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SIMULATION OF MONSOON RAINFALL OVER BANGLADESH USING WRF-ARW MODEL – A CASE STUDY OF 2014

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ABSTRACT

The present study attempts to simulate the rainfall of monsoon season over Bangladesh using Weather Research and Forecasting (WRF) model during June-September 2014. Initial boundary conditions, Final Analysis (FNL) data (1°×1°) were used from National Center for Environmental Prediction (NCEP) to simulate the monsoon rainfall. The WRF model run for everyday 0000 UTC initial conditions for 24, 48 and 72 hours for the prediction of daily rainfall of monsoon season of 2014. In this research WSM6-class graupel and Kain-Fritsch (KF) schemes have been used for simulating the daily rainfall monsoon season. The simulated rainfall was compared with Bangladesh Meteorological Department (BMD) observed and Tropical Rainfall Measuring Mission (TRMM) retrieved rainfall. The BMD observed and 24, 48, and 72 hours simulated rainfalls are also used for calculating Root Mean Square Error (RMSE), Mean Absolute Error (MAE) and Correlation Coefficient (CC) of rainfall. During the study period, the model simulated, observed and TRMM retrieved rainfall is found minimum in the west, north-northwest (NNW) and southwest (SW) regions and maximum in south-southeast (SSE) and northeastern (NE) regions of the country. The pattern of TRMM and observed rainfall are almost similar but the value of TRMM is much lower than that of observed rainfall. With the increase of simulated time, the simulated rainfall will also be increased. The RMSE of rainfall for 24- and 48-hours prediction is within 15-30 and 20-35 mm respectively and the MAE of rainfall is within 10-20 and 15-25 mm respectively all over Bangladesh except hilly regions. The RMSE and MAE are found minimum where the precipitation is minimum. Overall, the maximum CC is observed in the month of June 2014 for 24-hour simulation, then CC decreased from June to September and also decreased with the increased of simulated time. The WRF model is suitable for the simulation of rainfall up to 48 hours.

Keywords: *WRF model, monsoon season, RMSE, Mean Absolute Error and Correlation Coefficient*

1. INTRODUCTION

The climate of Bangladesh is tropical monsoon with significant variations in temperature and rainfall all over the country. The annual mean temperature of the country is 25°C but in extreme cases it is ever lowest minimum is 2.6°C and highest maximum is 45°C. In the dry season, the humidity ranges up to 60% or below and in the monsoon season (June-September) which ranges up to 98%. Most of the annual rainfall occurs in monsoon season. During this season, the country experiences huge amount of rainfall which is about 1000 to 3000 mm (Ohsawa *et al*., 2000). The maximum rainfall occurred in the NE region i.e., Sylhet and along the coastline in the southern region and minimum rainfall occurred in the western central region (Hussain and Sultana, 1996). Shilong Plateau is situated near the NE region of Bangladesh. This plateau acts as a topographic obstacle to dominate southwesterly summer monsoon wind flow; as a result, the amount of rainfall exceeds the value 5000 mm near the plateau (Ohsawa *et al*., 2000). The Cherrapunji experiences an average 8000 mm of monsoon rainfall, which is found 10 km away from the northern border of Bangladesh (Pant and Kumar, 1997). The wet and unsteady southerly air moves from the Bay of Bengal during monsoon seasons and then combine with the relatively dry and stable continental air over Bangladesh and its adjacent regions, as a consequence the heavy rainfall occurs within a very little instant of time over Bangladesh (Mannan *et al*., 2013).

Rainfall is the most important natural feature that acts a vital role to accelerate the agricultural growth as well as the economy of Bangladesh (Shahid, 2010). The change of rainfall variability or inconsistency in monsoon seasonal rainfall can strongly affects the agricultural system. Appropriate forecasting of the monsoon rainfall is extremely crucial for the sustainability of the agricultural systems and the economy of the country. Though it is very challenging task for the meteorologists to give the prediction of heavy rainfall, but very essential for the different agencies which involved in disaster awareness and mitigation (Alam, 2013; Sumi *et al*., 2018).Various methods are available to forecast such rainfall events. Among these methods Numerical Weather Prediction (NWP) model i.e., WRF model is very common because of the free availability of NCEP GFS data and different types of physics, cumulus parameterization and Planetary Boundary Layer (PBL) options available in it. So, this model can be a competent appliance for our country to estimate several rainfall episodes. Bangladesh Meteorological Department (BMD) also takes advantage of WRF model for forecasting several weather disturbances instead of other NWP models throughout the country (Saifullah *et al*., 2018).

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Many researchers have been working on different numerical model to forecast rainfall events for a long time. Das *et al.* (2012) studied the seasonal monsoon rainfall over the SAARC Region by means of WRF Model. They suggested that the large-scale rainfall distributions are simulated very well by the model which was detected by various sources. Khaladkar *et al*. (2007) studied the efficiency of National Centre for Medium Range Weather Forecasting (NCMRWF) models for the forecast of high precipitation incident through the SW monsoon period. They exposed that in general, all the models predicted good rainfall activity including the west coast area of India, which is consistent with the observations. Bhanu *et al*. (2012) investigated of heavy rainfall event simulation over the area of Andhra Pradesh throughout the summer monsoon period. They noticed that, the Indian Meteorological Department (IMD) observed rainfall and satellite derived dataset verify the circulation structures and rainfall amounts very well. Rahman *et al*. (2013) studied the summer monsoon rainfall forecasting by using simple multiple regression models over Bangladesh. The model exhibited very well competency in their hind cast seasonal monsoon rainfall over Bangladesh. The climatic change and its impacts on natural disasters were studied by Karmakar and Nessa (1997). They have shown that the predicted rainfall is likely to rise by 12.74 and 23.36 mm by the year 2050 and 2100, respectively. Begum and Alam (2013) conducted research on climate change impact on rainfall over Bangladesh and have found the decreasing and increasing tendency of annual and monsoon rainfalls during 1981-2010 and 1951-2011, respectively. The study by Hassan *et al*. (2015) stated the slight decreasing trend of the country averaged monsoon rainfall at the rate of (-0.057 mm/year) during 1951-2012.The decadal variation of monsoon rainfall over Bangladesh during 1948-2015 were studied by Reza *et al*. (2019) and have found the average rainfall of about 14.25 mm/day with standard deviation of 1.77 mm/day and coefficient of variation 12.43 %.

