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SIMULATION OF HEAVY RAINFALL EVENT OVER THE SOUTH AND SOUTHEASTERN PART OF BANGLADESH DUE TO MONSOON DEPRESSION USING WRF MODEL

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ABSTRACT

In our present study the rainfall event of 13-14 September, 2004 was nominated to simulate over the south and southeastern part of Bangladesh due to monsoon depression using WRF model. WRF Single-moment 6-class (WSM6) microphysics scheme, Kain-Fritsch cumulus parameterization scheme and Yonsei University (YSU) planetary boundary layer scheme was used to run the model. A domain was used with the horizontal resolution of 9 km for capturing the area of heavy rainfall event (HRE). On the basis of the initial condition 0000 UTC on 13 September, 2004 the model was run for 48 hours. The mean sea level pressure, wind pattern, relative humidity, low level vorticity, vertical wind shear, low level divergence and rainfall distribution have been examined on behalf of the evaluation of model performance. The model derived rainfall was compared with the rain gauge rainfall of Bangladesh Meteorological Department (BMD). The WRF model suggested that a cyclonic flow appears in between 850 and 500 hPa level, which remains over the southwestern part of Bangladesh also the adjacent area. Also the model suggested that, f*rom the enormous area of the Bay of Bengal a large amount of moisture carried by a strong southwesterly flow towards the southeastern part of Bangladesh and the adjoining area and so the HRE over these regions might be characterized by the positive vorticity and strong vertical wind shear between 850 to 200 hPa level.*

Keywords: *Cumulus parameterization scheme, Heavy rainfall event, Monsoon depression, Microphysics, Planetary boundary layer scheme, WRF Model*

1. INTRODUCTION

The Bay of Bengal is located to the south and the Himalayas to the north of Bangladesh. So the weather of Bangladesh is influenced by these two different environments (Wahiduzzaman, 2012). Among the SAARC regions this country experiences the maximum amount of rainfall because of its geographical position (Devkota *et al*., 2006). Bangladesh faces the two types of monsoon such as the summer monsoon/south west monsoon and the winter monsoon/north east monsoon. But almost 72% rainfall occurs in summer monsoon so the summer monsoon is the main rainy season in Bangladesh (Prasad, 2005; Ahasan *et al*., 2010). This huge amount of seasonal rainfall and the change in wind direction is conventionally characterizing the monsoon climate (Krishnamurti, 1979).

Thunderstorms, tropical disturbances and many other weather systems are contributing to the monsoon rainfall (Ramage, 1971). But among all these monsoon disturbances the monsoon depression (MD) is the most effective and well-organized rain producing system. During a monsoon season, an average of six or seven MD forms over the North Bay of Bengal and move along the monsoon trough (Routray *et al*., 2014). Almost half of the rainfall occurs due to the MDs. It spreads deeply in the continental area and along its track generates huge amount of rainfall (Krishnamurti, 1979). MD is defined as the weak cyclonic disturbances within the monsoon trough and mainly moves west-northwestward over the Indian subcontinent (Sinha *et al*., 2010). The regions where the MD stays, it causes the huge amount of rainfall and when it stays over the land, and then it is known as land depression (Raj, 2002). The MDs are strongly formed when the cold core in the lower troposphere and the warm core in the upper troposphere is present, the outermost closed isobar have a diameter of 1000 km and the wind distribution has a 200 km diameter light wind core (Sikka, 1977).

The intensification of the MDs occurs in association with the interaction between upper tropospheric divergence and lower tropospheric convergence. The westward propagating disturbances or the divergence in the upper tropospheric strong easterly flow deliver the favorable mechanism in the upper troposphere (Saha and Chang, 1983; Warner, 1984). These features are associated with upper level positive vorticity advection which favors upward motion and low level convergence in the North Bay of Bengal. However, synoptic experiences show that there are several cases when the development of the depressions takes place without significant changes in the upper tropospheric circulation occurring prior to the time of intensification (Sikka, 1977). One of the synoptic conditions for the genesis of these depressions is the presence of strong monsoon westerlies to the

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south of the genesis area (Saha and Chang, 1983). The intensification of the depression was accompanied with strengthening of lower tropospheric westerlies over the Peninsular India and the Gangatic valley to the north of the center. The distribution of the daily changes of sea level pressure rather than the pressure itself, finding that most of the depressions that form at the Head of the Bay of Bengal were associated with pressure disturbances coming from the east. Weak easterly vertical wind shear is a characteristic feature of the flows over the North Bay of Bengal during monsoon (Saha *et al*., 1981).

During the southwest summer monsoon season HREs are arising over the Indian subcontinent as well as Bangladesh (Dodla and Ratna, 2009). If the rainfall during the previous 24-h are 22-44 mm, 45-88 mm and ≥ 89 mm then it is said to be moderately HRE, HRE and very HRE, respectively which are categorized by BMD. When the rainfall duration is a few hours long it causes the HRE. In Bangladesh, these HREs are usually happening over the southern and northeast parts of Bangladesh. The northeast parts of Bangladesh experience HREs because of orographic features (Hatwar *et al*., 2005). Even though during the monsoon season heavy rainfall incidences were observed over the isolated locations (Rao and Prasad, 2005).

