Simulation of High Impact Monsoon Rainfall and its Thermodynamic Features over Bangladesh Using WRF Model

Shammi Akhter[1]*, **Ishtiaque M. Syed[1], Md. Shadekul Alam[2], M. A.K. Mallik[2], S. M. Quamrul Hassan[2] and S.M. Mahmudul Huque**

[1]*Department of Physics, University of Dhaka, Dhaka, Bangladesh*
[2]*Bangladesh Meteorological Department, Agargaon, Dhaka, Bangladesh*

ABSTRACT: An attempt has been made to simulate the heavy rainfall event on 25 July 2015 over the southeastern region of Bangladesh for detecting the insight physical processes using Weather Research and Forecasting (WRF) Model. The model was run on a single domain at 20 km horizontal resolution using WRF Single-Moment 3-class (WSM3) microphysics scheme and Kain-Fritsch (KF) (new eta) cumulous scheme. The model performance was evaluated by examining the different predicted parameters like mean sea level pressure, wind pattern, mid-level and lower-level vorticity, temperature, relative humidity and rainfall. The simulated rainfall had been validated with observed Tropical Rainfall Measuring mission (TRMM) and Bangladesh Meteorological Department (BMD) rainfall data. It was found that seasonal monsoon troughs passed through Bangladesh extending up to the North Bay. The analysis of the wind field showed that the areas of high impact rainfall exhibits that strong southwesterly flow causes transportation of large amount of moisture from the Bay of Bengal towards Bangladesh, especially over the regions where high impact rainfall occurred. The WRF model suggests that these heavy rainfall events over the southeastern parts of Bangladesh and adjoining areas might be due to the active phase of monsoon over Bangladesh and strong over the North Bay. During the life cycle of the system the pressure, wind, humidity, temperature and vorticity fields were very much supportive for generating high intensity rain bands over the southeastern parts of Bangladesh and adjoining areas. The results indicated that the WRF model is able to simulate the heavy rainfall event and associated synoptic features reasonably well. The amount of rainfall and its pattern was also well captured by the model which was in good agreement with observed TRMM and BMD data. It can be concluded from the study that the WRF model can be used for forecasting of heavy rainfall events, but furthermore experiments should be done.

1. Introduction

Primarily, Bangladesh is a low -lying plain with area of about 1, 47, 570 km^2 [1]. Being one of the largest deltas in the world, the country is formed by a dense network of the distributaries of the rivers Ganges, Brahmaputra and Meghna and more than 230 major rivers and their tributaries [2].Geographically, it extends from 20°34′ N to 26°38′ N latitude and from 88°01' E to 92°41′ E longitude. Bangladesh has a sub-tropical humid climate characterized by broad seasonal variations in rainfall, high humidity and moderately warm temperatures [3]. Southern Bangladesh faces the Bay of Bengal, from which southerly moist winds easily intrude over the country and bring plentiful moisture to Bangladesh. Four distinct seasons can be recognized in Bangladesh from climatic point of view: 1) Winter Season (December – February), 2) Pre-monsoon Season (March – May), 3) Summer Monsoon Season (June – September), and 4) Post-monsoon Season (October – November) ([4]; [5]). In Bangladesh the main rainy season is the summer monsoon season which accounts for 72% of the total annual rainfall [6].

On 25 July 2015, the axis of a preexisting monsoon trough ran through Rajasthan, Madhya Pradesh, Uttar Pradesh, Bihar, West Bengal, the center of the low and hence northeastwards to Assam across southern part of Bangladesh. Monsoon was fairly active over northern part and active over southern part of Bangladesh and strong over the North Bay on that day. Due to this active monsoon over the plain of Bangladesh, high amount of rainfall was gauged by BMD in different stations. The amount of rainfall observed by rain gauge of BMD was at Chittagong 299 mm, Cox's Bazar 116 mm, Kutubdia 178 mm and Teknaf 148 mm on 25 July. The amount of rainfall recorded by TRMM was at Chittagong 113 mm, Cox's Bazar 149 mm, Kutubdia 119 mm and Teknaf 142 mm.

Agricultural activities, river drainage systems, and hydrological parameters of Bangladesh depend on the summer monsoon season, all of which, in turn, affect the economy of the country [7]. Moreover heavy rains often lead to flood disasters over the flat, low-elevation lands of Bangladesh ([8], [9]). In 1987 and 1988, floods reached extreme calamity situations, when almost the whole country was affected extensively [10]. In July 2004, the Brahmaputra exceeded dangerous flood levels over a 2 weeks period and widespread flooding occurred for that

[11]. On the other hand, the failure of the monsoon rain causes severe droughts for which major crop failures occur. In northwestern part of the country, drought is a common phenomenon ([12]; [13]).

