 221, 189, 158, 155, 143, 139, 136, 128, 121, 120 and 116 mm respectively. The TD scheme simulated total rainfall position is almost matched with the observed heavy to VHR position but the amount is lower all over the country.

The ZM scheme has simulated heavy to VHR (Figure 24g) in the S-SW and SE regions, MHR in the central to NE regions, MR in the N-NW and LR in the western regions of Bangladesh. Maximum total rainfall is simulated at Kutubdia, Rangamati, Mongla, Cox-Bazar, Chittagong, and Sitakunda regions are 193,171, 153, 103, 99 and 98 mm respectively. The simulated total rainfall by ZM scheme is almost matched with the observed rain and its position in the central to SE and SW regions of Bangladesh. The MSKF scheme has simulated heavy to VHR (Figure 24h) in the S-SW and SE regions, MHR in the central to NE

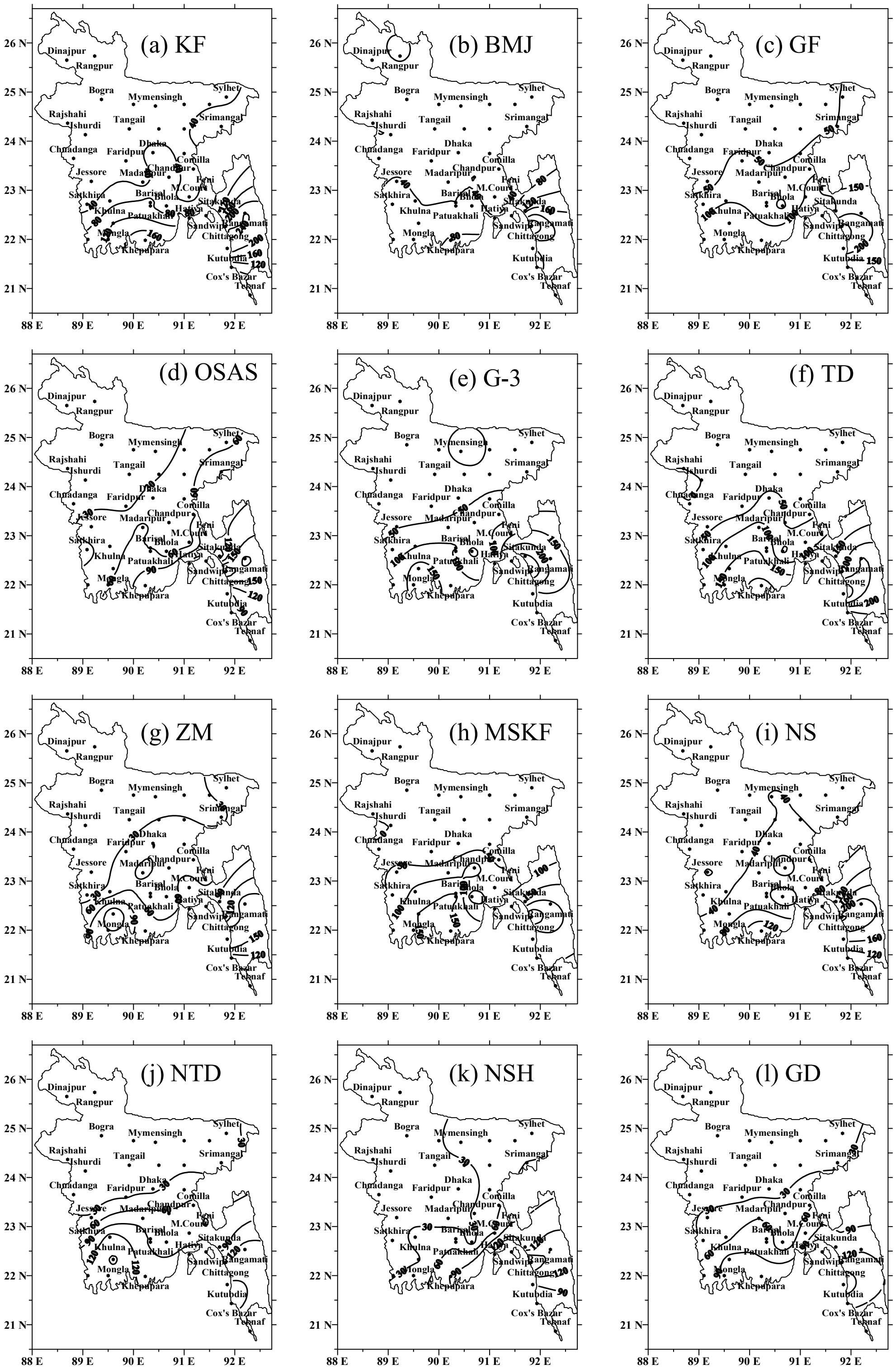

Figure 24: Spatial distribution of model simulated daily total rainfall using a) KF, b) BMJ, c) GF, d) OSAS, e) G-3, f) TD, g) ZM, h) MSKF, i) NS, j) NTD, k) NSH and l) GD schemes in combination with WDM6 scheme on 23 July 2017.

regions, MR in the N-NW and LR in the western regions of Bangladesh. Maximum total rainfall is simulated at Chittagong, Cox-Bazaar, Rangamati, Khepupara, Patuakhali, Sitakunda, Barishal, Sandwip, Kutubdia, Chandpur and Khulna regions are 307, 216, 209, 164, 163, 163, 141, 137, 135, 125 and 111 mm respectively. The simulated total rainfall by MSKF scheme is almost matched with the observed rain and its position with little shifting in the central to SE and SW regions of Bangladesh. The NS scheme has simulated heavy to VHR (Figure 24i) in the S-SW and SE regions, MHR in the central to eastern regions, MR in the N-NW and LR in the western regions of Bangladesh. Maximum total rainfall is simulated at Chittagong, Rangamati, Sandwip, Kutubdia, Khepupara, Chandpur and Sitakunda regions are 250, 221, 175, 170, 162, 109 and 109 mm respectively. The simulated total rainfall by NS scheme is almost matched with the observed rain and its position with little shifting in the central to SE and SW regions of Bangladesh. The NTD scheme has simulated heavy to VHR (Figure 24j) in the S-SW and SE regions, MHR in the central to eastern regions, MR in the N-NW and LR in the western regions of Bangladesh. Maximum total rainfall is simulated at Cox-Bazar, Mongla, Kutubdia, Khulna, Chittagong, Rangamati, Hatiya, Khepupara, Sandwip and Teknaf regions are 167, 155, 152, 137, 132, 126, 112, 108, 105 and 101 mm respectively. The HR is simulated by NTD scheme in the NE and NW regions but the position of HR is shifting and the amount of total rainfall is lower in the SE region and higher in the SW regions. The NSH scheme has simulated heavy to VHR (Figure 24k) in the S-SE regions, MHR in the NE regions, MR in the SW regions and LR in the W-NW regions of Bangladesh. Maximum total rainfall is simulated at Sandwip, Chittagong, Hatiya and Rangamati regions are 231, 181, 157 and 151 mm respectively. The simulated HR by NSH scheme is almost matched with the observed rain and its position with little shifting and the amount of total rainfall is lower in the SE region. The GD scheme has simulated heavy to VHR (Figure 24l) in the S-SE and SW regions, MHR in the NE and central regions and LR in the W-NW regions of Bangladesh. Maximum total rainfall is simulated at Kutubdia, Sandwip, Chittagong, Cox-Bazar, Rangamati, Khepupara, Mongla and Hatiya regions are 173, 146, 134, 128,118, 110, 100, 100 and 104 mm respectively. The simulated HR by GD scheme is almost matched with the observed rain and its position with little shifting and the amount of total rainfall is lower in the SE region.

4.3.3 Model simulated daily total rainfall on 24 July

The model predicted daily total rainfall for different CP schemes in combination with WDM6 scheme on 24 July 2017 are presented in Figure 25(a-l) with the initial conditions of 0000

UTC of 24 July. The KF scheme has simulated heavy to VHR (Figure 25a) in the Central to eastern and S-SW regions, moderate to MHR in the western and northern regions and LR in the NW regions of Bangladesh. Significant amount of total rainfall is simulated at Hatiya, Chandpur, Mongla, M.Court, Dhaka, Madaripur and Patuakhali regions are 183, 144, 144, 135, 113, 112 and 105 mm respectively. The simulated total rainfall by KF scheme is matched with the observed total rainfall in the southern regions but it could not match HR at Tangail-Faridpur regions. The BMJ scheme has simulated heavy to VHR (Figure 25b) in the central to eastern and southern regions, moderate to MHR in the SW, SE and NE regions and LR in W-NW regions of Bangladesh. Significant amount of total rainfall is simulated at Khepupara, Hatiya, Feni, M.Court, Patuakhali, Barishal and Cumilla regions are 210, 195, 182, 98, 80, 68 and 68 mm respectively. The simulated total rainfall by BMJ scheme is matched with the observed rain in the southern regions but it could not match heavy rain in the Tangail-Faridpur regions. The GF scheme has simulated heavy to VHR (Figure 25c) in the central to S-SW and eastern regions, moderate to MHR in the western, N-NE regions and LR in the NW regions of Bangladesh. Significant amount of total rainfall is simulated at Mongla, Hatiya, Chandpur, Khulna, Madaripur, M. Court and Barishal regions are 149, 105, 99, 99, 80, 87 and 63 mm respectively.GF scheme has simulated HR in the NW regions but HR observed in the S-SE and Tangail-Faridpur regions.

The OSAS scheme has simulated heavy to VHR (Figure 25d) in the central, southern and eastern regions, MHR in the SW and northern regions, MR in the western and SE regions and LR in the NW regions of Bangladesh. Significant amount of total rainfall is simulated at Dhaka, Faridpur, Sandwip, Hatiya, Madaripur and Mongla regions are 128, 98, 88, 82, 77 and 75 mm respectively. The simulated position of HR by OSAS scheme is shifted from Tangail-Faridpur to Dhaka region. The G-3 scheme has simulated heavy to VHR (Figure 25e) in the S-SE and SW, central to northern and eastern regions, MR in the NE region and LR NW regions of Bangladesh. Significant amount of total rainfall is simulated at M.Court, Dhaka, Khepupara, Mongla and Barishal regions are 113, 92, 89, 89 and 69 mm respectively. G-3 scheme has simulated HR all over but the position and amount is not matched with observed HR and its position. The TD scheme has simulated heavy to VHR (Figure 25f) in the S-SE and central regions, moderate to MHR in the western and N-NE regions and LR in the NW regions of Bangladesh. Significant amount of total rainfall is simulated at Sitakunda, Feni, Dhaka, Hatiya, Sandwip and Mymensingh regions are 129, 99, 95, 95, 82 and 75 mm respectively. Observed heavy rain is found at Tangail & Faridpur and Chittagong regions but TD scheme is simulated at Dhaka and Sitakunda.