The present study makes an effort for the simulation of monsoon rainfall throughout Bangladesh using Weather Research and Forecasting (WRF-ARW V3.5.1) model during monsoon (June-September) 2014. The foremost objective of study is to examine whether the high resolution WRF model is proficient for simulating the rainfall event during the monsoon period of 2014. An attempt has been made for finding the Root Mean Square Error (RMSE), Mean Absolute Error (MAE) of rainfall and the Correlation Coefficient (CC) between observed and simulated rainfall. TRMM retrieved rainfall is much lower than that of the observed rainfall all over Bangladesh, that's why TRMM data can't take into account for finding RMSE, MAE and CC.

2. MODEL SETUP

In this present study, the WRF model has been used for simulating the monsoon precipitation throughout Bangladesh during June-September 2014. The terrain following hydrostatic pressure is the vertical coordinate and Arakawa C-grid staggering is the horizontal grid of the model. There are various microphysics and cumulus parameterization (CP) options in WRF model but in this research WSM6-class (Hong and Lim, 2006) graupel and Kain-Fritsch (KF) (Kain and Fritsch, 1990, 1993; Kain, 2004) schemes have been used for simulating the monsoon rainfall. The Monin-Obukhov similarity theory (Hong and Pan, 1996) for surface layer and Yonsei University (YSU) scheme (Hong *et al*., 2006) for planetary boundary layer (PBL) has been used. For short wave radiation (SWR), the Dudhia (1989) scheme and for long wave radiation (LWR) the Rapid Radiative Transfer Model (RRTM) (Mlawer *et al.,* 1997) have been used in WRF model to simulate the monsoon rainfall. The model has been configured in single domain (Figure 1) of 6 km horizontal grid distance and the number of grid point in the east-west and north-south directions are 161 and 183, respectively and the vertical levels are 30. The computational stability of the model was maintained by using 3rd order Runge-Kutta time integration scheme and by setting the time step of integration of 36 seconds.

Figure 1: WRF Model Domain for monsoon rainfall simulation in Bangladesh.

WRF model has been used to predict 24, 48- and 72-hours rainfall for the prediction of monthly rainfall of June, July, August and September of 2014. We run WRF model for everyday 0000 UTC initial conditions for 24, 48 and 72 hours for the prediction of monsoon seasonal rainfall of 2014. The complete outline of WRF model configurations are presented in Table 1. The extrapolative equations for cloud water, rainwater, cloud ice, snow, and graupel mixing ratio are consisted in the WRF-single moment 6 class (WSM6) microphysics scheme. Many researchers (Hong and Lim, 2006; Hong *et al.,* 2006; Alam, 2014; Hasan and Islam, 2018; etc.) suggested that among all the microphysics schemes, the WSM6 class scheme is the most appropriate for cloud resolving grids, considering the efficiency and theoretical backgrounds. A new method for representing mixed-phase particle fall speeds for the snow and graupel by assigning a single fall speed to both that is weighted by the mixing ratios, and applying that fall speed to both sedimentation and accumulation processes is introduced of the three WSM

schemes. The WSM6 scheme has been advanced by adding supplementary process correlated to graupel to the WSM6 scheme (Hong and Lim, 2006).

Table 1: WRF model and domain configurations

Dynamics	Non-hydrostatic	Time integration	3rd order Runge-Kutta
Number of domains	1	Initial conditions	FNL Data (1° × 1°)
Horizontal grid distance	6 km	Microphysics	WSM 6-class
Integration time steps	36 s	CP scheme	Kain-Fritsch (KF)
Total grid points	161×183 points along $x \times y$ direction	PBL scheme	YSU scheme
Map projection	Mercator	Surface layer	Monin-Obukhov similarity theory scheme
Horizontal grid	Arakawa C-grid	Short wave radiation	Dudhia scheme
Vertical co-ordinate	Terrain following hydrostatic pressure	Long wave radiation	RRTM scheme

The performances of CP scheme assessed in accordance with their capability of the simulation of rainfall for the period of the heavy, moderate, and light phases of the event. Among them, the KF scheme was able to account of the mesoscale procedures that make possible improvement of the convective movement (Alam, 2014 and Pattanaik *et al.,* 2011). In the KF scheme, when the total condensate surpasses the threshold value in the updraft, they are transformed into rainfall. In this scheme, the convective available potential energy (CAPE) is consumed by the convection process in a definite time scale. Also, the shallow convection is included in the KF scheme except 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 Lifting Condensation Level (LCL) of rising air parcel (Kain *et al.,* 1990). In this scheme 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. The KF scheme is further efficient to capture the monsoon seasonal mean rainfall pattern with greater spatial correlations in the core rain-belts.

3. DATA AND METHODOLOGY

Final Reanalysis (FNL) data (1°x1°) was used as initial and lateral boundary conditions, which was brought from National Centre for Environment Prediction (NCEP). This data is updated at six hours interval. The model is adjusted with 0000, 0600, 1200 and 1800 UTC initial field of conforming date. The Tropical Rainfall Measuring Mission (TRMM) 3B42RT daily rainfall data sets were downloaded from their website whereas diurnal rain gauge data of 33 stations has been obtained from Bangladesh Meteorological Department (BMD) all over Bangladesh. The model simulated rainfalls have been extracted for 33 BMD rain gauge stations. We have also extracted daily TRMM rainfall data for the above mentioned 33 meteorological station points during the monsoon season of 2014. During the study period we made 3 hourly outputs from WRF model and these 3 hourly rainfall data then converted into daily and monthly rainfall data of June-September 2014. The WRF model output gives the control (ctl) file and which is converted into text (txt) format data by using the Grid Analysis and Display System (GrADS). These data transformed into Microsoft Excel and finally plotted with the help of Surfer software. The RMSE and MAE of rainfall have been determined for 33 meteorological stations all over Bangladesh for long time prediction using Microsoft Excel and then plotted with the help of Surfer software. The model simulated rainfalls have been compared with the BMD and TRMM observed rainfall at 33 meteorological stations. BMD observed monsoon seasonal rainfall and model simulated rainfalls are also used for calculating RMSE, MAE and CC of rainfall. The RMSE, MAE and CC are mathematically expressed as follows (El-Shafie *et al.,* 2011).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|x_i - y_i\right|$$

and

$$CC = \frac{\sum_{i=1}^{n}((x_i - \bar{x})(y_i - \bar{y}))}{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}$$

Where n is the total number of simulated outputs, x_i is the model simulated values, y_i is the observed values. $\bar{x}$ and $\bar{y}$ is the average of the model simulated and observed values, respectively.