There are several methods available to forecast rainfall events. However, most efficient and advance way of rainfall forecasting is using the numerical weather models (i.e., Numerical Weather Prediction (NWP) model). NWP is becoming an important tool in research and operational weather forecasting in recent years. The NWP model is the mathematical model which can forecast the weather phenomena according to the present weather conditions. Because of the free availability of NCEP GFS data, different types of physics options the WRF model becomes very popular in recent years. Therefore, to evaluate HREs over Bangladesh, WRF model can be an effective tool for operational forecast. BMD also uses the WRF model alongside other NWP models to forecast various weather events up to seven days over the country. BMD forecast 24-h, 48-h and 72-h rainfall using this model after every 6 hour time cycle. This model can be applied for different purpose like operational weather forecast, climate change study, atmospheric feedback study and various other atmospheric researches.

In previous years the simulation and the prediction of HREs including monsoon depressions during monsoon using NWP mesoscale models like MM5, WRF etc. has been done by many researchers. Ahasan *et al.* (2013) studied the heavy rainfall event over Chittagong, Bangladesh and found very intense and short lived convective cells over that region, which is liable for heavy rainfall and for estimating rainfall the Anthes-Kuo cumulus scheme performs well. Mallik *et al.* (2015) suggested that the WRF model is suitable for rainfall simulation with the parameter of geopotential height, strong vertical wind shear and relative humidity. Byun *et al.* (2015) found that the planetary boundary layer scheme influences the temporal progression of the precipitation more than the microphysics scheme. Alam (2014) studied the impact of cloud microphysics and cumulus parameterization on simulation of heavy rainfall event over Bangladesh and found that the Lin-KF combination gave the best result for simulation of heavy rainfall event over Bangladesh.

The main objectives of our study is to simulate the HRE of 13-14 September 2004 which observed over the south and southeastern parts of Bangladesh due to monsoon depression using WRF model and to identify which of the parameters (i.e., mean sea level pressure, wind pattern, relative humidity, low level vorticity, vertical wind shear, low level divergence etc.) are responsible for the occurrence of this HRE.

2. DATA USED, MODEL SETUP AND METHODOLOGY

For the initial and lateral boundary condition the National Centre for Environmental Prediction (NCEP) high-resolution Global Final (FNL) analysis data was used in this present study. This FNL data cover the whole world every six hours with 1.0°×1.0° grids. To simulate the terrain or topography the 30 second United States of Geological Survey (USGS) data was used. As the vegetation or land use coverage the 25 categories USGS data was used. The heavy rainfall occurs all over the country or different parts of the country have recorded by BMD. This BMD observed rainfall data was used for comparison with the model simulated data. The heavy rainfall event is a severe weather phenomenon which was selected for simulation over the south and southeastern part of Bangladesh on 13-14 September, 2004. There are several mesoscale models for simulation but in this study the Weather Research and Forecasting (WRF) model was used. The WRF is consists of fully compressible non-hydrostatic equations and different prognostic variables. The terrain following hydrostatic pressure is used as the model vertical coordinate. The Arakawa C-grid staggering is the horizontal grid of the model. In the model the 3rdorder Runge-Kutta time integration is used. A domain was used with the horizontal resolution of 9 km for capturing the area of heavy rainfall event. The domain is consists of 295 grid points in the east-west direction and 304 grid points in the north- south direction. The domain was configured to have the same vertical structure of 38 unequally spaced sigma (non-dimensional pressure) levels. The center (23.5^0 N, 90^0 E) of the domain was taken over Bangladesh. There are different physical schemes are used in this study. As a microphysics scheme the WRF Single Moment 6-class (WSM6) scheme (Hong and Lim, 2006), as a cumulus parameterization scheme the Kain-Fritsch (new Eta) scheme (Kain, 2004) and as a planetary boundary layer scheme the Yonsei University (YSU) scheme (Hong *et al*., 2006) was used. The prognostic equations for cloud water, rainwater, cloud ice, snow, and graupel mixing ratio are consisted in the WSM6 microphysics scheme. Alam (2014), Hong and Lim (2006) suggested that among all the microphysics schemes, the WSM6 scheme is the most suitable for cloud resolving grids, considering the efficiency and theoretical backgrounds.

Table 1: The model configurations

Dynamics	Non-hydrostatic
Number of domain	1
Central points of the domain	Central Lat.: 23.5^0 N, Central Lon.: 90^0 E
Horizontal grid distance	9 km
Integration time step	50s
Number of grid points	X-direction 295 points, Y-direction 304 points
Map projection	Mercator
Horizontal grid distribution	Arakawa C-grid
Vertical co-ordinate	Terrain-following hydrostatic-pressure co-ordinate (38 sigma levels)
Time integration	3rd order Runge-Kutta
Spatial differencing scheme	6th order centered differencing
Initial conditions	Three-dimensional real-data (FNL: 1° × 1°)
Lateral boundary condition	Specified options for real-data
Top boundary condition	Gravity wave absorbing (diffusion or Rayleigh damping)
Bottom boundary condition	Physical or free-slip
Diffusion and Damping	Simple Diffusion
Microphysics	WSM 6-class
Cumulus parameterization schemes	Kain-Fritsch (KF)
PBL parameterization	Yonsei University Scheme (YSU)
Land surface parameterization	5 Layer Thermal diffusion scheme
Radiation scheme	RRTM for long wave
Surface layer	Monin-Obukhov similarity theory scheme