It is apparent that an accurate and reliable prediction of the high impact rainfall events of summer monsoon claims to be an important and challenging task. Numerical weather prediction (NWP) model is one of the useful tools to predict such heavy rainfall events of monsoon season in Bangladesh. Application of NWP model in research and forecasting of high impact rainfall during monsoon season is very little in Bangladesh due to its limitations of computing platform and technical knowledge. In spite of limitations, some works have been done to investigate the synoptic features responsible for occurring the heavy rainfall activities during monsoon season over Bangladesh using NWP model by Prasad [14]; Das et. al. ([15]; [16]; [17]), Ahasan et al. ([18]; [19]) and Mannan et al. [20]. During recent years the Weather Research and Forecasting (WRF) model has become very popular for studying mesoscale weather systems. The primary objective of this study is to study the thermo-dynamics of the system and the overall synoptic features of such high impact rainfall event of 25 July, 2015 using WRF model in monsoon season over Bangladesh. The secondary objective is to test the predictability of such high impact rainfall events using WRF modeling systems.

Understanding the synoptic features of monsoon rainfall is helpful for disaster management and water management of an agricultural dependent countries such as Bangladesh. Our study will enhace the knowledge of the physics and dynamics of monsoon rain producing systems. Eventually, the society and people will receive advantages from our work through improved prediction of monsoon rainfall using WRF model.

2. Data used, Model experimental set up & Methodology

The Advanced research WRF model version 3.7.1 has been adopted for the mesoscale weather research and simulation in the present study. The data used, experimental set up of the model, and the methodology of the study are provided in this section.

2.1 Data Used

For the initial and lateral boundary condition, the National Centre for Environmental Prediction (NCEP) high-resolution Global Final (FNL) Analysis data on 1.0°×1.0° grids covering the entire globe every 6-h was adopted. The 30 second United States of Geological Survey (USGS) data were used to simulate the Terrain/Topography and 25 Categories USGS were adopted as vegetation/land use coverage. The daily 0.25° x 0.25° resolution TRMM 3B42V7 rainfall data have been downloaded from website of NASA [1] to justify the model simulated rainfall structure, development time and location. Moreover, daily observed rainfall data of 34 meteorological stations of Bangladesh have been collected from the archive of Bangladesh Meteorological Department (BMD) to validate the model derived rainfall.

2.2 Model Experimental Setup

The model was configured on a single domain with 20 km horizontal grid spacing. The coverage area of the domain is 14-30ºN and 82-98ºE. The domain has 95 and 95 grid points in the west-east and north-south directions respectively. The domain was configured to have the same vertical structure of 38 unequally spaced sigma (non-dimensional pressure) levels. The domain is centered (23.00°N, 90.00°E) over Dhaka, Bangladesh to represent the regional-scale circulations and to solve the complex flows in this region. The physical parameterization schemes used in this study are WRF Single Moment 3-class (WSM3) scheme for microphysics, Kain-Fritsch (new Eta) scheme for cumulus parameterization, Yonsei University scheme (YSU) for planetary boundary layer, RRTM for long wave and Dudhia for short wave radiation scheme for the selected case. The WSM3 MP scheme contains prognostic equations for cloud water, rainwater, cloud ice, snow, and graupel mixing ratio. The WRF model consists of fully compressible non-hydrostatic equations and different prognostic variables are utilized. The model vertical coordinate is terrain following hydrostatic pressure and the horizontal grid is Arakawa C-grid staggering. In this model, Third-order Runge-Kutta time integration is employed. The initial condition of the model simulation is taken as 0000 UTC of 24 July, 2015 (about 48-h before of the event).

2.3 Methodology

The model outputs help to investigate the synoptic and thermodynamic characteristics for the event. The model performance was evaluated by examining the different predicted parameters like mean sea level pressure, lower and mid-level winds, temperatures, lower level and mid-level relative vorticity, horizontal and vertical profile of relative humidity, accumulated rainfall etc. GrADS software has been used for displaying and analyzing the simulated and derived parameters. Observed daily rainfall data of BMD and daily TRMM 3B42v7 rainfall data have been used to validate / compare the model simulated rainfall. Surfer software has been used for this purpose. Both spatial and temporal comparison methods have been used to compare the model simulated rainfall with observed rainfall.

3. Results and Discussion

The Weather Research and Forecasting (WRF) model Version 3.7.1 has been used to investigate the possible causes and mechanisms behind the maintenance of this extraordinary high impact rainfall event on 25 July, 2015 over Bangladesh during southwest summer monsoon season. The analysis of the different meteorological fields and some of the derived parameters are presented in the Figures 2–11 and discussed accordingly. The results are described in the following section in details.

3.1 Mean sea level pressure analysis

The central pressure of the depression at 0000, 0600, 1200 and 1800 UTC of 25 July, 2015 are about 1002, 1001, 998 and 1000 hPa respectively over Bihar and adjoining Bangladesh. The lowest central pressure is about 998 hPa at 1200 UTC of 25 July, 2015. The central pressure of the depression at 0000, 0600, 1200 and 1800 UTC of 25 July, 2015 are about 1004, 1003, 1000 and 1001 hPa respectively over the North Bay. The lowest central pressure is about 1000 hPa at 1200 UTC of 25 July, 2015.