The ZM scheme is simulated heavy to heavy to VHR (Figure 25g) in the S-SE and eastern regions, MHR in the central to NE and SW regions, MR in the western and LR in the NW regions of Bangladesh. Significant amount of CR is simulated at Teknaf, Chandpur, Hatiya, M.Court and Sandwip regions are 170, 119, 89, 85 and 60 mm respectively. Observed heavy rain is found at Tangail & Faridpur and Chittagong regions but ZM scheme is simulated at Chandpur and Teknaf. The MSKF scheme is simulated heavy to VHR (Figure 25h) in the central to S-SW and E-SE regions, MR in the NE and LR in the NW regions of Bangladesh. Significant amount of total rainfall is simulated at M.Court, Sandwip, Madaripur, Patuakhali, Barishal, Mongla and Chandpur regions are 228, 158, 136, 135, 134, 116 and 112 mm respectively. The simulated rain by MSKF scheme is matched with observed HR in the SE regions but in the central region it shifted from Tangail-Faridpur to Madaripur-Barisal-Patuakhali regions. The NS scheme has simulated heavy to VHR (Figure 25i) in the central to eastern and northern regions, MHR in the western SW and NE regions and LR in the NW regions of Bangladesh. Significant amount of total rainfall is simulated at Chandpur, Dhaka, Feni, M.Court, Hatiya, Patuakhali and Mymensingh regions are 122, 142, 103, 90, 88, 78 and 74 mm respectively. The simulated rain by NS scheme is matched with observed HR in the central region but its position shifted from Tangail-Faridpur to Dhaka-Chandpur regions.

The NTD scheme has simulated heavy to VHR (Figure 25j) in the central to S-SW and eastern regions, moderate to MHR in the NE regions and LR in the NW regions of Bangladesh. Significant amount of total rainfall is simulated at Mongla, Khulna, Faridpur, Madaripur and Hatiya regions are 257, 124, 121, 118 and 92 mm respectively. The observed HR in the SE region could not match by NTD scheme but observed HR at Faridpur region is matched with model simulated rain. The NSH scheme has simulated HR (Figure 25k) in the central to eastern and northern regions, MHR in the NE and SW regions and LR in the NW regions of Bangladesh. Significant amount of total rainfall is simulated at Chandpur, Dhaka, Hatiya and Mymensingh regions are 68, 59, 71 and 53 mm respectively. The simulated total rainfall by NSH scheme could not match with observed rain. The GD scheme has simulated HR (Figure 25l) in the central to W-SW regions, moderate to MHR in the NE regions and LR in the NW regions of Bangladesh. Significant amount of total rainfall is simulated at Faridpur, Khulna, Dhaka, Hatiya and Sandwip regions are 90, 82, 56, 76 and 73 mm respectively. The simulated HR by GD scheme could not match with observed rain in the SE region but it could match at Faridpur region.

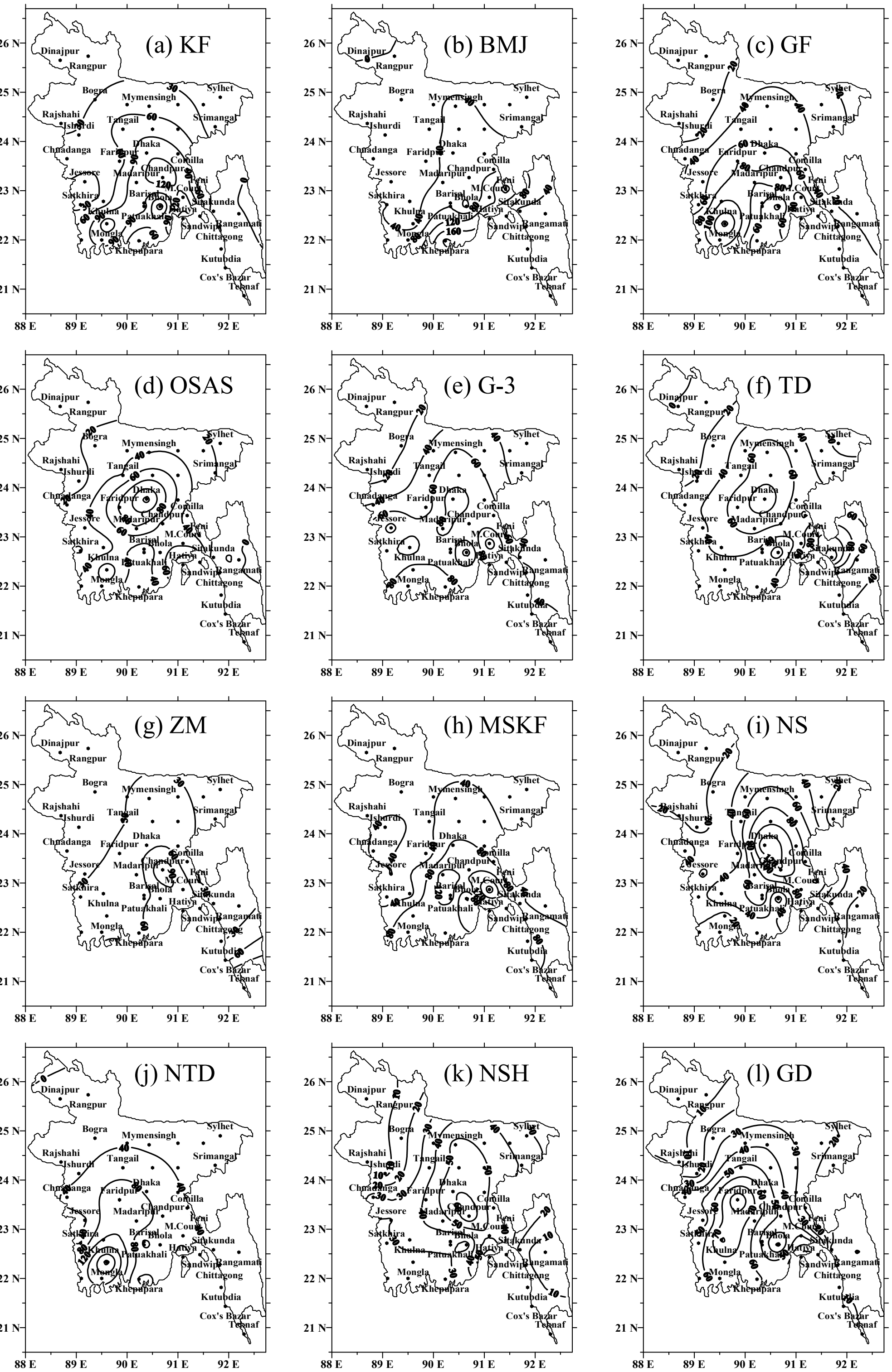

Figure 25: Spatial distribution of model simulated daily total rainfall using a) KF, b) BMJ, c) GF, d) OSAS, e) G-3, f) TD, g) ZM, h) MSKF, i) NS, j) NTD, k) NSH and l) GD schemes in combination with WDM6 scheme on 24 July 2017.

4.3.4 Model simulated daily total rainfalls on 24 July

The model predicted daily total rainfall for different CP schemes in combination with WDM6 scheme on 24 July 2017 are presented in Figure 26(a-l) with the initial conditions of 0000 UTC of 24 July. The KF scheme has simulated heavy to VHR (Figure 26a) in the central to S-SE, E-NE and NW regions and LR in the west and NW regions of Bangladesh. Maximum total rainfall is simulated at Khepupara, Madaripur, M.Court, Barishal, Cumilla, Chandpur, Hatiya, Feni, Patuakhali, Sandwip, Dhaka, Mymensingh, and Mongla regions are 460, 288, 255, 203, 199, 197, 196, 190, 189 170, 135, 117 and 104 mm respectively. The KF scheme is matched with observed HR position all over the country but amount is very high. The BMJ scheme has simulated VHR (Figure 26b) in the southern and eastern regions, HR in the SE regions, MR in the northern and NE regions and LR in the western regions of Bangladesh. Maximum total rainfall is simulated at Khepupara, Patuakhali, Barishal, Hatiya, Sitakunda, Mongla and M.Court regions are 429, 271, 244, 174, 161, 157 and 126 mm respectively. The simulated total rainfall position by BMJ scheme is matched with observed position in the southern region but amount is very high.

The GF scheme has simulated heavy to VHR (Figure 26c) in the central to S-SE and SW regions, moderate to MHR in the northern regions and LR in the NW regions of Bangladesh. Maximum total rainfall is simulated at Mongla, Madaripur, M.Court, Chandpur, Kutubdia, Barishal, Patuakhali, Sandwip, Khulna, Dhaka, Faridpur, Hatiya, Khepupara and Satkhira regions are 250, 237, 214, 160, 156, 152, 145, 136, 119, 116, 107, 110, 109 and 101 mm respectively. The simulated total rainfall by GF scheme is matched with the observed HR in the southern and SW regions. The OSAS scheme has simulated VHR (Figure 26d) in the eastern regions, HR in the S-SW and N-NE regions, MR in the western NW regions and LR in the SE regions of Bangladesh. Maximum total rainfall is simulated at Cumilla, M.Court, Hatiya, Chandpur and Khulna regions are 191, 177, 112, 79 and 78 mm respectively. The simulated total rainfall by OSAS scheme is not matched with the observed HR in the south-SE and central regions of the country. The G-3 scheme has simulated heavy to VHR (Figure 26e) in the central to S-SE and SW regions and LR in the NW regions of Bangladesh. Maximum total rainfall is simulated at M.Court, Khepupara, Patuakhali, Barishal, Mongla, Madaripur, Feni, Hatiya, Chandpur, Dhaka and Khulna regions are 507, 324, 307, 269, 263, 207, 196, 194, 165, 154 and 132 mm respectively. G-3 scheme is match. The simulated position of HR by G-3 scheme is matched with observed position in the S-SE region but the amount is very higher than observed.