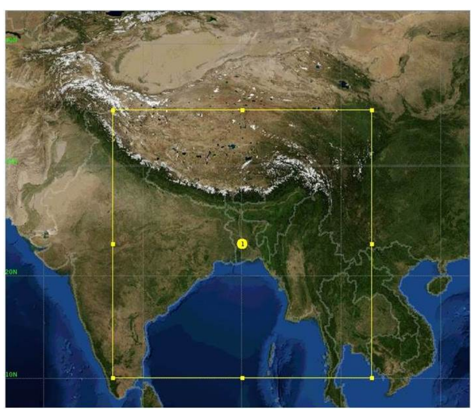

Figure 1: WRF model domain for rainfall simulation

The performances of cumulus parameterization schemes were evaluated in terms of their ability to simulate amount of rainfall during the heavy, moderate, and light phases of the event. Among them the KF scheme was able to account of the mesoscale processes that lead to the development of convection (Pattanaik *et al.,* 2011). On the basis of the initial condition 0000 UTC on 13 September, 2004 the model was run for 48 hours. The mean sea level pressure, wind pattern, relative humidity, low level vorticity, vertical wind shear, low level divergence and rainfall distribution have been examined on behalf of the evaluation of model performance. The synoptic situations valid for 0600 UTC, 1200 UTC and 1800 UTC of 13-14 September, 2004 are analyzed in the present paper. The model configurations are presented in Table 1 and also the model domain is given in Figure 1.

3. RESULTS AND DISCUSSION

This event is simulated by the WRF model with evaluating different meteorological parameters and described briefly in the following section.

3.1 Minimum Sea Level Pressure (MSLP)

The model derived MSLP (hPa) valid for 0600, 1200 and 1800 UTC on 13-14 September, 2004 is shown in Figure 2. For probable weather disorders the low pressure area formulation is a significant preliminary condition. If the favorable environments are appearing then, it may strengthen into a tropical depression. The central pressure of the depression at 0600, 1200 and 1800 UTC on 13 September, 2004 is about 1003, 1001 and 1002 and on 14 September, 2004 is about 1002, 999, and 1001 hPa, respectively. 999 hPa is the lowermost central pressure of the depression at 1200 UTC on 14 September, 2004. The most powerful synoptic scale low-pressure system is the monsoon depression. In the mature stage of the monsoon depression the pressure pattern can't change by the organization of its deep convective components but modify them properly keeping coherence. Over the Tibet the MSLP appears as very high and between 1014 hPa to beyond 1022 hPa the central pressure fluctuates at 0600, 1200 and 1800 UTC on 13-14 September 2004, respectively. As a consequence of the high pressure over the Tibetan plateau, the depression over the southwestern part of Bangladesh and the adjacent region remains static for a long spell. The depression didn't travel on the way to further east or southeast by reason of extreme high pressure dominant over these areas.

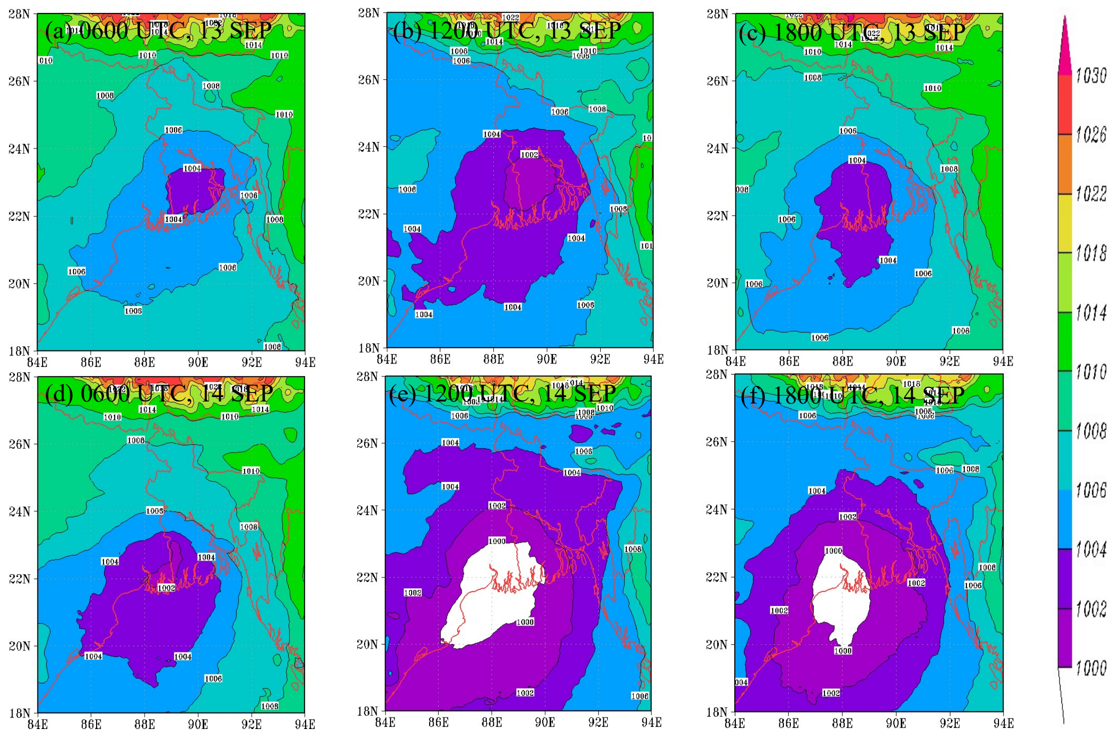

Figure 2: Model simulated MSLP (hPa) distribution valid for (a) 0600, (b) 1200 and (c) 1800 UTC of 13 September 2004 and (d) 0600, (e) 1200 and (f) 1800 UTC of 14 September 2004