The trough of low extends from Bihar and adjoining areas to the North Bay of Bengal and adjoining Bangladesh. The model simulated mean sea level pressures indicates that the monsoon phase was active over Bangladesh and adjoining areas and strong over the North Bay. So the pressure gradient was high over the North Bay which is the indication of high wind speed from the Bay of Bengal towards Bangladesh. Along the trough line, the moisture incursion is very high and it is very much supportive for the formation of stratiform/cumuliform clouds.
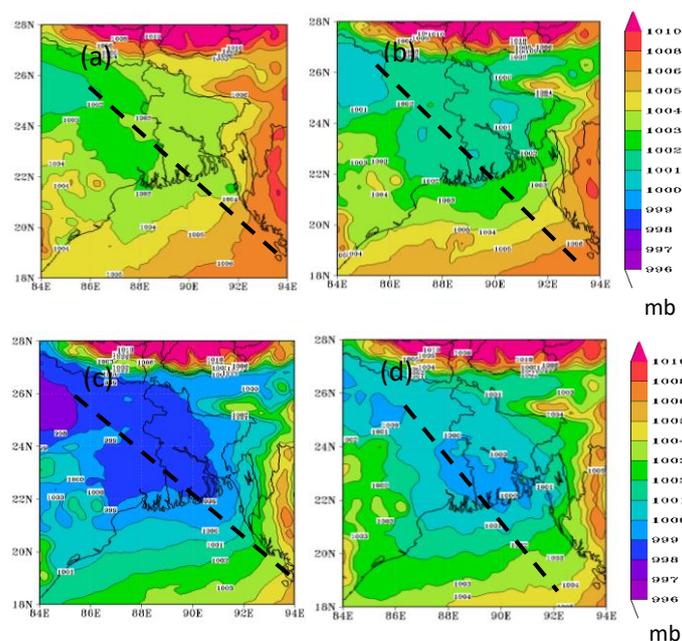

Figure 1: Analysis of mean sea level pressure (hPa) distribution at 850 hPa level valid for (a) 0000 UTC, (b) 0600 UTC, (c) 1200 UTC and (d) 1800 UTC of 25 July, 2015.

3.2 Wind Pattern Analysis

The distribution of lower level (850 hPa) and mid-level (500 hPa) wind flow (ms^{-1}) valid for 0000, 0600, 1200 and 1800 UTC of 25 July, 2015 is presented in Figure 2 and Figure 3 respectively. It is evident that a cyclonic circulation was formed over Bihar and adjoining areas at 850 hPa level. Another cyclonic circulation was formed over the northeast Bangladesh which further moved to the southeast part of the country. The wind is blowing from the Bay of Bengal to the southeastern part of Bangladesh and adjoining areas with speed (10-15) ms^{-1} which carries enormous amount of moisture through a narrow belt. The convergence zone was found to lie on the southeastern part of Bangladesh and adjoining areas. This convergence zone caused strong updraft of moisture and formation of clouds. The cyclonic circulation over the southeast part of Bangladesh persisted upto 500 hPa levels. It may be pointed out from the wind pattern analysis that the circulation pattern is tilted southeastwards. An anti-cyclonic circulation was observed over the southeastern part of Bangladesh and adjoining areas at 200 hPa level (figures are not included here).
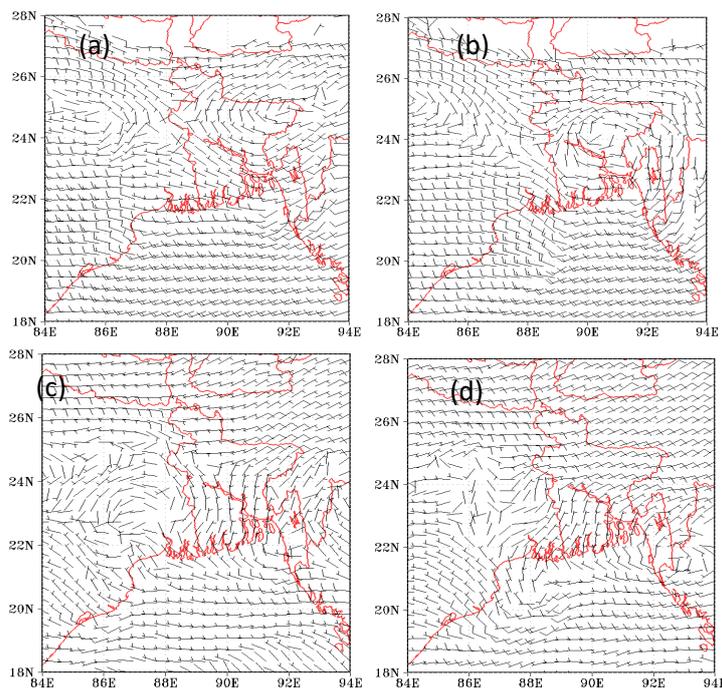
Figure 2: Analysis of wind flow distribution at (a-b) 850 hPa and (c-d) 500 hPa level valid for 0000 and 0600 UTC of 25 July, 2015 respectively.
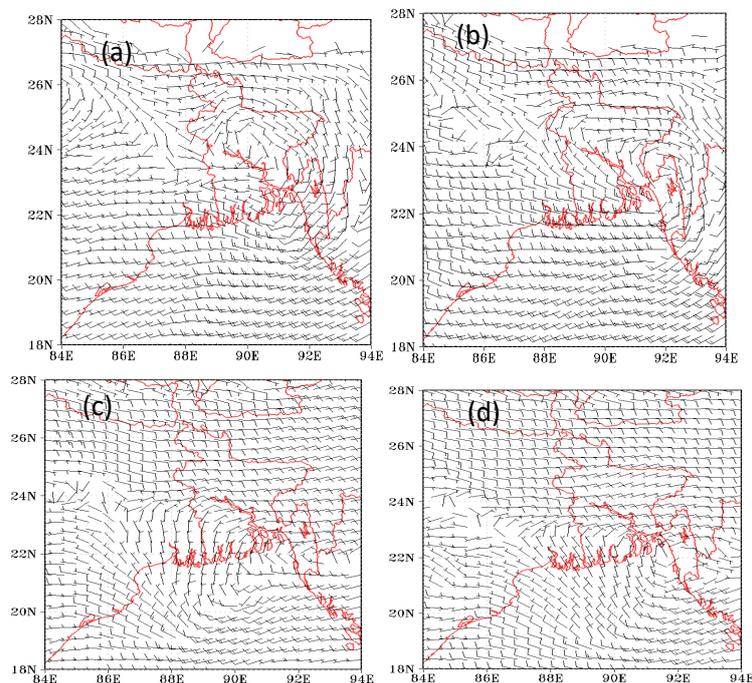