4. RESULTS AND DISCUSSION

BMD observed station wise monthly average, TRMM retrieved and model simulated rainfall of monsoon season, RMSE, MAE of rainfall and CC between observed and simulated rainfall have been analyzed and plotted in the following sub-sections.

4.1 Actual rainfall and TRMM retrieved rainfall of June-September 2014

The actual rainfall and the TRMM retrieved rainfall, respectively of June-September 2014 all over Bangladesh has been presented in Figures 2(a-h).Actual rainfall of June and July 2014 [Figures 2(a-b)] is maximum in the SSE part of Bangladesh i.e., rainfall at Chittagong is about 1300 mm and at Teknaf it is about 900 mm. The significant amount of rainfall is also observed in the NE region i.e., 600 mm at Sylhet and in the southern region i.e., 500 mm at Khepupara. The observed rainfall has decreased from south, NE towards WNW region and minimum of 200-300 mm is found at Ishwardi, Chuadanga in June and about 100-200 mm at Chuadanga and Rangpur regions in July. The rainfall of around 400-450 mm and around 200-250 mm is observed in June and July respectively, in the middle of the country i.e., Dhaka, Faridpur and Madaripur regions. From Figures 2(c) and 2(d),it is seen that the actual rainfall of August and September 2014 is maximum in the SE region i.e., 1000 mm is at Teknaf and in the NE region i.e., 700 mm is at Sylhet, respectively. The observed rainfall has decreased from NE towards WSW region and minimum of 200 mm is found at Satkhira, Jashore and Dinajpur in August and about 150 mm at Chuadanga and Rajshahi regions in September. The rainfall of around 200-400 mm is observed in the central region of the country i.e., Dhaka, Faridpur, Tangail and Madaripur regions.

The TRMM retrieved rainfall of June and July 2014 [Figures 2(e-f)] is maximum in the SSE region i.e., TRMM rainfall is about 300 mm at Chittagong in June and about 240 mm at Teknaf in July. The TRMM rainfall is about 300 mm at Sandwip in June and about 150 mm at Sandwip in July. The TRMM rainfall has decreased from NE towards WNW region and minimum of 100 mm is found at Rajshahi, Satkhira and Chuadanga in June and about 60-70 mm at Chuadanga and Rangpur regions in July. The TRMM rainfall of around 150 mm and around 80-100 mm is observed in June and July respectively, in the middle of the country i.e., Dhaka, Faridpur and Madaripur. The TRMM retrieved rainfall of August and September 2014 [Figures 2(g-h)] is maximum in the NE region i.e., TRMM rainfall is about 270 mm at Sylhet in August and about 220 mm at Sylhet in September. The TRMM rainfall has decreased from NE towards WSW region and minimum of 80 mm is found at Khulna, Satkhira and Mongla in August and about 60 mm at Chuadanga and Rajshahi regions September. The TRMM rainfall of around 100-150 mm and around 80-120 mm is observed in August and September respectively, in the middle of the country i.e., Dhaka, Faridpur and Madaripur. The distribution patterns of TRMM and BMD rainfall for the month of June-September 2014 are almost similar but the value of TRMM derived rainfall is much lower than that of the observed rainfall all over Bangladesh.

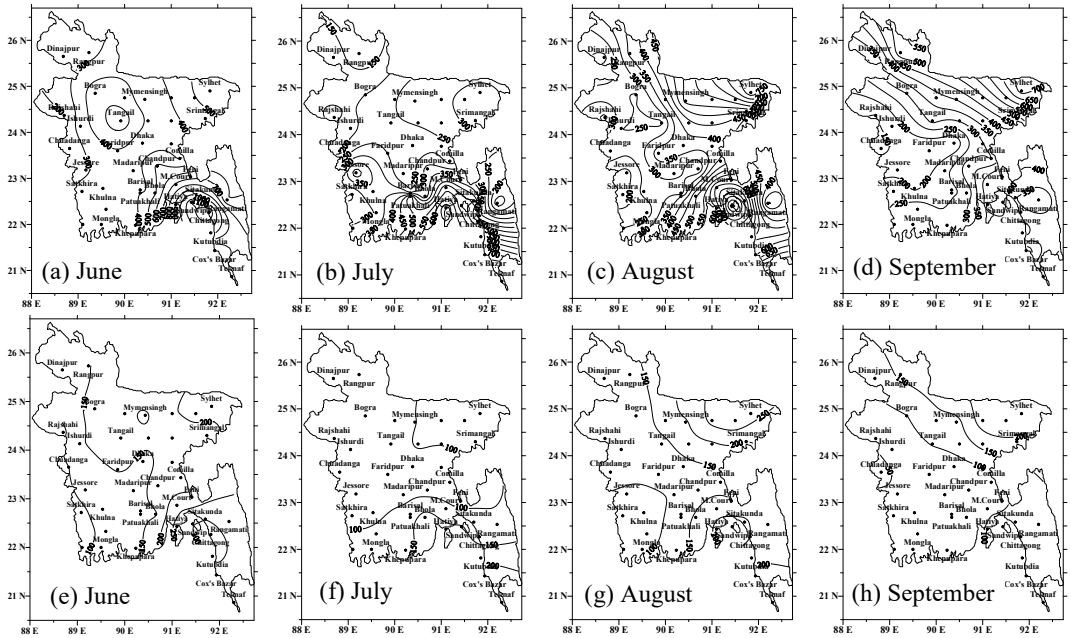

Figure 2: The distribution of (a-d) Actual rainfall and (e-h) TRMM retrieved rainfall of June-September 2014 all over Bangladesh.

4.2 Model simulated rainfall for 24, 48 and 72 hours of June-September 2014

The model simulated rainfall at different stations of Bangladesh during June-September 2014 for 24, 48 and 72 hours are shown in Figures 3(a-d), 3(e-h) and 3(i-l), respectively. The 24 hours model simulated rainfall of June and July 2014 [Figures 3(a-b)] has the maximum value in SSE region having about 2700 and 2500 mm at Teknaf in June and July and in the NE region having about 700 and 800 mm at Sylhet in June and July, respectively. Simulated rainfall has decreased from NE and SSE regions towards western region. Minimum simulated rainfall is about 200 mm at Rajshahi, Ishwardi and Chuadanga and is about 200-300 mm at Bogura, Rangpur and Dinajpur region.24 hours simulated rainfall of around 400-500 mm and around 200-300 mm is observed in June and July respectively, in the central region of the country i.e., Dhaka, Tangail, Mymensingh and Faridpur regions. The 24 hours model simulated rainfall of August and September 2014 [Figure 3(c-d)] has the maximum value in SSE region having about 2000 and 700 mm at Teknaf in August and September and in the NE region having about 900 and 600 mm at Sylhet in August and September, respectively. Simulated rainfall has decreased from NE region towards west and SW region. Minimum simulated rainfall is about 200 mm at Rajshahi, Ishwardi and Chuadanga and is about 200-300 mm at Jashore, Faridpur, Rangamati and Patuakhali region. 24 hours simulated rainfall of around 400-500 mm and around 200 mm is observed in August and September respectively, in the central region of the country i.e., Dhaka, Tangail, Mymensingh and Faridpur regions.