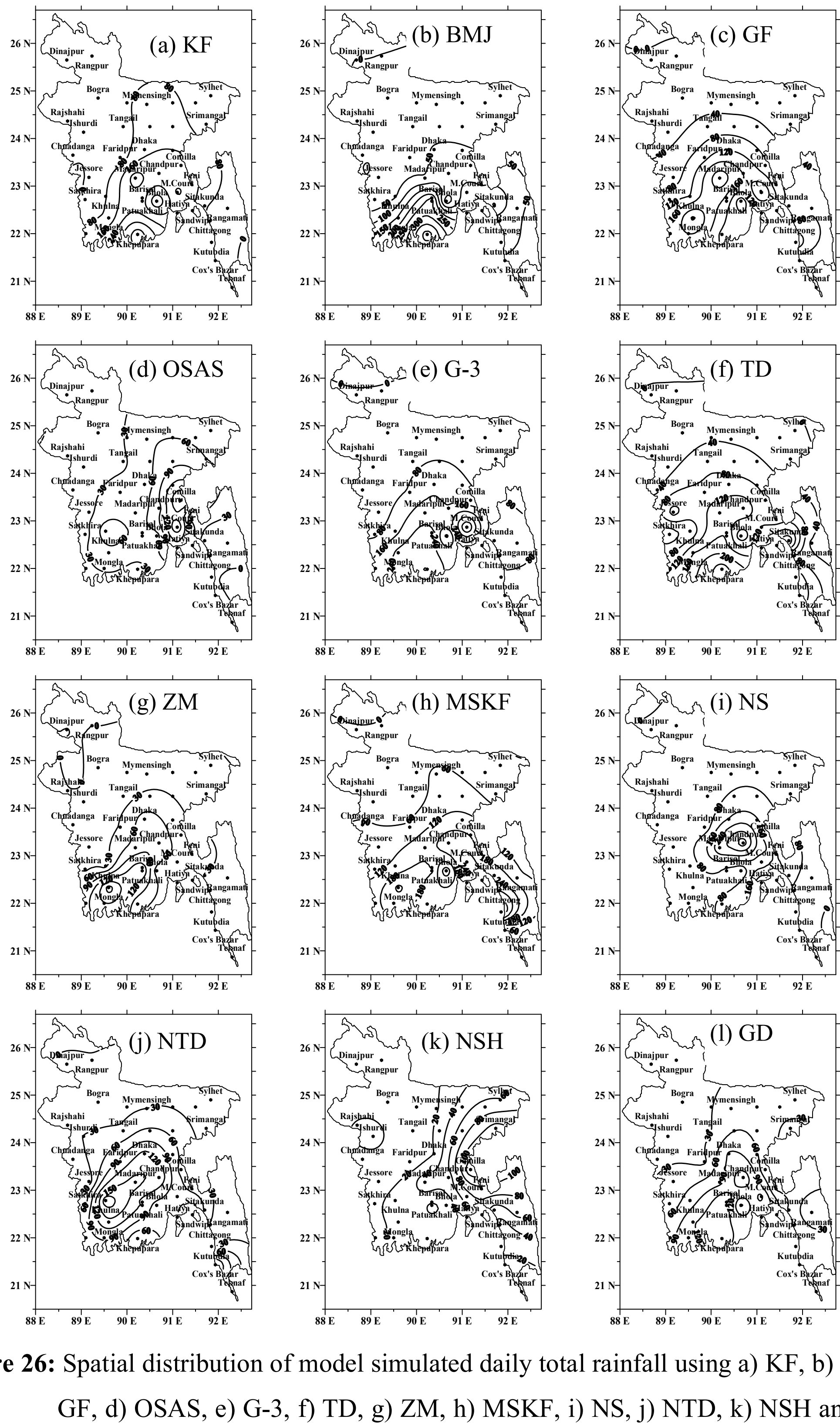

Figure 26: Spatial distribution of model simulated daily total rainfall using a) KF, b) BMJ, c) GF, d) OSAS, e) G-3, f) TD, g) ZM, h) MSKF, i) NS, j) NTD, k) NSH and l) GD schemes in combination with WDM6 scheme on 24 July with the initial conditions at 23 July 2017.

The TD scheme has simulated heavy to VHR and HR (Figure 26f) in the S-SW, eastern and SE regions, MHR in the northern regions and LR in the NW and NE regions of Bangladesh. Maximum total rainfall is simulated at Khepupara, Sitakunda, Sandwip, Patuakhali, Mongla, Hatiya, Kutubdia, Madaripur, Cox-Bazar, Barishal, Chandpur, Dhaka and Jashore regions are 262, 235, 189, 160, 159, 154, 153, 152, 150, 147, 148, 140 and 122 mm respectively. The simulated position of HR by TD scheme is matched with observed position in the S-SE region but the amount is very high than that of observed. The ZM scheme has simulated heavy to VHR (Figure 26g) in the S-SW regions, MHR in the central regions and LR in the W-NW and NE regions of Bangladesh. Maximum total rainfall is simulated at Mongla, Patuakhali, Barishal and Chandpur regions are 195, 148, 137 and 88 mm respectively. The simulated total rainfall by ZM scheme is not matched with the observed HR all over the country.

The MSKF scheme has simulated heavy to VHR (Figure 26h) in the S-SW and E-SE regions, MHR in the western and NE regions and LR in the NW regions of Bangladesh. Maximum total rainfall is simulated at Kutubdia, M.Court, Chittagong, Sandwip Mongla, Chandpur, Sitakunda, Hatiya, Patuakhali, Cumilla, Barishal, Madaripur and Feni regions are 458, 309, 298, 296, 254, 221, 229, 202, 193, 177, 175, 168 and 149 mm respectively. MSKF scheme is match. The simulated HR position by MSKF scheme is matched with the observed HR position in the S-SE regions but the amount is not matched. The NS scheme has simulated heavy to VHR (Figure 26i) in the southern and eastern regions, MHR in the western and NE regions and LR in the NW regions of Bangladesh. Maximum total rainfall is simulated at Chandpur, Hatiya, Madaripur, Sandwip, Feni, Dhaka, Sitakunda, Cumilla and M.Court regions are 452, 326, 306, 236, 166, 163, 127, 122 and 107 mm respectively. The simulated HR by NS scheme is not matched with the observed HR and its position.

The NTD scheme has simulated heavy to VHR (Figure 26j) in the central to SW, eastern and SE regions, MR in the western and NE regions and LR in the NW regions of Bangladesh. Maximum total rainfall is simulated at Khulna, Cox-Bazar, Barishal, Sandwip, Chandpur, Mongla, Dhaka, Patuakhali and Madaripur regions are 202, 166, 159, 152, 146,142, 129, 118 and 109 mm respectively. NTD scheme has simulated maximum rain in the central region but the position is shifted from Faridpur to Madaripur Khulna regions. The NSH scheme has simulated heavy to VHR (Figure 26k) in the eastern and NE regions, MR in the northern and western regions and LR in the NW regions of Bangladesh. Maximum total rainfall is simulated at Cumilla, Srimangal and Feni regions are 138, 109 and 95 mm respectively. The simulated HR amounts and position by NSH scheme could not match. The GD scheme has simulated heavy to VHR (Figure 26l) in the central to S-SW and eastern regions, MR in the SE regions and LR in the NW regions of Bangladesh. Maximum total rainfall is simulated at Barishal, Patuakhali, Chandpur, Hatiya, Khepupara, M.Court and Mongla regions are 150, 148 140, 116, 134, 128 and 117 mm respectively. The simulated HR by GD scheme is matched with observed HR position in the S-SW region but not in other regions.

4.3.5 Model simulated daily Convective rain on 23 July

The model predicted daily CR for different CP schemes in combination with WDM6 scheme on 23 July 2017 are presented in Figure 27(a-l) with the initial conditions of 0000 UTC of 23 July. The KF scheme has simulated MHCR to HCR (Figure 27a) in the S-SE regions, MCR in the western and SW regions and light CR in the N-NW regions of the country. Maximum CR is found at Kutubdia, Chittagong, Khepupara, Sandwip and Bhola regions are 86, 70, 62, 42 and 41mm respectively during 24 hour period. The significant amount of CR is simulated by KF scheme in the S-SE regions of the country. The BMJ scheme has simulated insignificant (Figure 27b) amount of CR all over the country. The GF scheme has simulated heavy to VHCR (Figure 27c) in the S-SE regions, MHCR in the SW regions, MCR in the E-NE and NW and LCR in the western regions of Bangladesh. The simulated maximum CR at Kutubdia, Chittagong, Teknaf, Cox-Bazar, Hatiya, Khepupara and Mongla regions are 100, 82, 62, 59, 59, 56 and 57 mm respectively. The amount of convective rain simulated by GF scheme is significant but it also lower than NCR in the S-SE regions of the country. The OSAS scheme has simulated HCR (Figure 27d) in the SE region, moderate to MHCR in the southern regions and light CR in all other regions of Bangladesh. Maximum CR is simulated at Sandwip, Hatiya, Cox-Bazar, Kutubdia and Teknaf regions are 92, 73, 65, 69 and 64 mm respectively. The amount of convective rain simulated by OSAS scheme is significant but it also lower than that of NCR in the S-SE regions of the country. The G-3 scheme has simulated HCR (Figure 27e) in the S-SE and SW regions, MHCR in the northern regions and moderate CR in the NE regions and LCR in the central to western and NW regions of Bangladesh. Maximum CR is simulated at Sandwip, Chittagong, Kutubdia, Cox-Bazaar, Teknaf, Khepupara, Mongla and Sitakunda regions are 88, 85, 79, 65, 65, 52, 48 and 49 mm respectively. The amount of convective rain simulated by G-3 scheme is significant but it is also lower than that of NCR in the S-SE and SW regions and higher in the northern region of the country. The TD scheme has simulated MCR (Figure 27f) in the SE and SW regions and LCR all over the country. Maximum CR is simulated at Cox-Bazar and Kutubdia regions are