Figure 3: Analysis of wind flow distribution at (a-b) 850 hPa and (c-d) 500 hPa level valid for 1200 and 1800 UTC of 25 July, 2015 respectively.

3.3 Analysis of temperature profile

The model simulated temperature profile (℃) at 850 hPa level valid for 0000, 0600, 1200 and 1800 UTC of 25 July, 2015 are depicted in Figure 4. The highest model simulated temperature over Bihar, West Bengal and adjoining Bangladesh was found to be almost 22℃ on that day. It indicates that the temperature has decreased by (2-3)℃ over southeastern part of Bangladesh on 25 July. This is the indication of occurring high amount of rainfall over the southeastern part of Bangladesh and adjoining area.
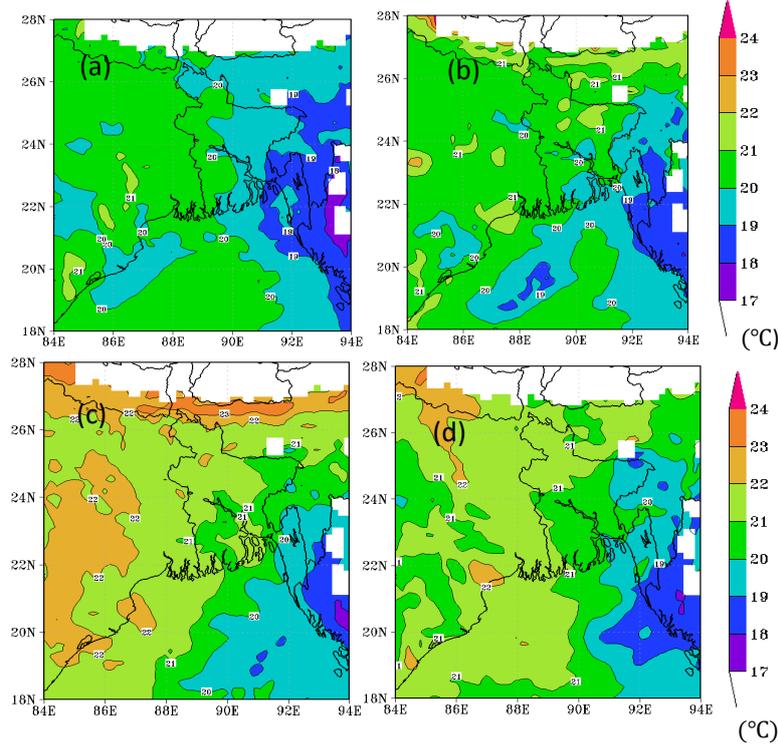
Figure 4: Analysis of temperature profile at 850 hPa valid for (a) 0000 UTC, (b) 0600 UTC, (c) 1200 UTC and (d) 1800 UTC of 25 July, 2015.