3.2 Low and Upper Level Wind Flow

The wind flow (ms^{-1}) distribution of 13-14 September, 2004 at 850 hPa and 500 hPa level valid for 0600, 1200 and 1800 UTC is presented in Figure 3 and Figure 4, respectively. A cyclonic flow appears at 850 hPa and 500 hPa level, which remains over the southwestern part of Bangladesh also the adjacent area. The midpoint of the cyclonic movement at 850 hPa is situated at 23^0N, 89^0E and at 500 hPa is situated over the western part of Bangladesh and adjoining area (23^0N, 90^0E) which is northeast of 850 hPa location.

Thus, the vertical axis of the land depression (LD) is slightly tilted in northeastward with height. From Figure 3 it is clearly seen that a large amount of moisture carried out by a strong southwesterly flow from the enormous area of the Bay of Bengal towards the south-southeastern and southwestern part of Bangladesh at 0600, 1200 and 1800 UTC of 13-14 September 2004.

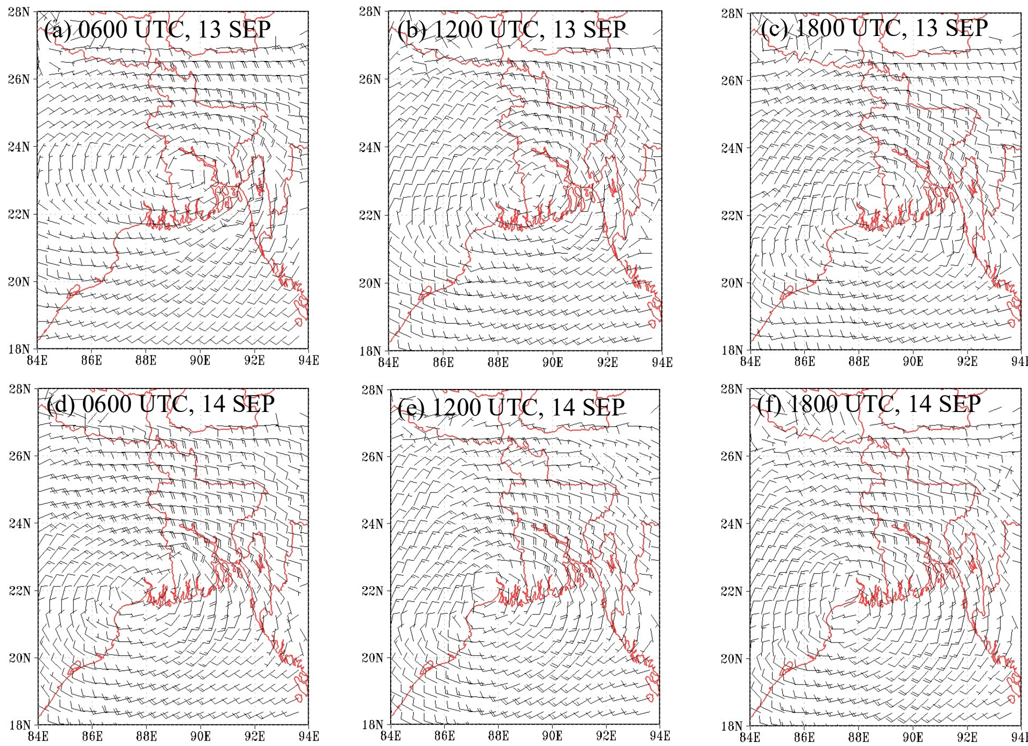

Figure 3: Wind flow distribution at 850 hPa level valid for (a) 0600, (b) 1200 and (c) 1800 UTC of 13 September 2004 and (d) 0600, (e) 1200 and (f) 1800 UTC of 14 September 2004