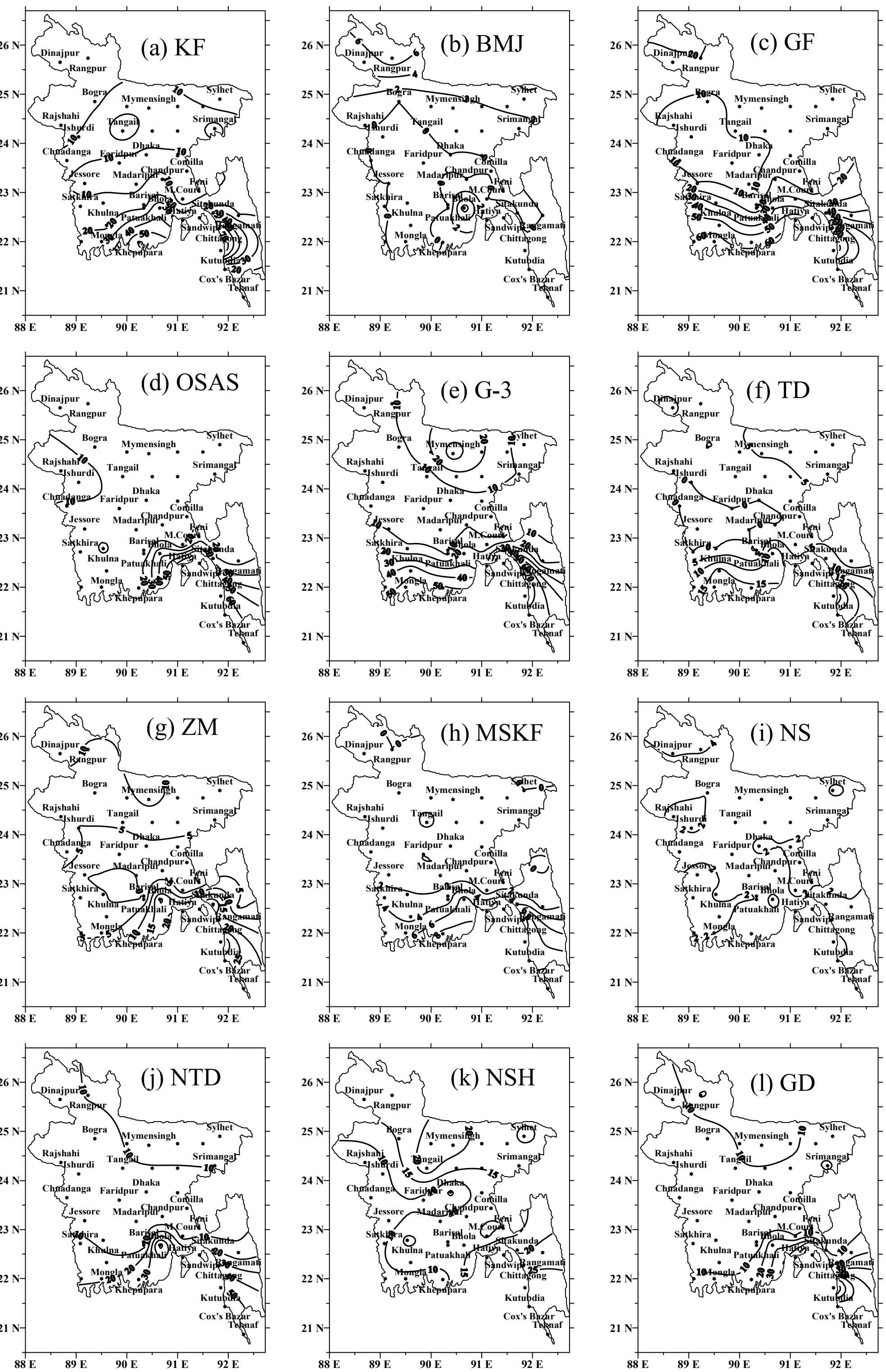

Figure 27: Spatial distribution of model simulated daily CR using different CP schemes in combination with WDM6 scheme on 23 July 2017 all over Bangladesh.

22 and 37 mm respectively and convective rain are insignificant. The ZM scheme has simulated MCR (Figure 27g) in the S-SE regions and LCR in the eastern towards western

along the central region and NE regions of Bangladesh. The maximum CR is simulated at Bhola, Cox-Bazar, Hatiya, Kutubdia and Sandwip regions are 21, 27, 20, 36 and 24 mm. The simulated convective rain is insignificant. The MSKF scheme has simulated moderate CR (Figure 27h) at Chittagong, Kutubdia, Sandwip and Teknaf regions and LCR in the S-SW and northern regions of Bangladesh. The NS scheme has simulated LCR (Figure 27i) all over Bangladesh. The NTD scheme has simulated moderately heavy to HCR (Figure 27j) in the S-SE regions and MCR and in the SW, NE and northern regions and LCR in other regions of Bangladesh. Maximum CR is simulated at Bhola, Cox-Bazar, Chittagong, Kutubdia, Sandwip and Teknaf regions are 56, 57, 35, 52, 39 and 51 mm respectively. The simulated CR by NTD scheme is significant in the S-SE and SW regions. The NSH scheme has simulated MCR (Figure 27k) all over Bangladesh. The maximum CR is simulated at Chittagong, Cox-Bazar, Kutubdia, Mymensingh, Sandwip and Teknaf regions are 23, 26, 29, 23, 29 and 25 mm respectively. The simulated by NSH scheme CR is significant in the S-SE and SW regions. The GD scheme has simulated HCR (Figure 27k) in the S-SE regions, MCR in the southern and northern regions and LCR all other regions of Bangladesh. The maximum CR is simulated at Hatiya, Kutubdia, Sandwip and Teknaf regions are 48, 88, 85 and 44 mm respectively.

4.3.6 Model simulated daily Convective rain on 24 July

The model predicted daily CR for different CP schemes in combination with WDM6 scheme on 24 July 2017 are presented in Figure 28(a-l) with the initial conditions of 0000 UTC of 24 July. The KF scheme has simulated HCR to VHCR (Figure 28a) in the southern and eastern regions, MCR in the northern and SE regions and LCR in the west, SE and N-NW regions of the country. Maximum rainfall is simulated at Hatiya, Chandpur, Sandwip and M.Court regions are 137, 67, 58 and 50 mm respectively. The simulated rain by KF scheme is mainly convective at Hatiya and M. Court regions. The BMJ scheme has simulated LCR (Figure 28b) at Bhola, Hatiya Cox-Bazar and Teknaf regions. Maximum CR is simulated at Bhola and Hatiya regions are 14 and 10 mm respectively. The BMJ scheme has simulated insignificant amount of CR. The GF scheme has simulated moderately heavy to HCR (Figure 28c) in the S-SW, eastern and northern regions, MCR in the western, SE and NE regions and LCR in the NW regions of Bangladesh. Maximum CR is simulated at Hatiya, Mongla, M.Court and Barishal regions are 67, 57, 53, 51 mm respectively. GF scheme has simulated HCR but the amount of CR is lower than that of NCR.

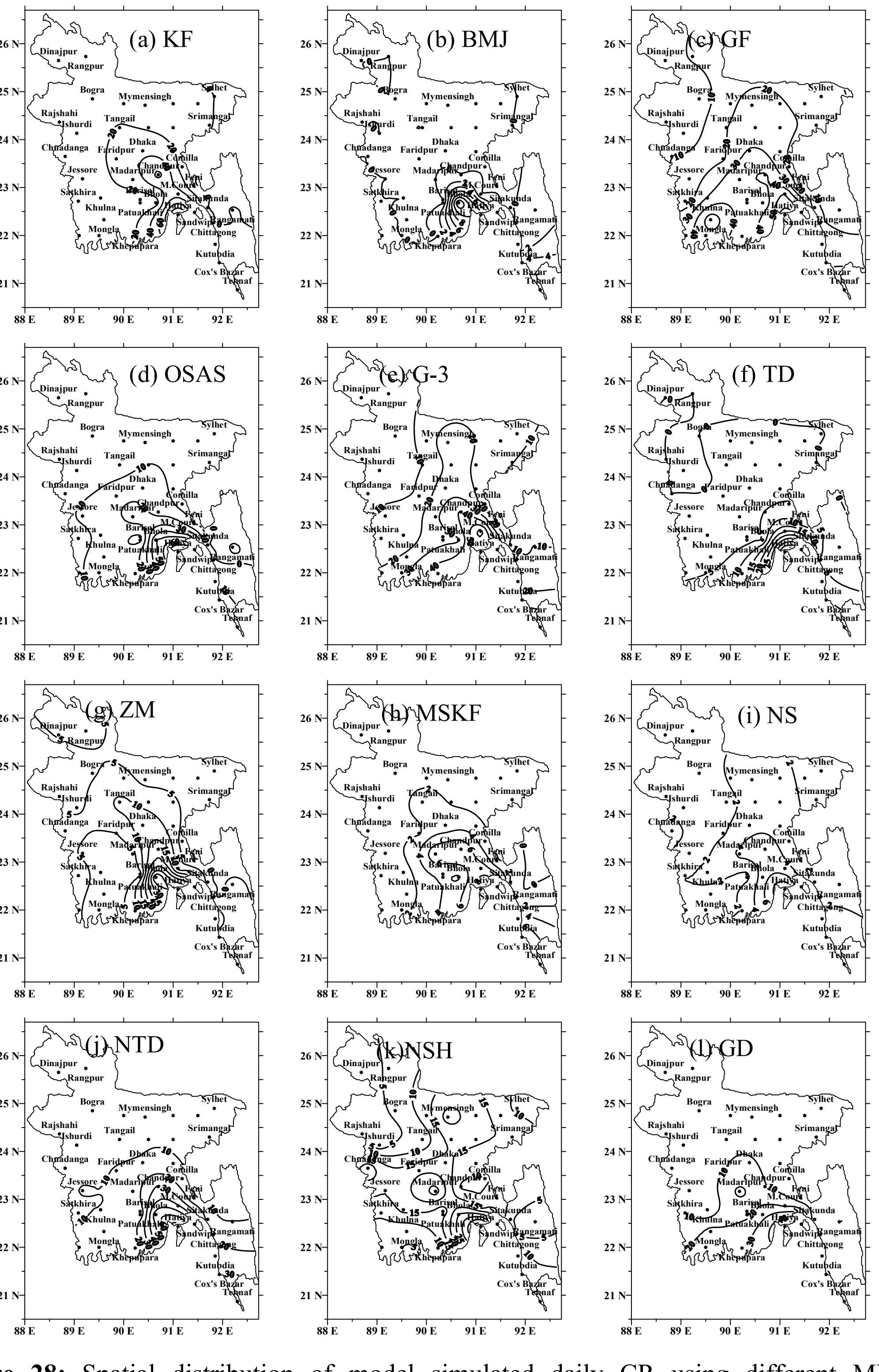

Figure 28: Spatial distribution of model simulated daily CR using different MPs in combination with WDM6 scheme on 24 July 2017 all over Bangladesh.