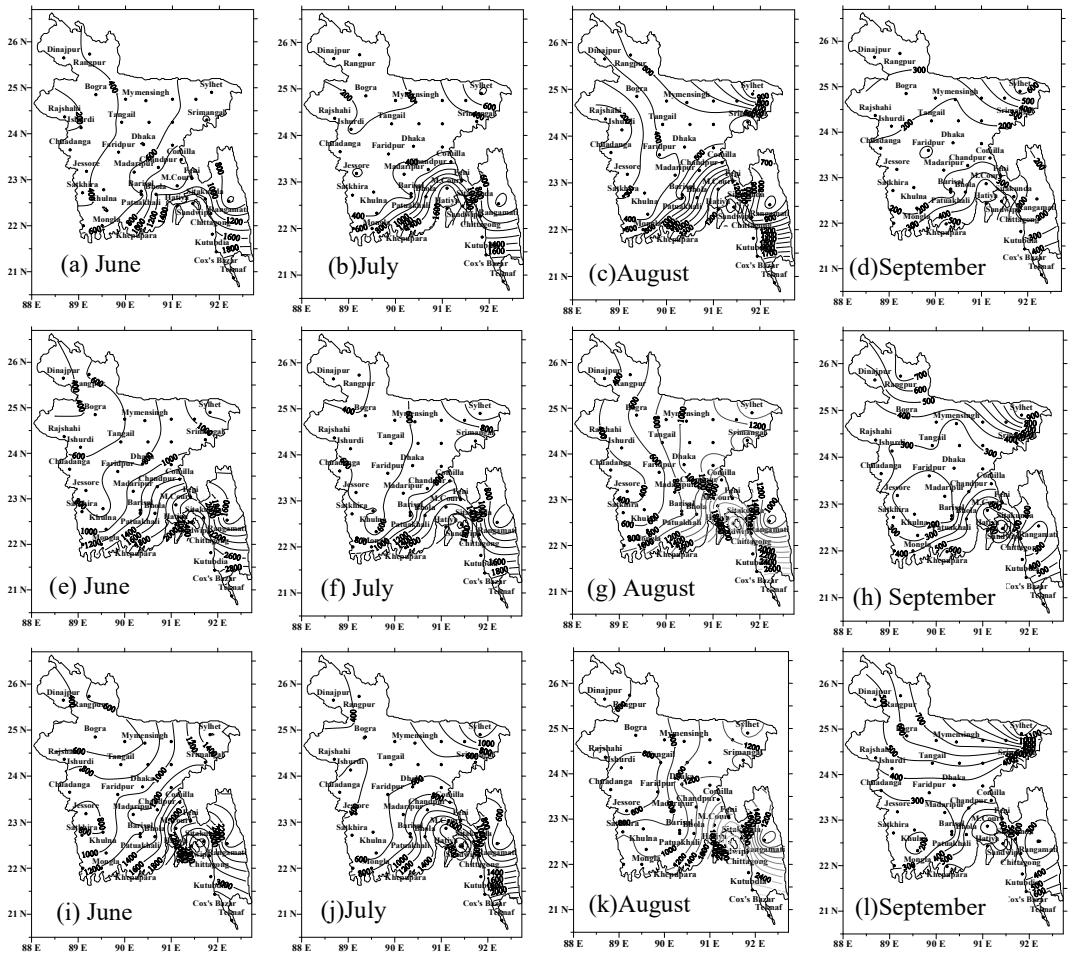

Figure 3: The distribution of (a-d) 24 hours, (e-h) 48 hours and (i-l) 72 hours model simulated rainfall of June-September 2014 all over Bangladesh.

The 48 hours model simulated rainfall of June and July 2014 [Figures 3(e-f)] has the maximum value in SSE region having about 3000 and 3000 mm at Teknaf in June and July and in the NE region having about 1200 and 1000 mm at Sylhet in June and July, respectively. Simulated rainfall has decreased from NE and SSE region towards western region. Minimum simulated rainfall is about 400-500 mm at Dinajpur, Bogura, Rajshahi and Ishwardi in June and is about 300-400 mm at Bogura, Rangpur and Dinajpur region in July.48 hours simulated rainfall of around 600-700 mm and around 500-600 mm is observed in June and July respectively, in the middle

of the country i.e., Dhaka, Tangail, Mymensingh and Faridpur regions. The 48 hours model simulated rainfall of August and September 2014 [Figures 3(g-h)] has the maximum value in SSE region having about 3700 and 900 mm at Teknaf in August and September and in the NE region having about 1200 and 900 mm at Sylhet in August and September, respectively. Simulated rainfall has decreased from SSE and NE towards east and WNW region in August and towards west and SW region in September. Minimum simulated rainfall is about 300 mm at Jashore, Dinajpur and Chuadanga in August and is about 300-500 mm at Jashore, Satkhira, Khulna and Mongla in September. 48 hours simulated rainfall of around 600-800 mm and around 300mm is observed in August and September respectively, in the middle of the country i.e., Dhaka, Tangail, Mymensingh and Faridpur regions.

The 72 hours model simulated rainfall of June and July 2014 [Figures 3(i-j)] has the maximum value in SSE region having about 3300 and 3400 mm at Teknaf in June and July and in the NE region having about 1600 and 1200 mm at Sylhet in June and July, respectively. Simulated rainfall has decreased from NE and SSE towards western region. Minimum simulated rainfall is about 600-800 mm at Chuadanga and Rajshahi in June and is about 400 mm at Chuadanga and Rajshahi in July. 72 hours simulated rainfall of around 600-900 mm and around 500-600 mm is observed in June and July respectively, in the central region of the country i.e., Dhaka, Tangail, Mymensingh and Faridpur regions. The 72 hours model simulated rainfall of August and September 2014 [Figures 3(k-l)] has the maximum value in the SSE region having about 3200 and 1000 mm at Teknaf in August and September and in the NE region having about 1200 and 1100 mm at Sylhet in August and September, respectively. 72 hours simulated rainfall of around 800-1000 mm and around 400-700 mm is observed in August and September respectively, in the central region of the country.