3.4 Lower level relative vorticity analysis

The WRF model simulated relative vorticity $\times 10^5$ s^{-1} at 850 hPa and 500 hPa levels valid for 0000, 0600, 1200 and 1800 UTC of 25 July, 2015 are represented in Figure 5 and Figure 6. The positive vorticity of wind flow indicates cyclonic flow while negative vorticity refers to anti-cyclonic flow. It is found that the model simulated relative vorticity at 850 hPa levels and 500 hPa levels are of the order of (10-80) $\times 10^5$ s^{-1} on 25 July, 2015 over southeastern part of Bangladesh and adjoining areas which reveals that severe convective activity may occur over these regions and which is very much supportive for heavy rain.
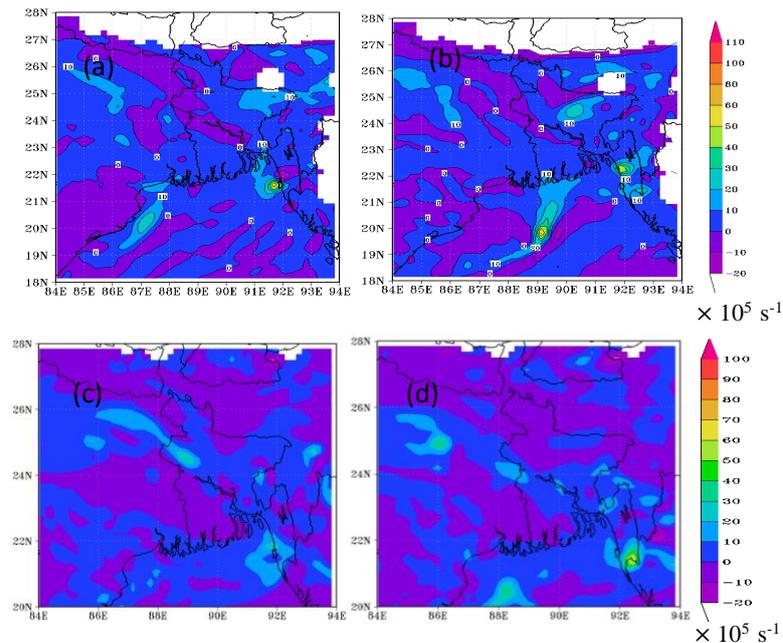

Figure 5: The distribution of relative vorticity at (a-b) 850 hPa and (c-d) 500 hPa valid for 0000 and 0600 UTC of 25 July, 2015 respectively.
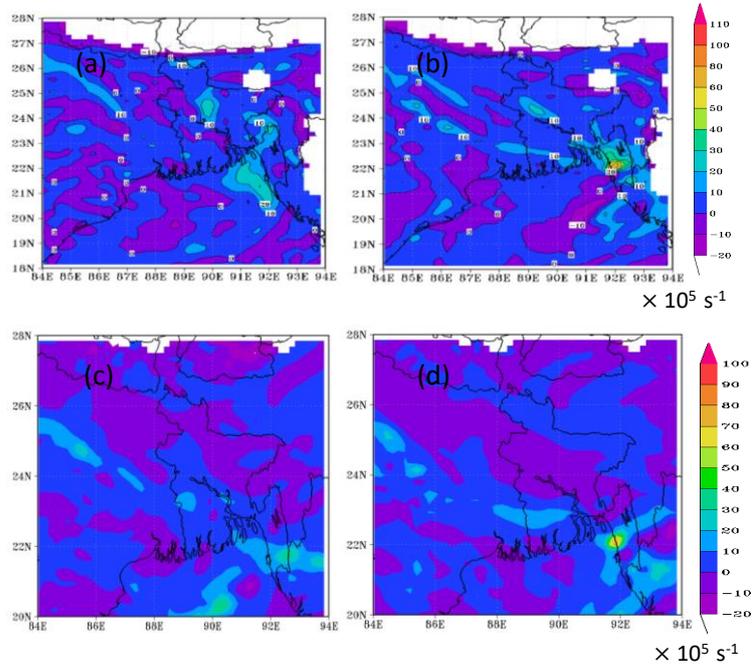
$\times 10^5$ s^{-1}

$\times 10^5$ s^{-1}

Figure 6: The distribution of relative vorticity at (a-b) 850 hPa and (c-d) 500 hPa valid for 1200 and 1800 UTC of 25 July, 2015 respectively.