The OSAS scheme has simulated HCR (Figure 28d) in Hatiya, Sandwip and Bhola regions, and LCR in the SW, NE and NW regions of Bangladesh. Maximum rainfall is simulated at

Hatiya, Sandwip, Bhola and M.Court regions are 85, 77, 49 and 27 mm respectively. OSAS scheme has simulated HCR at Hatiya, Sandwip, Bhola regions but in other regions the CR is insignificant. The G-3 scheme has simulated HCR (Figure 28e) in the central to southern regions, MCR in the NE and SW region and LCR in the W-NW regions of Bangladesh. Significant amount of CR is simulated at M.Court, Hatiya, Khepupara and Sandwip regions are 65, 57, 47 and 49 mm respectively. The rain simulated by G-3 scheme mainly convective at Hatiya and M. Court region. The TD scheme has simulated HCR (Figure 28f) at Hatiya and Sandwip regions and LR in all other regions of Bangladesh. Significant amount of CR is simulated at Hatiya and Sandwip regions are 49 and 43 mm respectively. The TD scheme has simulated insignificant amount of CR.

The ZM scheme has simulated MHCR (Figure 28g) at Bhola, Hatiya and Sandwip regions, MCR in the central regions and LCR all other regions of Bangladesh. Significant amount of CR is simulated at Bhola, Hatiya and Sandwip regions are 41, 37 and 29 mm respectively.ZM scheme has simulated significant amount of CR at Bhola and Hatiya but the amount is lower than that of NCR. The MSKF scheme has simulated LCR (Figure 28h) most of the regions of Bangladesh and no CR in the western regions of the country. MSKF scheme has simulated insignificant amount of CR. The NS scheme has simulated LCR (Figure 28i) all over Bangladesh. The simulated CR by NS scheme is insignificant. The NTD scheme has simulated moderately heavy to HCR (Figure 28j) at Bhola and Hatiya, regions and LCR in the western, N-NE and NW regions of Bangladesh. Significant amount of CR is simulated at Bhola, Hatiya, M.Court, Sandwip and Teknaf regions are 57, 78, 41, 47 and 42 mm respectively. The rainfall simulated by NTD in the SE regions mainly convective. The NSH scheme has simulated moderate to MHCR (Figure 28k) in the southern, eastern northern, NE and SE regions but LCR all other regions of Bangladesh. Significant amount of CR is simulated at Hatiya, Bhola, Chuadanga and Madaripur regions are 48, 25, 24 and 28 mm respectively. The GD scheme has simulated MHCR (Figure 28l) in the southern regions, and MCR and LR all other regions of Bangladesh. Significant amount of CR is simulated at Sandwip, Hatiya, Bhola and Khepupara regions are 58, 54, 26 and 28 mm respectively.

4.3.7 Model simulated daily Non-Convective rain on 23 July

The model predicted daily non-convective rainfall for different CP schemes in combination with WDM6 scheme on 23 July 2017 are presented in Figure 29(a-l) with the initial conditions of 0000 UTC of 23 July. The KF scheme has simulated heavy to VHNCR (Figure 29a) in the S-SE regions, MNCR to HNCR in the SW and NE regions, MNCR in the northern and SW regions and LNCR in the western and NW regions of Bangladesh. Maximum NCR is simulated at Rangamati, Chittagong, Kutubdia, Khepupara and Mongla regions are 223, 165, 145, 132 and 104 mm respectively. The rainfall simulated by KF scheme mainly non-convective in the eastern and S-SE regions of the country. The BMJ scheme has simulated heavy to VHNCR (Figure 29b) in the S-SE and SW regions, and MNCR in the central to N-NE regions and LNCR in the western region of Bangladesh. The simulated maximum rainfalls are Chittagong, Teknaf, Rangamati, Sitakunda, Kutubdia and Cox-Bazar regions are 288, 196, 166, 151, 151 and 148 mm respectively. The rainfall simulated by BMJ scheme mainly non-convective all over the country. The GF scheme has simulated heavy to VHNCR (Figure 29c) in the S-SW and E-SE regions, MHNCR in the NE regions and LNCR in the W-NW regions of Bangladesh. The simulated maximum NCR is found at Chittagong, Feni, Cox-Bazar, Kutubdia, Rangamati and Sitakunda regions are 187, 150, 143, 149 and 112 mm respectively. The simulated NCR by GF scheme is higher than that of CR all over the country. The OSAS scheme has simulated heavy to VHNCR (Figure 29d) in S-E and NE regions, MHNCR in the eastern and SW regions, light NCR in the W-NW and northern regions of Bangladesh. The maximum NCR is simulated at Chittagong, Feni, Cox-Bazar, Rangamati and Srimangal regions are 172, 169, 92 and 81 mm respectively. OSAS scheme has simulated mainly non-convective in the central to SE regions of the country. The G-3 scheme has simulated heavy to VHNCR (Figure 29e) in the S-SE and eastern regions, MNCR in the northern and NE region and LNCR in the western and NW regions of Bangladesh. Maximum NCR is simulated at Chittagong, Sitakunda, Sandwip, Rangamati, Feni, Mongla, Barishal, M.Court, Khepupara and Khulna regions are 219, 210, 196, 155, 132, 124, 96, 94, 89 and 85 mm respectively.The rainfall simulated by G-3 scheme mainly non-convective in the S-SE and SW regions of the country and other regions have simulated convective rain.

The TD scheme has simulated heavy to VHNCR (Figure 29f) in the S-SE and SW regions, MHNCR at central region, MNCR in the NE regions and LNCR in the SW and NW regions of Bangladesh. The simulated maximum NCR at Khulna, Rangamati, Khepupara, Chittagong, Sitakunda, Patuakhali, Mongla, Barishal, Sandwip, Madaripur, Kutubdia, Cox-Bazar, Hatiya and Feniregions are 332, 254, 205, 175, 149, 139, 137, 136, 132, 120, 116, 106, 116and 85 mm respectively. The rainfall simulated by G-3 scheme mainly non-convective in the S-SE and SW regions of the country. The ZM scheme has simulated heavy to VHNCR (Figure 29g) in the S-SW and SE regions, MHR in the central regions and LR in the W-NW regions of Bangladesh. The maximum NCR is simulated at Rangamati, Kutubdia, Mongla, Chittagong, Cox-Bazar and Sitakunda regions are 167, 156, 152, 83, 76 and 83 mm respectively. The simulated rainfall by ZM scheme is almost non-convective in the SE and SW regions. The MSKF scheme has simulated heavy to VHNCR (Figure 29h) in the S-SW and SE regions, MHR in the central to NE regions, MR in the N-NW and LR in the western regions of Bangladesh. The NCR is simulated maximum at Chittagong, Cox-Bazar, Rangamati, Patuakhali, Khepupara, Mongla, Barishal, Chandpur, Kutubdia, Sandwip and Khulna regions are 296, 208, 208, 161, 155, 148, 138, 124, 126, 126 and 109 mm respectively. The rainfall simulated by MSKF scheme mainly non-convective in the S-SW and SE regions of the country. The NS scheme has simulated heavy to VHNCR (Figure 29i) in the S-SE and SW regions, MHNCR in the NE region, MNCR in the northern and LNCR in the western and NW regions of Bangladesh. The maximum NCR is simulated at Chittagong, Rangamati, Sandwip, Kutubdia, Khepupara, Chandpur and Sitakunda regions are 247, 219, 171, 166, 159, 106 and 106 mm. The rainfall simulated by NS scheme mainly non-convective in the S-SE and SW regions of the country.

The NTD scheme has simulated heavy to VHNCR (Figure 29j) in the S-SW and SE regions, MHNCR in the central to eastern regions, MNCR in the N-NW and LNCR in the western regions of Bangladesh. The maximum NCR is simulated at Mongla, Khepupara, Rangamati, Kutubdia, Chittagong and Satkhira regions are 142, 124, 124, 101 and 110 mm respectively. The rainfall simulated by NTD scheme mainly non-convective in the S-SE and SW regions of the country. The NSH scheme has simulated heavy to VHNCR (Figure 29k) in the S-SE regions, MHNCR in the NE regions, MNCR in the SW regions and LR in the W-NW regions of Bangladesh. The maximum NCR is simulated at Sandwip, Chittagong, Hatiya and Rangamati are 202,157, 135 and 129 mm respectively. The rainfall simulated by NSH scheme mainly non-convective in the S-SE and SW regions of the country. The GD scheme has simulated moderate to MHNCR (Figure 29l) in the S-SE and central to SW regions, MNCR in central to NE regions and LNCR in the W-NW regions of Bangladesh. Maximum NCR is simulated at Chittagong, Rangamati, Khepupara, Mongla, Barishal, Cox-Bazar, Feni and Kutubdia regions are 119, 101, 97, 92, 81, 89, 86 and 85 mm respectively. The rainfall simulated by GD scheme mainly non-convective in the S-SE and SW regions of the country.