4.3 RMSE of rainfall for 24, 48- and 72-hours simulation of June-September 2014

The RMSEs of rainfall for 24, 48- and 72-hours simulations at different meteorological stations of Bangladesh during June-September 2014 are shown in Figures 4(a-d), 4(e-h) and 4(i-l), respectively. The RMSE contributes a very good complete measure of model performance. To be a perfect model, the value of RMSE near to zero. When the RMSE has maximum, the model simulation deviates more from the observed value (El-Afandi *et al.,* 2013; Kondowe, 2014). The RMSE of rainfall for 24 hours simulation of June 2014 (Figure 4a) has minimum in the west, NW and SW region of Bangladesh. The RMSE of rainfall have increased from NNW region towards SSE region and is maximum in Teknaf which is about 125 mm and lies between 20-40 mm all through the country except SE region. The RMSE of rainfall for 24 hours simulation of July 2014 (Figure 4b) has minimum in the western, NNW region. The RMSE at Rangpur is about 10 mm and increases from NW region towards SSE region and maximum value is about 100 mm at M. Court. The RMSE of rainfall of August 2014 (Figure 4c) for 24 hours prediction has minimum in the western and southwestern regions and lowest value is found at Bogura and Ishwardi regions, the lowest value being 15 mm. The RMSE of rainfall has increased from west towards NE, eastern and SE region and is maximum at Teknaf, having about 90 mm and at Sandwip it is about 60 mm. The RMSE of rainfall for 24 hours simulation of September 2014 (Figure 4d) has minimum in the WSW region and the lowest value at Ishwardi and Faridpur is about 15 mm and maximum is about 35-55 mm at Dinajpur, Rangpur, Mymensingh, Sylhet and M. Court regions. Since RMSE is maximum in SSE, NE and eastern regions, this indicates that the model deviates more from the observed results in these regions and the model deviates less in the west, NW and SW regions i.e., Rangpur, Bogura, Ishwardi and Faridpur.

The RMSEs of rainfall for 48 hours simulation of June 2014 (Figure 4e)are minimum in the west, NW and northern region of Bangladesh and have increased from NNW regions towards SSE region and is maximum in Teknaf where it is about 140 mm and lies between 25-45 mm all through over the country except SE region. The RMSE of rainfall for 48 hours simulation of July 2014 (Figure 4f) is minimum in the western, NNW region i.e., about 25 mm at Rangpur and rainfall increases from NW region towards SSE region and the maximum value is about 80-85 mm at Sandwip and Teknaf. The RMSE of rainfall for 48 hours simulation of August 2014 (Figure 4g) is minimum in the western, SW region and the lowest value is found at Jashore and Satkhira regions where RMSE is about 20 mm. The RMSE of rainfall has increased from west towards NE, eastern and SE region and is maximum at Teknaf where it is about 135 mm and at Sandwip it is about 90 mm. The RMSE of rainfall for 48 hours prediction of September 2014 (Figure 4h) is minimum in the west, SW region and the lowest value is about 15 mm at Ishwardi and Faridpur and maximum is about 40-85 mm at Dinajpur, Rangpur, Mymensingh, Sylhet and M. Court regions. The RMSE is maximum in SSE, NE and eastern regions, which indicate that the model deviates more from the observed results in these regions and the model deviates less in the west, northwest and SW regions i.e., Rangpur, Jashore, Satkhira, Ishwardi and Faridpur.

The RMSE of rainfall for 72 hours simulation of June 2014 [Figure 4(i)] is minimum in the NNW i.e., Mymensingh, Rangpur and Dinajpur regions where it is about 20-35 mm and it increases from NNW region towards SSE region and is found maximum at Teknaf and Sitakunda where it is about 140 and 135 mm, respectively. The RMSE of rainfall for 72 hours simulation for July 2014 (Figure 4j) is minimum at Rangamati

and Srimangal regions, having the value of about 20-25 mm and maximum in the SSE region i.e., Sandwip and Sitakunda with RSME of about 95 mm. The RMSE of rainfall for 72 hours simulation of August 2014 (Figure 4k) is minimum in the western and NW region and the lowest value is simulated at Dinajpur and Rangpur region where RSME is about 20 mm and maximum in the SSE region. The values of RSME at Sandwip and Teknaf are about 95 and 100 mm, respectively. The RMSE of rainfall for 72 hours simulation of September 2014 (Figure 4l) is minimum in the central to southwest and western i.e., Mongla, Satkhira, Khulna, Faridpur, Madaripur and Rangamati regions where it is about 15-25 mm and is found maximum at Dinajpur, Rangpur, Mymensingh, Sylhet and M. Court where it is about 50-75 mm. Since RMSE is maximum in SSE and NE regions, this indicates that the model simulation is more deviated from the observed results in these regions and the model deviate less in the north, west, NW and SW regions. As a whole, the minimum RMSE is observed in the month of June 2014, which indicates that the model deviated less in this month than the others and RMSE is found to increase from June to September and also increases with the increase of simulated time.