3.5 Analysis of relative humidity and its vertical profile

The relative humidity at 2 m height valid for 0000, 0600, 1200 and 1800 UTC of 25 July, 2015 are shown in Figure 7. The high relative humidity is an important environmental variable associated with cloud and rain formation. From Figure it is found that the strong southwesterly flow transports abundant amount of moisture of the order of 80-100% to the plain of southeastern part of Bangladesh and adjoining area from the vast area of the Bay of Bengal. The contents of high magnitude of moisture play an important role for the formation of the shallow/severe convective activities over this region. The maximum moisture zone was the southeastern part of the country that caused heavy to very heavy rainfall. The vertical cross-section of relative humidity analysis at Cox's Bazar (along 21.5° N) valid for 0000 and 1200 UTC of 25 July, 2015 are shown in Figure 8. It is found that the relative humidity of the order of 80-100% vertically extended above 300 hPa level which emphasizes rapid warm and cold core convective clouds. These warm and cold core convective clouds are the indication of formation of high impact rainfall.
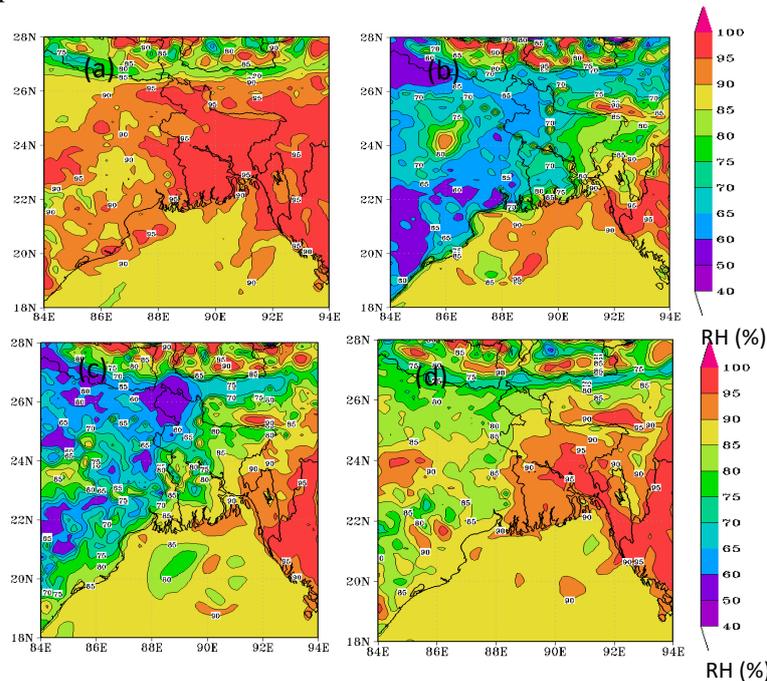

RH (%)

RH (%)

Figure 7: Analysis of relative humidity distribution at 2 m height valid for (a) 0000 UTC, (b) 0600 UTC, (c) 1200 UTC and (d) 1800 UTC of 25 July, 2015.
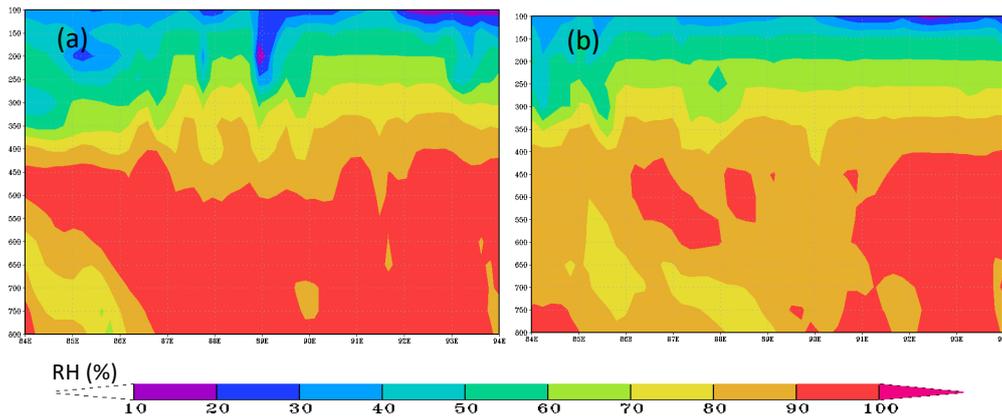
Figure 8: The vertical cross-section of relative humidity analysis along the 21.5° N (position of Cox's Bazar) valid for (a) 0000 UTC and (b) 1200 of 25 July, 2015.

3.6 Rainfall analysis

The spatial distribution of model simulated 6 hourly rainfall on 25 July, 2015 is given in Figure 9. 6 hourly highest rainfall of 25 July was found 75-100 mm, 125-150 mm, 175-200 mm and mm at 0600, 1200 and 1800 UTC respectively.
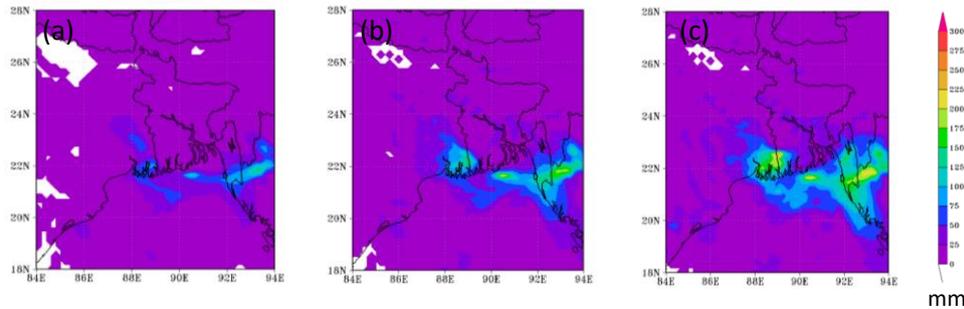

Figure 9: The distribution of rainfall valid for (a) 0600 UTC, (b) 1200 UTC and (c) 1800 UTC of 25 July, 2015.