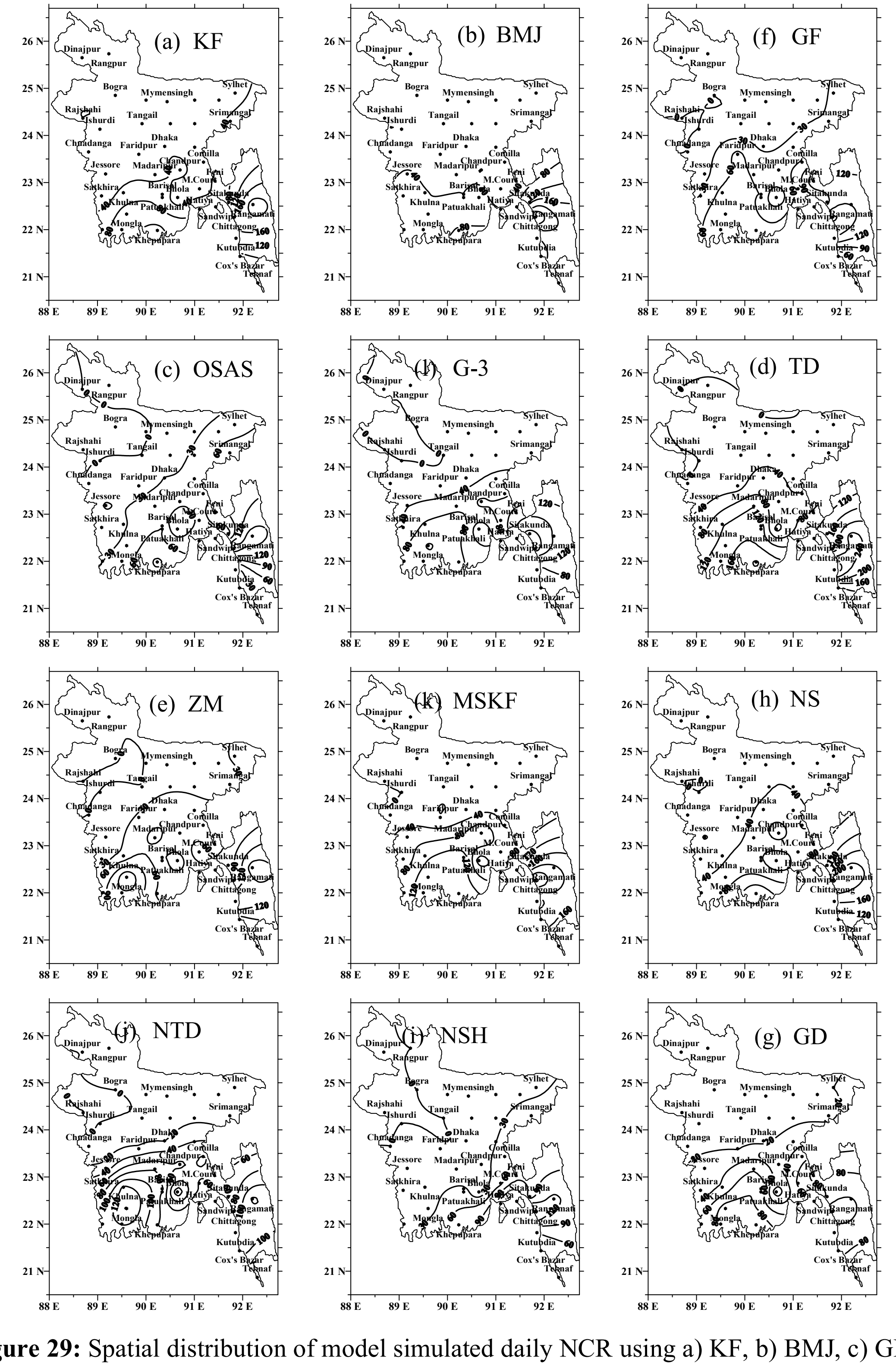

Figure 29: Spatial distribution of model simulated daily NCR using a) KF, b) BMJ, c) GF, d) OSAS, e) G-3, f) TD, g) ZM, h) MSKF, i) NS, j) NTD, k) NSH and l) GD schemes in combination with WDM6 scheme on 23 July 2017 all over Bangladesh.

4.3.8 Model simulated daily Non-Convective rain on 24 July

The model predicted daily NCR for different CP schemes in combination with WDM6 scheme on 24 July 2017 are presented in Figure 30(a-l) with the initial conditions of 0000 UTC of 24 July. The KF scheme has simulated heavy to VHNCR (Figure 30a) in the central to eastern and SW regions, moderate to MHNCR in the western, northern and NE regions and LNCR in the SE and NW regions of Bangladesh. Maximum NCR is simulated at Mongla, Patuakhali, Barishal, Cumilla, Madaripur and M.Court regions are 140, 94, 84, 83, 83 and 85 mm respectively. The rainfall simulated by KF scheme mainly non-convective in the central to eastern and SW regions of the country. The BMJ scheme has simulated heavy to VHNCR (Figure 30b) in the central to eastern and southern regions, moderate to MHNR in the SW, SE and NE regions and LR in W-NW regions of Bangladesh. Maximum NCR is simulated at Khepupara, Hatiya, Feni, M. Court and Patuakhali regions are 210, 186, 182, 98, and 80 mm respectively. The simulated rainfall by BMJ scheme is mainly non-convective all over the country. The GF scheme has simulated moderately heavy to HNCR (Figure30c) in the S-SW, eastern and northern regions, MNCR in the NE and western regions and LNCR in the NW and SE regions of Bangladesh. The maximum NCR is simulated at Mongla, Faridpur, Khulna and Chandpur regions are 91, 61, 69 and 57 mm respectively.GF scheme has simulated HNCR all over the country but the amount of NCR is higher than that of CR. The OSAS scheme has simulated heavy to VHNCR (Figure 30d) at Dhaka, Faridpur, Madaripur and Mongla regions, MNCR in the NE and SW regions and LNCR in the SE and NW regions of Bangladesh. Significant amount of NCR is simulated at Dhaka, Faridpur, Madaripur, Mongla and Chandpur regions are 111, 67, 51, 58 and 30 mm respectively. The rainfall simulated by OSAS scheme mainly non-convective.

The G-3 scheme has simulated moderately heavy to HNCR (Figure 30e) in the central to SW and eastern regions, MNCR in the NE and SE region and LNCR in the NW regions of Bangladesh. Significant amount of NCR is simulated at Jashore, Dhaka, Mongla, Madaripur, Cumilla, Satkhira and Feni regions are 73, 66, 66, 59, 54, 51 and 47mm respectively. The G-3 scheme has simulated higher NCR than that of CR in the S-SW and central regions of the country. The TD scheme has simulated heavy to VHNCR (Figure 30f) in the S-SE and central to northern region, MHNCR in the western and NE regions and LR in all other regions of Bangladesh. Significant amount of NCR is simulated at Dhaka, Feni, Faridpur, Madaripur, Mymensingh and Rangamati regions are 95, 92, 71, 65, 74 and 53 mm respectively.TD scheme simulated significant amount of NCR all over the country.

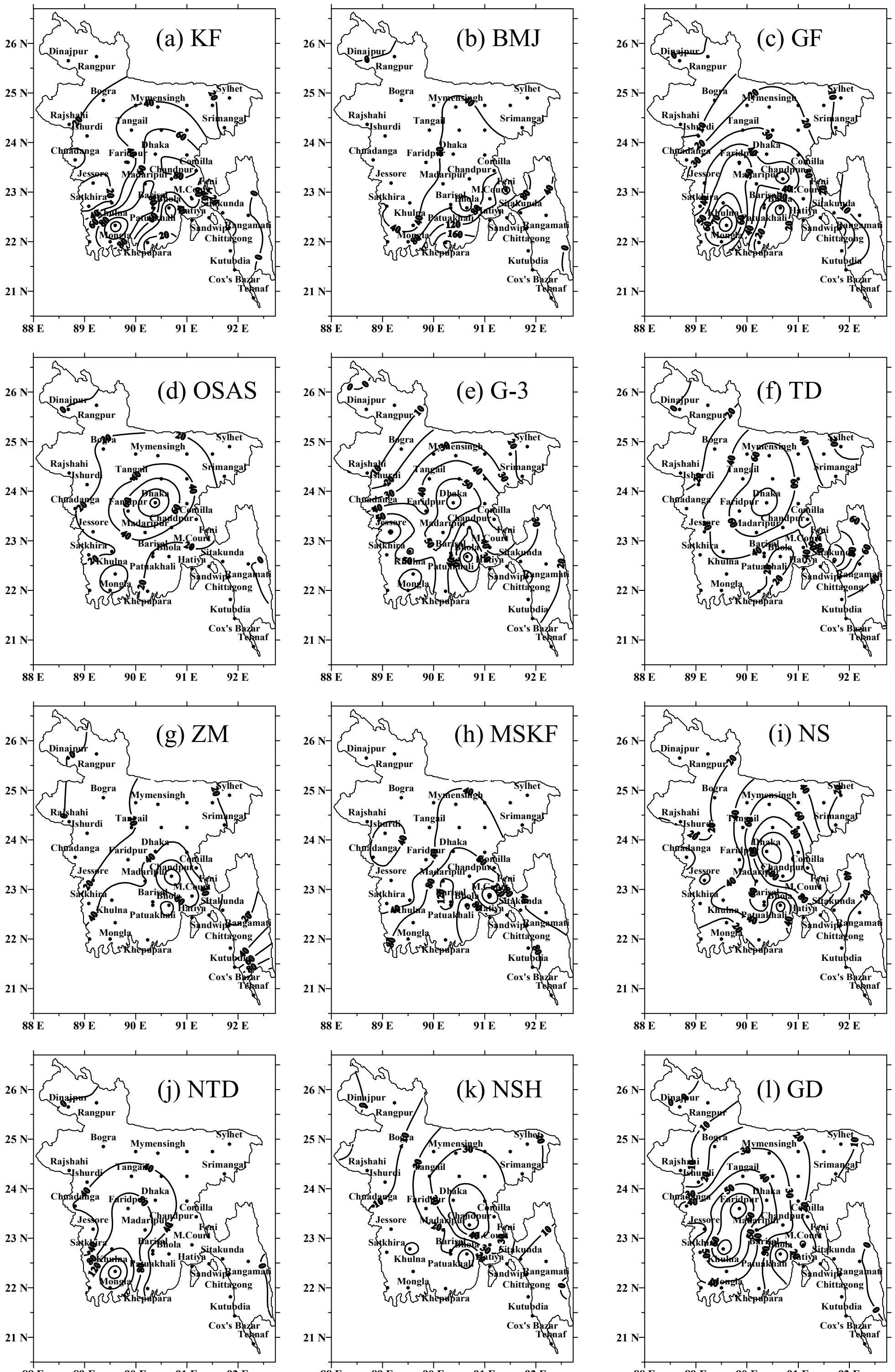

Figure 30: Spatial distribution of model simulated daily NCR using a) KF, b) BMJ, c) GF, d) OSAS, e) G-3, f) TD, g) ZM, h) MSKF, i) NS, j) NTD, k) NSH and l) GD schemes in combination with WDM6 scheme on 24 July 2017 all over Bangladesh.