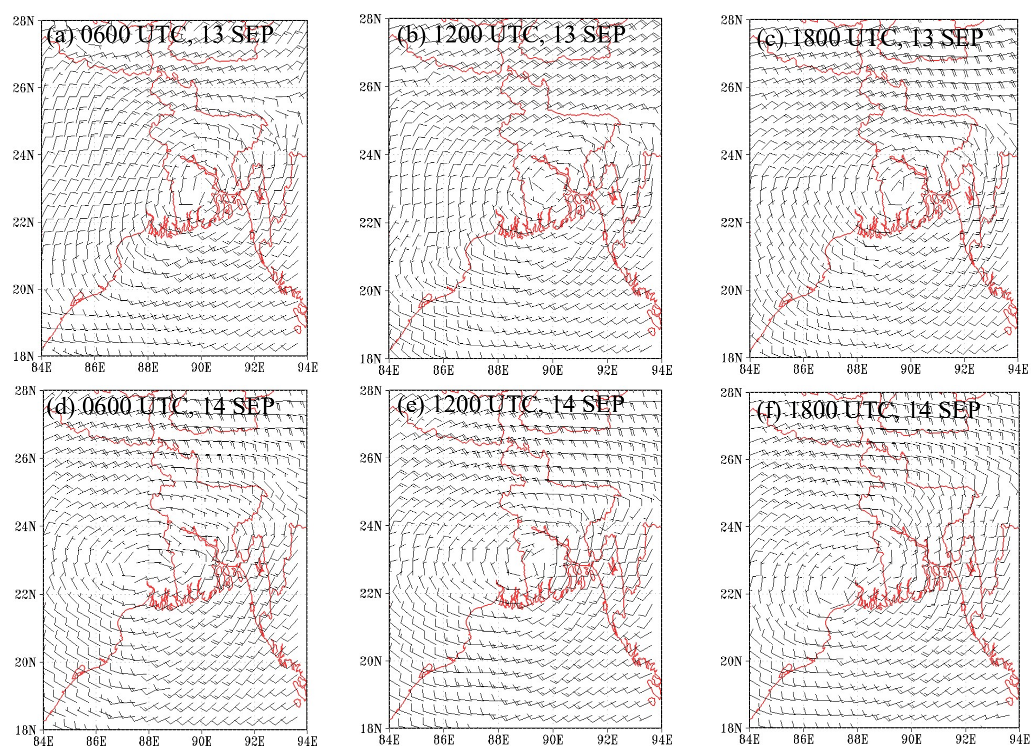

Figure 4: Wind flow distribution at 500 hPa level valid for (a) 0600, (b) 1200 and (c) 1800 UTC of 13 September 2004 and (d) 0600, (e) 1200 and (f) 1800 UTC of 14 September 2004

The area of high convective activity or the area of convergence is observed over the eastern part of the depression i.e., Sandwip, M. Court and its surrounding area. From Figure 4 it is observed that up to 500 hPa level, this southwesterly flow is appearing over the North Bay of Bengal and from central to southern part of

Bangladesh. An anticyclonic circulation was observed over the southwestern part of Bangladesh at 200 hPa level (Figure not shown) and so, no convective activity was detected at 200 hPa.

3.3 Relative Vorticity

The WRF model simulated relative vorticity ($\times10^{-5}$ s^{-1}) at 850 hPa level valid for 0600, 1200 and 1800 UTC on 13-14 September, 2004 is presented in Figure 5. The positive vorticity of wind flow denotes cyclonic flow while negative vorticity supports anti cyclonic flow. It is found that the model simulated vorticity at 850 hPa level is of the order of (10-40) $\times10^{-5}s^{-1}$ valid for 0600, 1200 and 1800 UTC on 13-14 September, 2004 which indicates that the cyclonic circulation contributes to the severe convective activity over this region.