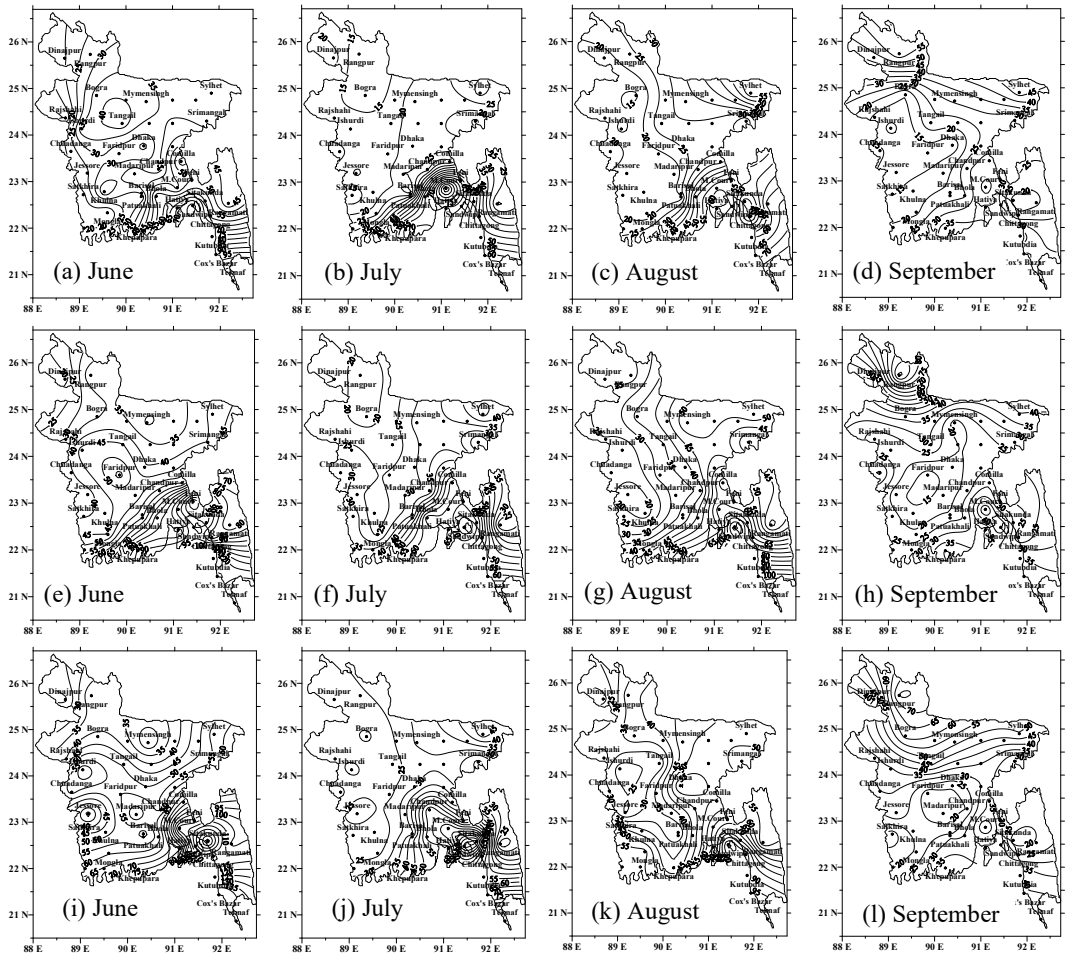

Figure 4: The distribution of RMSE of rainfall for (a-d) 24 hours, (e-h) 48 hours and (i-l) 72 hours simulation of June-September 2014 all over Bangladesh.

4.4 Mean Absolute Error of rainfall for 24, 48- and 72-hours simulation of June-September 2014

The mean absolute error (MAE) of rainfall at different stations of Bangladesh during June-September 2014 for 24, 48- and 72-hours simulations are shown in Figures 5(a-d), 5(e-h) and 5(i-l), respectively. The model with a lower MAE has a good ability of prediction. Where the value of MAE is maximum, the model is deviated more from the observed value. The RMSE and MAE both are indifferent to the direction of errors. The MAE of rainfall for 24 hours simulation of June 2014 [Figure 5(a)] is minimum in the west, NW and SW region. Minimum value of MAE is found 10 mm at Rajshahi. It increases from NW region towards SSE region and is found maximum at Teknaf where it is about 55 mm. The MAE of rainfall for 24 hours simulation of July 2014 [Figure 5(b)] is minimum all over the country except SSE region. Minimum value of MAE is found 10-15 mm at Mymensingh, Tangail, Madaripur, Faridpur, Jashore, Satkhira, Rajshahi, Ishwardi, Dinajpur, Srimangal and Rangamati regions and is found maximum in the SSE region i.e., Hatiya, Kutubdia where it is about 45-55 mm.

The MAE of rainfall for 24 hours simulation of August 2014 [Figure 5(c)] is minimum in the west, NW and SW region and is found minimum at Ishwardi, Jashore and Satkhira where it is about 10 mm. It increases from west NW towards NE and SSE regions and is found maximum at Sandwip and Teknaf where it is about 40-65 mm. The MAE of rainfall for 24 hours simulation of September 2014 [Figure 5(d)] is minimum in the central, western and SW region and is found minimum at Madaripur, Faridpur, Dhaka, Khulna, Satkhira and Rajshahi regions where it is about 5-10 mm. It increases from west, central towards NE and SE regions and is found maximum at Sylhet, Rangpur, Sandwip and Teknaf where it is about 20-25 mm. Since MAE of rainfall is maximum in SSE, NE regions i.e., Hatiya, Kutubdia, Teknaf, Sandwip and Sylhet [Figure 5(a-d)], which indicates that the predicted rainfall is deviated more from the observed rainfall in these regions and the model prediction is less deviated in the west, NW and SW regions.