The ZM scheme has simulated heavy to VHNCR (Figure 30g) in the southern and SE regions, MHNCR in the southern regions, MNCR in the SW and NE regions LNCR in the western and NW regions of Bangladesh. Significant amount of NCR is simulated at Teknaf, Chandpur, M.Court, Hatiya, Khulna and Mongla regions are 167, 99, 78, 53, 57 and 58 mm respectively. The ZM scheme has simulated significant amount of NCR all over the country and mainly NC Chandpur, M. Court and SE regions. The MSKF scheme is simulated heavy to VHNCR (Figure 30h) in the central to S-SW and E-SE regions, MNCR in the NE and LNCR in the NW regions of Bangladesh. Significant amount of rainfall is simulated at M.Court, Barishal, Patuakhali, Madaripur, Mongla and Chandpur regions are 221, 131, 130, 128, 115 and 104 mm respectively. The rainfall simulated by MSKF scheme mainly non-convective all over the country. The NS scheme has simulated heavy to VHNCR (Figure 30i) in the central to southern, eastern and northern regions, MHNCR in the SW and SE regions, MNCR in the western and NE regions of Bangladesh. Significant amount of NCR is simulated at Dhaka, Chandpur, Feni, Hatiya, M.Court and Patuakhali regions are 138, 117, 100, 77, 85 and 76 mm. The NS scheme has simulated NCR all over the country and maximum NCR is found at Dhaka-Chandpur regions.

The NTD scheme has simulated heavy to VHNCR (Figure 30j) in the central to SW regions, MHNCR in the southern, eastern, northern and NE regions light NCR in the NW and SE regions of Bangladesh. Significant amount of NCR is simulated at Mongla, Khulna, Faridpur, Madaripur regions are 237, 114, 110 and 103 mm respectively. The NTD scheme has simulated NCR mainly in the central to SW of the country.

The NSH scheme has simulated moderately heavy to HNCR (Figure 30k) in the central to eastern regions, MNCR in the NW regions and LNCR in the NW and SE regions of Bangladesh. Significant amount of NCR is simulated at Chandpur, Dhaka, M.Court and Mymensingh regions are 59, 43, 30 and 26 mm respectively. The GD scheme has simulated moderately heavy to HNCR (Figure 30l) in the central to W-SW regions, MNCR in the NE regions and LNCR in the NW and SE regions of Bangladesh. Significant amount of NCR is simulated at Faridpur, Khulna, Chuadanga and Dhaka regions are 80, 80, 46 and 45 mm respectively. The rain simulated by GD scheme mainly non-convective.

4.4 Verification methods of different rainfall events

For better prediction of rainfall we try to find out the threat score (TS), equitable threat score (ETS) and bias score (BS) for different heavy rainfall events. TS and ETS are applicable to make out the accuracy of forecasts without the contribution from the correct rejections events. The accuracy of forecasts is higher as TS and ETS approaches to the maximum value of unity.

4.4.1 Verification methods of rainfall event during 3-5 July 2017

The model simulated heavy rain predicted region, predicted area (km^2), observed heavy rainfall region and intersected regions and intersected area (km^2) have been identified for different CPs in combination with WDM6 scheme during 3-5 July 2017 for the initial conditions at 0000 UTC of 3-5 July respectively. The observed HR region lies between 88–92.75°E and 20.5–26.7°N and the area is 336555.2 km^2.

Table 4: TS for different CPs in combination of WDM6 for the HR event of 3-5 July with the initial conditions at 0000 UTC of 3-5 July 2017 respectively

CP schemes	03 July	04 July		05 July		
	24 h	24 h	48 h	24 h	48 h	72 h
KF	0.21	0.38	0.33	0.26	0.41	0.18
BMJ	0.00	0.00	0.30	0.00	0.56	0.00
GF	0.32	0.94	0.64	0.35	0.17	0.00
OSAS	0.27	0.40	0.45	0.34	0.37	0.58
G-3	0.00	0.45	0.40	0.88	0.40	0.19
TD	0.00	0.00	0.32	0.00	0.00	0.26
ZM	0.00	0.00	0.38	0.00	0.46	0.91
MSKF	0.26	0.00	0.39	0.00	0.70	0.25
NS	0.00	0.00	0.00	0.19	0.00	0.00
NTD	0.31	0.37	0.45	0.00	0.65	0.66
NSH	0.32	0.33	0.33	0.31	0.23	0.50
GD	0.22	0.39	0.13	0.52	0.36	0.32

The maximum TS (Table 4) has found for GF and G-3 schemes and their values are 0.94 and 0.88 on 4 and 5 July at 24 hour prediction. The maximum value at 48 hour prediction is found for GF scheme on 4 July is 0.64 and for MSKF and NTD schemes are 0.70 and 0.65 on 5 July. The maximum value of TS at 72 hour prediction is found for ZM and NTD schemes on 5 July are 0.91 and 0.66.The TS scores suggest that for 24 hour prediction GF and G-3 schemes, for 48 hour prediction GF, MSKF and NTD schemes and for 72 hour prediction ZM and NTD schemes give the better forecast among all studied combinations.

The maximum ETS (Table 5) has found for GF and G-3 schemes and their values are 0.93 and 0.86on 4 and 5 July at 24 hour prediction. The maximum value at 48 hour prediction is found for GF scheme on 4 July is 0.56 and for MSKF and NTD schemes are 0.63 and 0.59 on 5 July. The maximum value of ETS at 72 hour prediction is found for ZM and NTD schemes on 5 July are 0.89 and 0.62. The ETS scores suggest that for 24 hour prediction GF and G-3 schemes, for 48 hour prediction GF, MSKF and NTD schemes and for 72 hour prediction ZM and NTD schemes give the better forecast among all studied combinations.

Table 5: ETS for different CPs in combination of WDM6 for the HR event of 3-5 July with the initial conditions at 0000 UTC of 3-5 July 2017 respectively

CP schemes	03 July	04 July		05 July		
	24 h	24 h	48 h	24 h	48 h	72 h
KF	0.12	0.32	0.21	0.14	0.29	0.09
BMJ	-0.06	-0.09	0.19	-0.08	0.50	-0.05
GF	0.21	0.93	0.56	0.23	0.05	-0.11
OSAS	0.17	0.30	0.34	0.22	0.25	0.48
G-3	-0.07	0.33	0.27	0.86	0.26	0.06
TD	-0.07	-0.08	0.20	-0.08	-0.06	0.14
ZM	-0.07	-0.05	0.27	-0.11	0.35	0.89
MSKF	0.17	-0.07	0.27	-0.07	0.63	0.14
NS	-0.08	-0.06	-0.02	0.08	0.04	-0.06
NTD	0.22	0.30	0.32	-0.09	0.59	0.62
NSH	0.23	0.24	0.21	0.17	0.11	0.37
GD	0.15	0.28	0.02	0.46	0.25	0.19

Table 6: BS for different CPs in combination of WDM6 for the HR event of 3-5 July with the initial conditions at 0000 UTC of 3-5 July 2017 respectively

CP schemes	03 July	04 July		05 July		
	24 h	24 h	48 h	24 h	48 h	72 h
KF	1.37	0.50	1.48	1.01	1.40	0.62
BMJ	0.72	0.72	1.17	0.56	0.56	0.31
GF	2.73	0.94	1.25	1.21	0.94	0.84
OSAS	2.19	1.07	1.64	1.16	1.36	1.28
G-3	0.88	1.58	1.65	0.88	1.52	1.21
TD	0.79	0.58	1.37	0.55	0.39	1.06
ZM	0.80	0.34	1.43	0.22	1.06	0.91
MSKF	1.56	0.49	1.48	0.42	0.97	0.90
NS	1.12	0.37	0.14	0.82	0.24	0.40
NTD	1.66	0.61	2.05	0.66	0.72	0.49
NSH	1.81	0.87	1.48	1.50	1.02	1.99
GD	0.91	1.29	1.02	0.52	1.13	1.23

The maximum BS (Table 6) is found for 24 hour prediction in G-3 and NS schemes on 3 July 0.88 & 1.12 and on 5 July 0.88 & 0.82 respectively. GD scheme gives the better performance on 48 hour prediction and TD, ZM and MSKF scheme gives the better performance on 72 hour prediction. The Bias score is greater than 1 for CPs suggests over predictions the rain occurrence and less than 1 refers under predictions of rain occurrence.GF &G-3 and GF &MSKF schemes give the better performance for 24 hour and 48 hour prediction respectively on the basis of Threat Score, Equivalent Threat Score and Bias Score during 3-5 July 2017.

4.4.2 Verification methods of rainfall event during 19-20 July 2017

The maximum TS (Table 7) has found for KF and MSKF schemes and their values are 0.64 & 0.58 on 19 July and 0.49 & 0.65 on 20 July at 24 hour prediction. BMJ, MSKF and GD schemes gives the maximum values are 0.67, 0.63 and 0.71 respectively at 48 hour prediction on 20 July. The maximum ETS (Table 7) has found for KF and MSKF schemes and their values are 0.51 and 0.59 on 19 and 20 July respectively for 24 hour prediction. BMJ, MSKF and GD schemes gives the maximum values are 0.60, 0.55 and 0.64 respectively at 48 hour prediction on 20 July. The obtained TS and ETS scores suggest that the KF scheme in combination with WDM6 scheme gives the better forecast among all studied combinations at 24 and 48 hour prediction. The maximum BS (Table 7) is found for KF and G-3 schemes at 24 hour prediction and NS and NSH schemes at 48 hour prediction. G-3 and NSH schemes in combination with WDM6 scheme give the better performance. KF and MSKF schemes give the better performance on the basis of Threat Score, Equitable Threat Score and Bias Score on 19-20 July 2017.