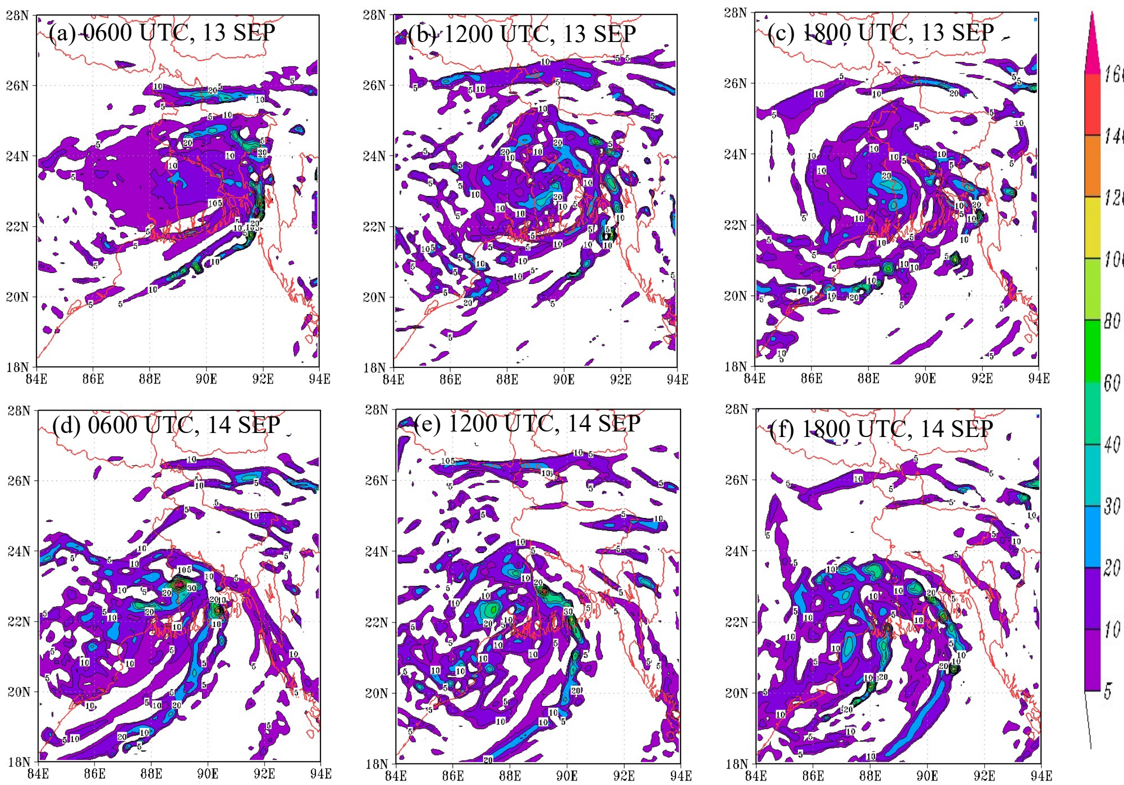

Figure 5: Relative vorticity (unit: $\times10^{-5}s^{-1}$) distribution at 850 hPa valid for (a) 0600, (b) 1200 and (c) 1800 UTC of 13 September 2004 and (d) 0600, (e) 1200 and (f) 1800 UTC of 14 September 2004

3.4 Relative Humidity

The relative humidity at 850 hPa valid for 0600, 1200 and 1800 UTC on 13-14 September, 2004 are presented in Figure 6. For the cloud and rain formation the high amount of relative humidity is an essential parameter. It is clearly observed that from the Figure 6, a massive amount of moisture is of the order of 90-100% is transported by the strong southwesterly flow from the Bay of Bengal to the land of central and eastern part of Bangladesh and also the neighboring area. As a consequence of this plenteous amount of moisture a strong convective activity performs over these regions. The relative humidity prolonged up to 400 hPa level is of the order of 90-100% and prolonged up to 200 hPa level is about 60-70% that enriches the convective movement along 22.50^0 N (Position of M. Court) which were observed from the Figure 7 of the vertical profile of humidity.

3.5 Vertical Wind Shear

The u-component of wind between 200 hPa and 850 hPa level (u_{200}- u_{850}) is called the wind shear. The model derived vertical wind shear presented in Figure 8, which is effective at 0600, 1200 and 1800 UTC on 13-14 September, 2004. From this figure, it is observed that, due to the characterization of the strong vertical wind shear the atmosphere of Sandwip, M. Court and neighborhood experiences a very heavy precipitation. These regions experience a strong vertical wind shear, which fluctuates between 15 to 30 ms^{-1}. The strong and tiny survived multi-cell thunderstorms are developed because of this wind shear over these regions. Consequently a very heavy rainfall event occurs with the combination of multi-cell thunderstorms and the monsoon flow.

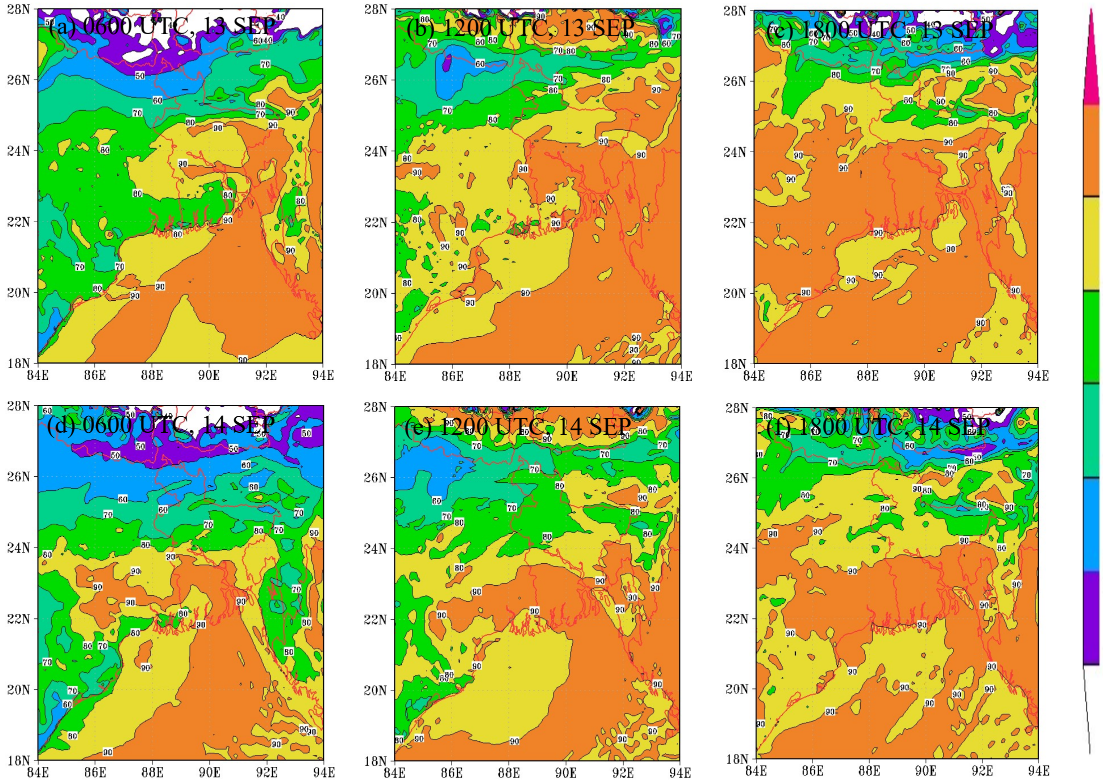

Figure 6: Relative humidity distribution at 850 hPa level valid for (a) 0600, (b) 1200 and (c) 1800 UTC of 13 September 2004 and (d) 0600, (e) 1200 and (f) 1800 UTC of 14 September 2004