Model simulated 24-h accumulated rainfall valid for 25 July 2015, was validated with that of observed TRMM 3B42V7 and BMD rain gauge data which are presented in Figure 10. It is found that the model has captured the rainfall pattern over the southeast coastal region of Bangladesh and adjoining areas which is in good agreement with the observations. So it can be inferred that the model simulated this high impact rainfall reasonably well. It is found that model simulated and BMD observed rainfall over the country overestimates the rainfall compared to that of TRMM observed rainfall.
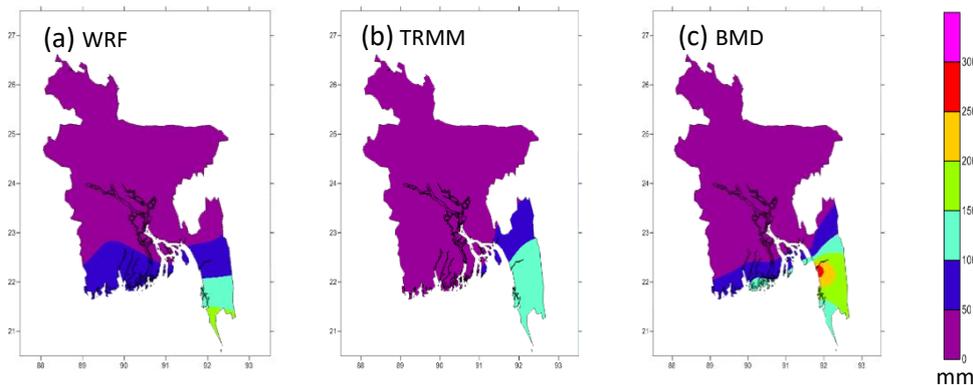

Figure 10: The spatial distribution of 24-h model simulated, 24-h TRMM and 24-h observed rainfall of BMD (mm) respectively on 25 July, 2015.

The model simulated rainfall is further compared quantitatively with that of TRMM and BMD which are presented in the Figure 11. It is found that the model simulated rainfall predicts low values over Cox's bazaar and Teknaf and high values over Chittagong, Rangamati, Kutubdia and Khepupara than BMD observed rainfall. Also the model predicts low values over Cox's bazaar and high values over Chittagong, Rangamati, Kutubdia, Teknaf and Khepupara than the observations produced by TRMM satellite rainfall data.

However, the WRF model not only captured the location of the heavy rainfall area over southeastern Bangladesh and its neighborhood but also in many other places providing a picture of spatial variability. Thus it is expected that the model would have generated the realistic rainfall throughout the country. Thus, the WRF model simulated rainfall seems to be more or less realistic both for quantitative assessment of rainfall and geographical distribution.
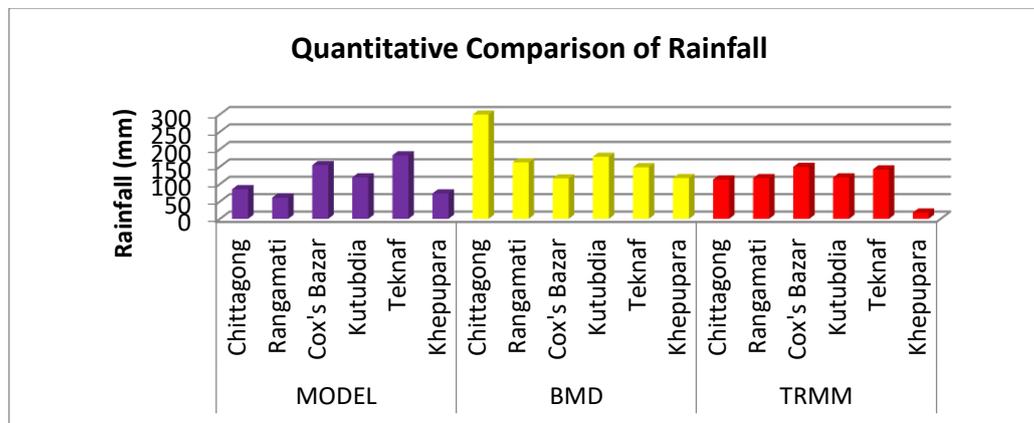

Figure 11: Quantitative comparison of WRF model simulated rainfall with observed TRMM and BMD rainfall on 25 July.

4. Conclusions

On the basis of the present study, the following conclusions can be drawn:

1) The analysis of the mean sea level pressure field shows that the monsoon trough has been produced and it extends up to the North Bay.