Table 7: TS, ETS and BS for different CPs in combination of WDM6 for the HR event of 19-20 July with the initial conditions at 0000 UTC of 19-20 July 2017 respectively

CP schemes	TS			ETS			Bias score		
	19 July	20 July		19 July	20 July		19 July	20 July	
	24 h	24 h	48 h	24 h	24 h	48 h	24 h	24 h	48 h
KF	0.64	0.58	0.41	0.51	0.50	0.35	0.64	0.67	0.41
BMJ	0.27	0.27	0.67	0.13	0.21	0.60	0.45	0.27	0.76
GF	0.21	0.33	0.38	0.12	0.27	0.26	0.24	0.33	0.91
OSAS	0.21	0.45	0.44	0.14	0.38	0.34	0.21	0.49	0.77
G-3	0.14	0.56	0.47	0.08	0.47	0.37	0.15	0.81	0.71
TD	0.25	0.38	0.24	0.17	0.27	0.14	0.25	0.78	0.61
ZM	0.39	0.50	0.53	0.28	0.41	0.45	0.39	0.71	0.60
MSKF	0.49	0.65	0.63	0.36	0.59	0.55	0.49	0.65	0.69
NS	0.00	0.00	0.42	-0.11	-0.04	0.29	0.33	0.16	1.04
NTD	0.32	0.51	0.43	0.22	0.44	0.36	0.32	0.51	0.49
NSH	0.19	0.33	0.59	0.06	0.27	0.49	0.39	0.33	0.98
GD	0.22	0.50	0.71	0.14	0.41	0.64	0.22	0.71	0.71

4.4.3 Verification methods of rainfall event during 23-24 July 2017

The maximum value of TS (Table 8) is found 0.94, 1.00, 0.85 and 0.71, 0.66, 0.66 for KF, OSAS and G-3 schemes on 23 and 24 July respectively for 24 hour prediction. TD and NSH schemes give the maximum value at 0.80 and 0.64 respectively for 48 hour prediction. The maximum value of ETS (Table 8) is found 0.90, 1.00, 0.74 and 0.59, 0.53, 0.53 for KF, OSAS and G-3 schemes on 23 and 24 July respectively for 24 hour prediction. TD and NSH schemes give the maximum value at 0.69 and 0.50 respectively for 48 hour prediction. The maximum value of BS (Table 8) is found 0.94, 1, 1.06 and 0.97 for KF, OSAS, TD and NS schemes respectively at 24 hour prediction for 23 July. TD and NSH schemes perform better for 48 hour prediction.

TD and KF schemes give the better performance on the basis of Threat Score, Equitable Threat Score and Bias Score for the prediction of HR during 23-24 July 2017.

Table 8: TS, ETS and BS for different CPs in combination of WDM6 for the HR event of 23-24 July with the initial conditions at 0000 UTC of 23-24 July 2017 respectively

CP schemes	TS			ETS			Bias score		
	24 h	24 h	48 h	24 h	24 h	48 h	24 h	24 h	48 h
KF	0.94	0.71	0.41	0.90	0.59	0.28	0.94	0.71	0.41
BMJ	0.55	0.36	0.25	0.41	0.24	0.16	0.55	0.36	0.25
GF	0.45	0.64	0.54	0.31	0.50	0.40	0.49	0.64	0.54
OSAS	1.00	0.66	0.43	1.00	0.53	0.30	1.00	0.66	0.43
G-3	0.85	0.66	0.33	0.74	0.53	0.22	1.18	0.66	0.33
TD	0.75	0.75	0.80	0.59	0.63	0.69	1.06	0.75	0.80
ZM	0.73	0.24	0.47	0.56	0.16	0.34	1.09	0.24	0.47
MSKF	0.73	0.47	0.46	0.56	0.33	0.31	1.09	0.47	0.53
NS	0.81	0.45	0.37	0.70	0.32	0.25	0.97	0.45	0.37
NTD	0.68	0.53	0.54	0.48	0.39	0.40	1.17	0.53	0.54
NSH	0.89	0.49	0.64	0.83	0.35	0.50	0.89	0.49	0.64
GD	0.64	0.62	0.46	0.42	0.48	0.32	1.14	0.62	0.46

Chapter V

Conclusions

In the present study the Advanced Research WRF (ARW) v3.8.1 model have been used to simulate the heavy rainfall events in the southern and southeastern regions of Bangladesh during 3-5 and 19-20 July 2017 and southern, eastern and southeastern region during 23-24 July 2017. In this research convective rain and non-convective rain have been studied to observe the impact of these rainfalls on total rainfall. The different verification methods such as TS, ETS and BS have been studied to identify the performance of different cumulus parameterization schemes. The following conclusions have been drawn:

- The simulated total rainfall by BMJ, GF, OSAS, G-3, TD, ZM, NSH and NS schemes are matched with observed HR in the NW regions but it could not simulate HR in the S-SE regions on 3 July 2017. The simulated HR by KF, NTD, GD schemes are matched with the observed heavy to VHR in the NW and SE regions, but it could not predicted HR in the southern regions. MSKF could simulate HR in the SE region, shifted from NW to NE regions and could not simulate HR in the southern region on 3 July 2017.
- The simulated position and amount of HR by KF, MSKF and G-3 schemes are found to match with the observed heavy to VHR in the S-SE and NE regions on 4 July 2017. The simulated total rainfall by ZM and NS schemes are matched with the observed HR position in the NE regions, NTD and GD schemes are matched with the observed HR position in the SE regions and GF scheme is matched with the observed rain in the SW regions of Bangladesh. The BMJ, TD scheme has not simulated and matched with the observed HR regions all over Bangladesh 4 July 2017. The simulated HR by G-3, NTD, NSH and GD schemes are almost matched with the observed HR but the amount is low on 5 July 2017. GF and OSAS schemes have not simulated any HR on this day.
- The maximum simulated rain by KF scheme mainly convective in the SE and NE regions of Bangladesh on 3 July 2017. GF, ZM, NTD, NSH and GD have simulated significant amount of CR in the central region but not in the HR area on 3 July 2017. BMJ, TD, MSKF and NS schemes have simulated insignificant amount of CR.
- KF, OSAS, G-3, NTD and GD schemes have simulated significant amount of CR in SE regions of the country and other CPs have simulated insignificant amount on 4 July.
- The observed rain from central N-NE regions mainly convective. The simulated rain mainly convective by KF, GF, OSAS, G-3, TD, NTD, NSH and GD schemes in the

central to NE and NW regions but not in the heavy rain area 5 July 2017. The amount of CR is insignificant in comparison with the observed rainfall. BMJ, ZM, MSKF, NS schemes have simulated insignificant amount of CR on 5 July 2017.

- The position and amounts of observed HR are matched with the simulated total rainfall by KF, BMJ, GF, G-3, TD, NTD and GD schemes but the schemes are not simulated HR in the central regions on 19 July 2017. The ZM scheme could not simulate HR, MSKF scheme has simulated HR in the SE regions and shifted from Dhaka to Faridpur regions and NS scheme has simulated HR at Dhaka regions and it could not simulate any rain in the SE regions on 19 July 2017.
- The amounts and position of HR simulated by MSKF scheme is matched with its positions in the SE and SW regions and BMJ scheme in the SE region of Bangladesh on 20 July 2017. The simulated position of HR by KF, OSAS, G-3, TD, NS, NTD, NSH and GD schemes are matched with observed total rainfall position in the SE regions but the amounts of rainfall are not matched and could not simulate HR in the SW regions on 20 July 2017. The position of simulated HR by GF scheme is matched in the SE and SW regions but the amounts of rainfall is not matched. Among these MSKF and BMJ schemes have shown better performance all over Bangladesh on 20 July.
- The rainfall simulated by KF, BMJ, OSAS, G-3, TD, ZM, NTD, NSH and GD schemes are mainly convective in the S-SE regions but it is insignificant in other regions of the country on 19 July 2017. OSAS, G-3, TD, ZM, NTD, NSH and GD have simulated higher amount of CR than that of NCR and KF, BMJ, GF, MSKF and NS scheme have simulated lower amount of CR than that of NCR on 20 July 2017.
- The rainfall simulated by BMJ, G-3, TD, MSKF and NS schemes are mainly non-convective and insignificant by KF, GF, OSAS, ZM, NTD, NSH and GD schemes on 19 July 2017. The rainfall simulated by KF, BMJ, GF, OSAS, TD, MSKF and NS schemes are mainly non-convective in different regions of the country and insignificant by NTD, NSH and GD schemes on 20 July 2017.
- The simulated rainfall by KF, GF, OSAS, G-3, ZM schemes are almost matched with the observed heavy to VHR position and amounts all over the country and MSKF, NS, NSH, GD schemes matched with observed rain and little shifting its position from central to SE and SW regions on 23 July 2017. The TD and NTD schemes simulated lower amount of rainfall all over the country on 23 July 2017.

- OSAS, TD, ZM, MSKF, G-3 and NS schemes have simulated HR in the central and SE regions but their positions are shifted towards S-SE regions on 24 July 2017. The simulated rainfall by KF, BMJ schemes are matched with the observed rainfall in the SE regions but it could not match HR at Tangail-Faridpur regions, by NTD and GD schemes could not match in the SE regions but it could match in the Faridpur region, by GF and NSH schemes could not match all over the country on 24 July 2017.
- The significant amount of CR is simulated by KF, NTD and NSH schemes in the S-SE regions and GF, OSAS and G-3 schemes is also simulated significant amount of CR but it is lower than NCR in the S-SE regions of the country and other schemes simulated insignificant amounts of CR on 23 July 2017.
- The significant amount of CR is simulated by KF, NTD and G-3 schemes in the S-SE regions and GF, OSAS, ZM, NSH, GD schemes is also simulated significant amount of CR but it is lower than NCR in the S-SE regions of the country and BMJ, TD, MSKF and NS schemes have simulated insignificant amounts of CR on 24 July 2017.
- The simulated rainfall by KF, BMJ, OSAS, MSKF and GD schemes mainly non-convective all over the country and all other CPs have simulated higher amount of NCR than that of CR on 23 and 24 July 2017.
- The model simulated rainfall mainly convective for KF, GF, OSAS, G-3, TD, ZM, NTD, NSH and schemes and mainly non-convective for BMJ, MSKF and NS schemes during all over Bangladesh during 3-5 July 2017.
- BMJ, MSKF and NS schemes have simulated higher NCR and all other cumulus parameterization schemes have simulated higher CR all over Bangladesh during 19-20 July 2017. OSAS and NSH schemes have simulated higher convective rain and all other cumulus parameterization schemes have simulated higher non-convective rain all over Bangladesh during 23-24 July 2017. It is also seen that during the two simulation periods (i.e., 3-5 and 23-24 July 2017) the CR is found to decrease continuously and NCR increased during the period and opposite in case of 19-20 July 2017.
- GF and G-3, GF and MSKF schemes give the better performance for 24 hour and 48 hour prediction respectively on the basis of Threat Score, Equivalent Threat Score and Bias Score during 3-5 July 2017. On the basis of Threat Score, Equitable Threat Score and Bias Score for the prediction of HR KF and MSKF schemes during 19-20 July 2017, TD and KF schemes during 23-24 July 2017give the better performance.

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Conference Publication

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