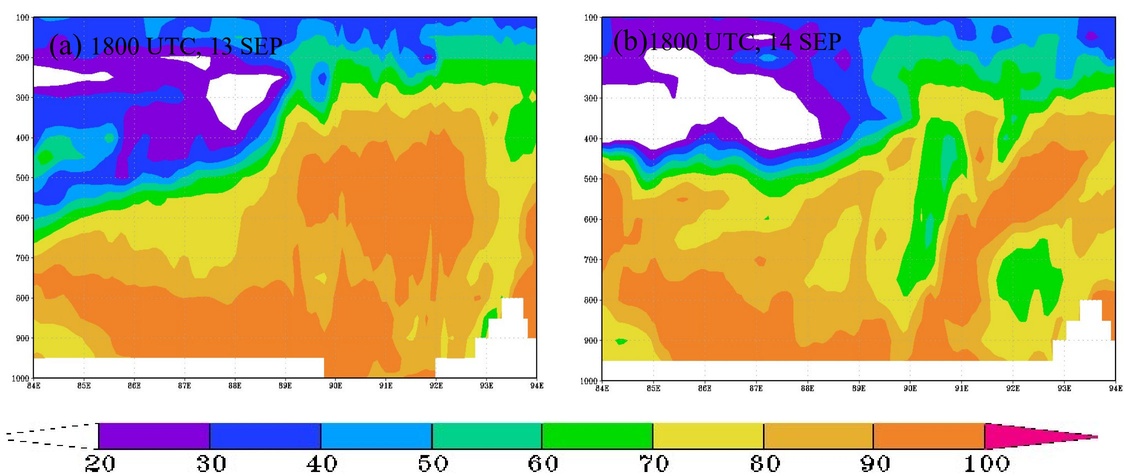

Figure 7: The vertical cross-section of relative humidity along the 22.5^0 N (position of M. Court) valid for (a) 1800 UTC of 13 September 2004 and (b) 1800 UTC of 14 September 2004

3.6 Rainfall Distribution

The WRF model simulated and BMD observed 24-h accumulated rainfall distribution on 14 September 2004 is presented in Figure 9(a-b). The BMD observed rainfall distribution are chosen for validation with the model simulated rainfall. The BMD observed rainfall at M. Court, Dhaka, Sandwip, Hatiya, Bhola, Sitakunda and Kutubdia were 376, 341, 209, 196, 179, 89 and 48 mm, respectively but the model simulated rainfall were 101, 25, 148, 135, 79, 40 and 86 mm, respectively. Over the area of Kutubdia the model shows the overestimated rainfall than that of BMD observed rainfall. But over the region of M. Court, Dhaka, Sandwip, Hatiya, Bhola and Sitakunda the model simulated rainfall was underestimated.