2) The low level wind field shows that there was southwesterly flow with wind speed (10-15) ms^{-1} from the Bay of Bengal towards the southeast coast of Bangladesh which converged over the southeast region of Bangladesh. The confluence of strong low level southwesterly flow causes transportation of large amount of moisture from the Bay of Bengal towards Bangladesh, especially over the areas of high impact rainfall and neighborhoods.

3) The high impact rainfall areas were characterized by high atmospheric relative humidity which extends up to the upper troposphere along a narrow vertical column. The strong low level convergence helped to carry moisture up to 300 hPa level and accordingly high relative humidity extended up to this level.

4) Analysis of model simulated temperature profile shows that there is decrease in temperature of (2-3)℃ over the areas where high impact rainfalls occur.

5) The study shows that the areas where high impact rainfall events were observed are characterized by high low level and mid-level positive relative vorticity (10-80) $\times$ 10^5 s^{-1} which refers to severe convective activity over those regions.

6) The model captures the heavy rainfall event over southeast region of Bangladesh reasonably well. The spatial distributions of rainfall are almost the same compared to the BMD and TRMM observed rainfall although the quantities of rainfall vary location wise.

7) The WRF model suggests that this high impact rainfall event over those regions might be due to active phase of monsoon over Bangladesh and strong over the North Bay.

Finally, it may be concluded that the WRF Model (Version 3.7.1) with the right combination of the parameterization scheme might be able to simulate the heavy rainfall event over southeast region of Bangladesh and associated synoptic and thermo-dynamical features reasonably well.

Further study is required to understand more about such cases, bias corrections and data assimilation may be some of the possible solutions.

Acknowledgements

References

[1] Bangladesh Bureau of Statistics (BBS), The People's Republic of Bangladesh (2010).

[2] Mirza, M.M.Q., Global warming and changes in the probability of occurrence of floods in Bangladesh and implications, Global Environmental Change, 12, 127-138 (2001).

[3] Rashid, H.E., Geography of Bangladesh, University Press Ltd:Dhaka (1991).

[4] BMD, Climatological Data and Charts, 1961-1980, Bangladesh Meteorological Department (BMD), WMO/UNDP/BGD/79/013 Tech. Note. No.9, 619 pp (1985).

[5] Mobassher, A., Synoptic Seasons in Bangladesh, Chittagong Univ. Stud., Part-II: Sci., 15 (2), 107-117 (1991).

[6] Ahasan, M.N., Chowdhary, M.A.M. and Quadir, D.A., Variability and Trends of Summer Monsoon Rainfall over Bangladesh, Journal of Hydrology and Meteorology, Nepal, Vol. 7, No. 1, pp. 1-19 (2010).

[7] Johnson, B. L. C., Bangladesh, Barnes and Noble Imports, Heinemann, London (1982).

[8] Chowdhury, M.R., The El Nino-Southern Oscillation (ENSO) and seasonal flooding – Bangladesh, Theoretical and Applied Climatology, 76: 105–124 (2003).

[9] Murata, F., Terao, T., Hayashi, T., Asada, H. and Matsumoto, J., Relationship between atmospheric conditions at Dhaka, Bangladesh, and rainfall at Cherrapunjee, India, Natural Hazards, 44: 399–410 (2008).

[10] Brammer H., Floods in Bangladesh-I: Geographical background to 1987 and 1988 floods, Geographical Journal, 156(1), 12-22 (1990).

[11] Ali, A.M.S., September 2004 flood event in South-western Bangladesh: a study of its nature, causes, human perception and adjustments to a new hazard, Natural Hazards, Volume 40, pp. 89-111 (2007).

[12] Shahid, S., Spatial and temporal characteristics of droughts in the western part of Bangladesh, Hydrological Processes 22(13): 2235–2247 (2008).

[13] Shahid, S. and Behrawan, H., Drought risk assessment in the western part of Bangladesh, Natural Hazards, 46(3): 391–413 (2008).

[14] Prasad, K., Monsoon forecasting with a limited area numerical weather prediction system, SAARC Meteorological Research Centre (SMRC) Scientific Report 11, (2005).

[15] Das. S., SMRC Scientific Report No. 28, 45 pp (2009).

[16] Das, S., SMRC Scientific Report No. 35, 62 pp (2010).

[17] Das, S., Rahman, M. and Singh, J., SMRC Scientific Report No. 42, 38 pp (2012).

18] Ahasan, M.N., Rayhun, K.M.Z., Mannan, M.A. and Debsarma, S.K., Synoptic analysis of a heavy rainfall event over southeast region of Bangladesh using WRF model, Journal of Scientific Research, ISSN: 2070-0237, 5 (3), 421-434 (2013).

[19] Ahasan, M.N., Chowdhury, M.A.M. and Quadir, D.A., Simulation of high impact rainfall events over southeastern hilly region of Bangladesh using MM5 model, International Journal of Atmospheric Sciences, Article ID 657108 (2013).

[20] Mannana, M.A., Chowdhury, M.A.M. and Karmakar, S., Application of NWP model in prediction of heavy rainfall in Bangladesh, Elsevier Ltd., 1877-7058 (2013).