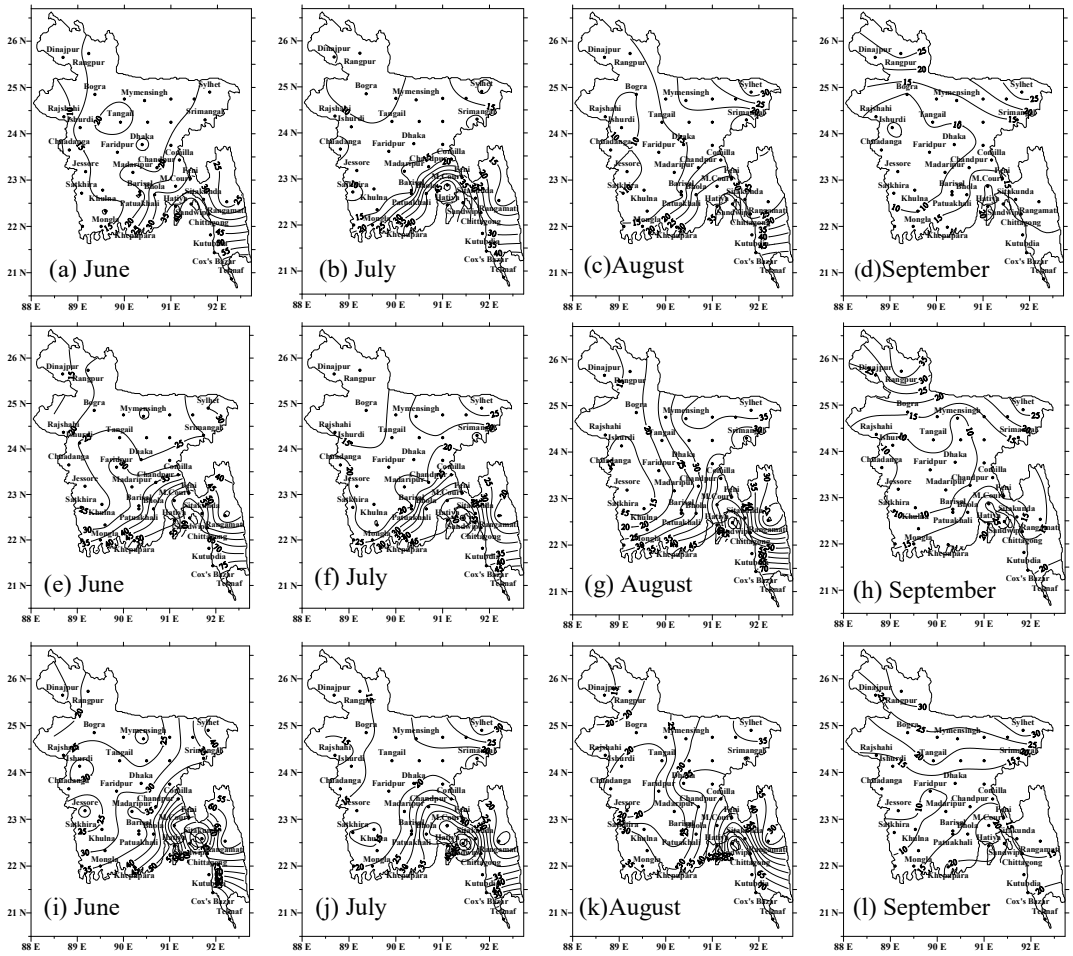

Figure 5: The distribution of MAE of rainfall for (a-d) 24 hours, (e-h) 48 hours and (i-l) 72 hours simulation of June-September 2014 all over Bangladesh.

The MAE of rainfall for 48 hours simulation of June 2014 [Figure 5(e)] is minimum in the west, NW and SW region and is found minimum at Dinajpur where it is about 15 mm. It increases from NW region towards south-SE region and is found maximum at Teknaf. The MAE of rainfall for 48 hours simulation of July 2014 [Figure 5(f)] is minimum at Mymensingh, Tangail, Madaripur, Faridpur, Jashore, Satkhira, Rajshahi, Ishwardi, Dinajpur, Srimangal and Rangamati regions where it is about 10-20 mm and is found maximum at Sandwip, Hatiya and Teknaf where it is about 45-50 mm. The MAE of rainfall for 48 hours simulation of August 2014 [Figure 5(g)] is minimum in the WNW and SW region and is found minimum at Ishwardi, Jashore and Satkhira where it is about 15 mm. It increases from WNW towards NE and SSE region and is found maximum at Sandwip and Teknaf where it is about 60-95 mm. The MAE of rainfall for 48 hours simulation of September 2014 [Figure 5(h)] is minimum in the central, western and SW region and is found minimum at Madaripur, Faridpur, Dhaka, Khulna, Satkhira and Rajshahi where it is about 5-10 mm. It increases from west, central towards NE and SE regions and is found maximum at Sylhet, Rangpur, Sandwip and Teknaf where it is about 30-35 mm. Since MAE of rainfall is maximum in SSE, NE regions i.e., Hatiya, Teknaf, Sandwip and Sylhet [Figure 5(e-h)], which indicates that the predicted rainfall is deviated more from the observed rainfall in those

regions and the model prediction is less deviated in the WNW and SW regions i.e., Mymensingh, Tangail, Madaripur, Faridpur, Jashore, Satkhira, Ishwardi, Dinajpur, Srimangal and Rangamati and Rajshahi.

The MAE of rainfall for 72 hours simulation of June 2014 [Figure 5(i)] is minimum in the west-NW regions and is found minimum at Dinajpur where it is about 15 mm. It increases from NW towards SE region and is found maximum at Cox's Bazar where it is about 105 mm. The MAE of rainfall for 72 hours simulation of July 2014 [Figure 5(j)] is minimum in the central to west, NW and SW regions and is found minimum at Rajshahi, Ishwardi, Rangpur and Dinajpur where it is about 10-15 mm. It increases from west towards SSE region and is found maximum at Teknaf and Sandwip where it is about 50 mm. The MAE of rainfall for 72 hours simulation of August 2014 [Figure 5(k)] is minimum in the west and NW region and is found minimum at Tangail, Rajshahi, Ishwardi, Dinajpur and Rangpur where it is about 15-20 mm. It increases from WNW towards NE and SE region and is found maximum at Sandwip and Teknaf where it is about 70-80 mm. The MAE of rainfall for 72 hours simulation of September 2014 [Figure 5(l)] is minimum at Dhaka, Faridpur, Madaripur, Chuadanga, Rajshahi, Ishwardi, Jashore, Satkhira and Rangamati where it is about 10-15 mm. It increases from SW towards central, north and SE region and is found maximum at Rangpur, Sylhet, M. Court and Teknaf where it is about 25-30 mm. Since MAE of rainfall is maximum in SSE, NE regions i.e., Cox's Bazar, M. Court Teknaf, Sandwip and Sylhet [Figure 5(i-l)], which indicates that the predicted rainfall is deviated more from the observed rainfall in those regions and the model prediction is less deviated in the west, NW and SW regions i.e., Dhaka, Tangail, Faridpur, Madaripur, Chuadanga, Rajshahi, Ishwardi, Jashore, Satkhira and Rangamati. The station wise RMSE is larger than that of MAE throughout over the country but the distribution pattern is almost similar. The RMSE gives a relatively high weight to large errors, because errors are squared before they are averaged. The RMSE should be more useful when the large errors are particularly undesirable.