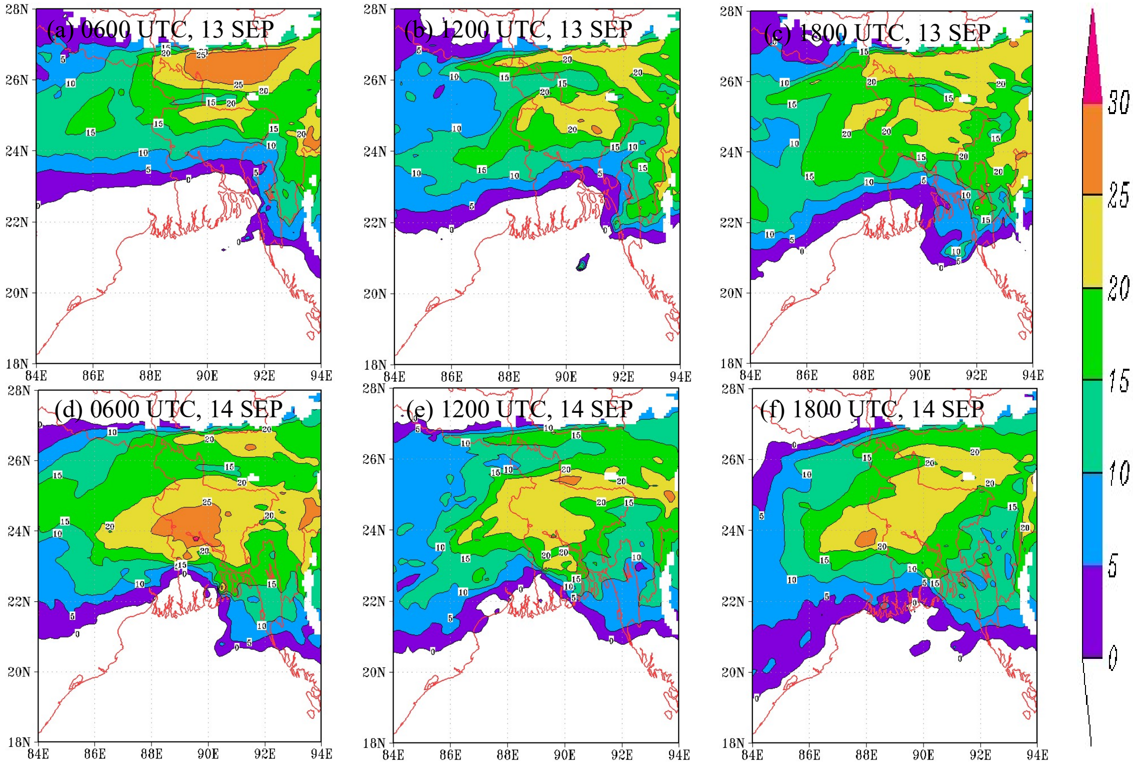

Figure 8: The vertical wind shear distribution of the u-component of the wind between 200 hPa and 850 hPa level (u_{200}-u_{850}) valid for (a) 0600, (b) 1200 and (c) 1800 UTC of 13 September 2004 and (d) 0600, (e) 1200 and (f) 1800 UTC of 14 September 2004

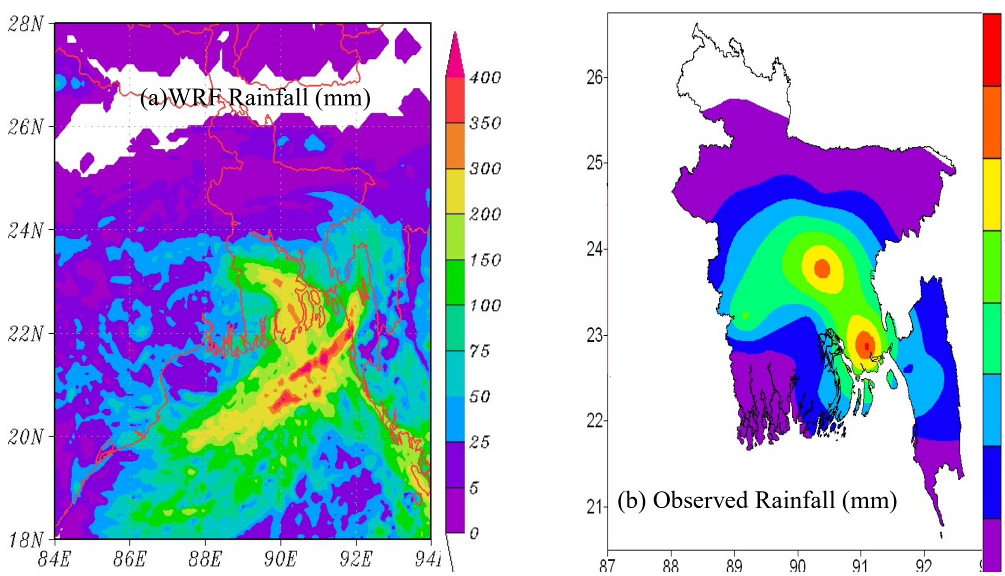

Figure 9: (a) WRF model simulated and (b) BMD observed rainfall distribution on 14 September 2004

The capital of the country Dhaka experiences 341 mm rainfall which was observed by BMD rain gauge but the model simulated rainfall was only 25 mm. In case of Dhaka, the model simulated and BMD observed rainfall was mismatched. It is clearly observed that from the model simulated and BMD observed rainfall distribution the area of the southern, southeastern and southwestern part of Bangladesh experiences significant amount of rainfall, but the northern part of the country has the smallest amount of rainfall. Here we indicate that, the number of rain gauge stations in Bangladesh is very few and so they are not close enough for capturing the convincing view of the mesoscale processes. For most of the stations, the WRF model is able to capture the location where the heavy rainfall occurs and also give the picture of spatial variability of some other places. Therefore, it is expected that the model would have generated the realistic rainfall throughout the country.

4. CONCLUSIONS

According to our current research work, the subsequent conclusions can be made as follows:

The lowermost central pressure of the depression is about 999 hPa at 1200 UTC on 14 September, 2004 in accordance of the model simulation. As a consequence of the high pressure over the Tibetan plateau, the depression over the southwestern part of Bangladesh and the contiguous region remains static for a long spell. The depression didn't travel on the way to further east or southeast by reason of extreme high pressure dominant over these areas. A cyclonic flow appears at 850 hPa and 500 hPa level, which remains over the southwestern part of Bangladesh also the adjacent area. The convergence of strong southwesterly flow transports high amount of moisture from the vast area of the Bay of Bengal towards the eastern and southeastern part of Bangladesh and neighborhood. The humidity sustained up to 400 hPa level that enriches the convective movement along 22.50^0 N (Position of M. Court) which we observed from the vertical profile of humidity. The WRF model recommends that, for the formation of depression and moist air updrafts the positive vorticity, resilient vertical wind shear, strong convergence at 850hPa and prominent divergence at 200 hPa level was so much advantageous. The heavy rainfall event was observed over the area of Sitakunda, Sandwip, Hatiya, Kutubdia, M. Court, Bhola and neighborhood.

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