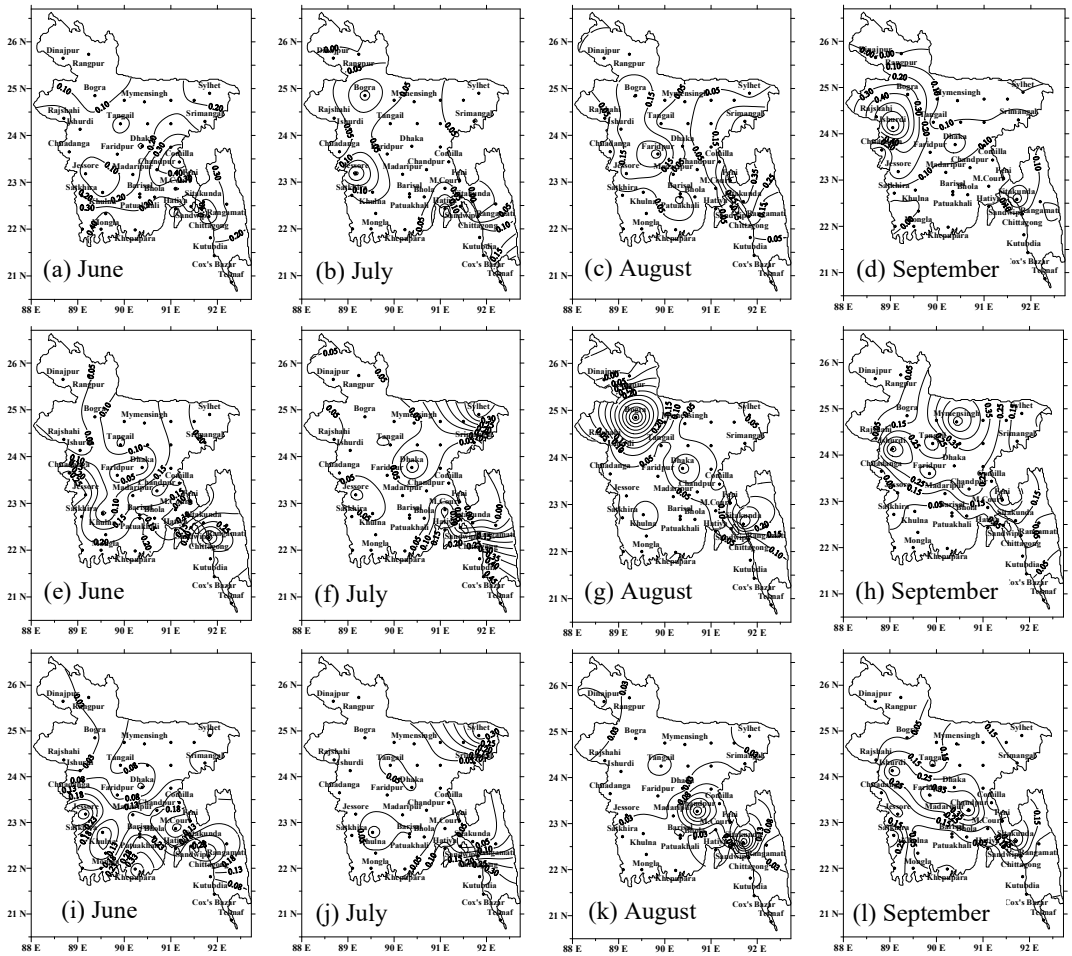

Figure 6: The distribution of CC between observed and simulated rainfall for (a-d) 24 hours, (e-h) 48 hours and (i-l) 72 hours of June-September 2014 all over Bangladesh.

4.5 CC between observed and simulated rainfall for 24, 48 and 72 hours of June-September 2014

The distribution of CC between observed and simulated rainfall at different stations of Bangladesh during June-September 2014 for 24, 48 and 72 hours are shown in Figures 6(a-d), 6(e-h) and 6(i-l), respectively. When the value of CC is closer to 1, then it is the indicator of a good simulation (El-Shafie *et al.,* 2011). The CC is found maximum for 24-hour simulation in June 2014 (Figure 6a) in the east, south and SE regions and the highest value of CC is found 0.4 at Cumilla region. The level of significance of this CC at Cumilla region in June is 95%. The CC is insignificant for 24-hour simulation in July 2014 (Figure 6b) and maximum in August 2014 (Figure 6c) at Sitakunda and Feni regions where CC is about 0.25-0.35. The CC is found maximum for 24-hour simulation in September 2014 (Figure 6d) at Chuadanga, Rajshahi and Bogura regions and the values were 0.3-0.4, the level of significance at this region being 90-95% and almost nil in the other regions of the country.

The CC is found maximum for 48-hour simulation in west and SSE region and the highest value is found 0.25 at Chittagong and Jashore regions in June 2014 (Figure 6e). The maximum value of CC is found 0.45 at Cox's Bazar and Teknaf regions for 48-hour simulation in July 2014 (Figure 6f), the level of significance at these regions is 99%. The CC is found maximum for 48-hour simulation in August 2014 (Figure 6g) at Bogura and Sitakunda and its value is 0.20. The maximum value of CC is found 0.35at Mymensingh and Tangail regions for 48-hour simulation in September 2014 (Figure 6h).

The CC is found maximum for 72-hour simulation for the month of June 2014 (Figure 6i) in SSE region and highest value is found 0.33 at Khepupara region, the level of significance at this region is 90%. The CC is found maximum for 72-hour simulation for the month of July 2014 (Figure 6j) at Sylhet and SE regions and the maximum value has found 0.30 at Kutubdia and Sylhet regions; the level of significance at these regions is 90%. The maximum value of CC is found 0.08-0.13 at Chandpur and Sitakunda regions for 72-hour simulation in August 2014 (Figure 6k); this value of CC is not so significant. The maximum value of CC is found 0.35 at Chandpur, Madaripur and Faridpur regions and is found 0.5 at Chittagong and Rangamati regions for 72-hour simulation in September 2014 (Figure 6l). The level of significance at Chittagong and Rangamati is 99% in September. Overall, the maximum CC is observed in the month of June 2014 for 24 hours simulation, and then CC is found to decrease from June to September and also decreases with the increase of simulated time.

5. CONCLUSIONS

The distribution patterns of TRMM and BMD rainfall for the month of June-September 2014 are almost similar but the value of TRMM derived rainfall is much lower than that of the observed and simulated rainfall all over Bangladesh. The distribution patterns of model simulated 24, 48 and 72 hours lead time simulated rainfall are almost similar to that of observed rainfall. During the study period, the model simulated 24, 48 and 72 hours, observed and TRMM rainfall is found minimum in the west, NNW and SW regions and maximum in SSE and NE regions of the country. With the increase of simulated time the simulated rainfall increases. The RMSE is found minimum in a region where the observed rainfall is minimum. The RMSE of rainfall is almost similar for 24, 48 and 72 hours. The value of RMSE of rainfall for 24- and 48-hours prediction is within 15-30 and 20-35 mm, respectively all over Bangladesh except hilly regions. The RMSE increases as the simulation time increases. The MAE of rainfall for 24- and 48-hours simulation is within 10-20 and 15-25 mm, respectively all over Bangladesh except hilly regions. The station wise RMSE is larger than the MAE throughout over the country but the distribution pattern is almost similar. Overall, the maximum CC is observed in the month of June 2014 for 24-hour simulation, and then CC is found to decrease from June to September and also decreases with the increase of simulated time. On the basis of above finding it may be concluded that WRF model is suitable for the simulation of rainfall up to 48 hours.

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