Simulation of Monsoon Depression over the Bay of Bengal and Its Features using Weather Research and Forecasting Model

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Abstract

An attempt has been made to simulate the monsoon depression over the Bay of Bengal during 13-16 June, 2008 and its associated rainfall using Weather Research and Forecasting Model. The model was run on a single domain of 10 km horizontal resolution using Morrison 2-moment microphysics with Kain-Fritsch cumulus parameterization scheme and Yonsei University planetary (YSU) boundary layer scheme, MM5 surface layer physics scheme, Unified Noah LSM land surface physics, Rapid Radiative Transfer Model (RRTM) for longwave and Dudhia scheme for short-wave scheme are used in version 3.9.1 for the simulation. The NCEP high resolution FNL 6-hourly data is used for initial and lateral boundary conditions. GrADS is used to visualize the different graphics. The model predicting capability is evaluated by analyzing Mean Sea Level Pressure (MSLP), wind pattern, vorticity, vertical wind shear, reflectivity, temperature and rainfall distribution. The model has successfully captured the system, its initial condition, propagation, landfall time and location reasonably well. The model has simulated rainfall, wind and rh sensibly well compared with the observed data by BMD and Tropical Rainfall Measuring Mission (TRMM). It can be concluded that the WRF model with the accurate arrangement of the domain, horizontal resolution and the appropriate parameterization schemes is proficient to simulate and forecast the monsoon depressions over the Bay of Bengal and its associated rainfall over Bangladesh up to 96-hours advance reasonably well.

Keywords: Morrison 2-mom, Kain-Fritch, YSU scheme, Vorticity, TRMM, NCEP

1. Introduction

Different factors are responsible behind Monsoon Low Pressure Systems (MLPSs). Srivastava et al. (2017) studied several synoptic systems such as lows, Well Marked Lows, depressions, and deep depressions (collectively referred to as MLPS) are an important feature of the southwest Summer Monsoon. Most of these systems originate in the Bay of Bengal (BoB) and move north-westward over the central Indian landmass as well as Bangladesh along the monsoon trough. The LPS typically have length and time scales of 1000–2000 km and 3–6 days, respectively [Mooley, 1973; Godbole, 1977; Sikka, 1977]. Monsoon is a global phenomenon. The southwest summer monsoon is perhaps the best defined and well organized amongst the monsoons of the world (Ding and Das, 2002). Monsoon disturbances are the most important transient synoptic features of the summer monsoon. They are the principal rain bearing systems during the summer monsoon season. BMD classified the monsoon disturbances into various categories in terms of the maximum sustained wind speed realized within its vicinity (BMD and Debsarma, S. K., 2004). The synoptic-scale tropical disturbances, which periodically form in the quasi-stationary monsoon trough during the summer monsoon season spanning June-July-August September (JJAS), are considered to be the main rain-bearing systems (Krishnamurthy, V. and R. S. Ajayamohan, 2010). Being a country having a large fraction of agriculture depends on the seasonal rains; variation in the monsoon rainfall affects the lives of billions of people and influence the economy of the country considerably. There have been several studies on the inter-annual variation of the summer monsoon (June–September) rainfall. It is well known that the summer monsoon is maintained by northward progression of the ITCZ (Sikka and Gadgil 1980) and the synoptic scale systems, usually known as MLPSs, which normally form over the BoB or cross over the BoB from south-China sea and propagate westward/Northwestward to the mainland (Sikka 2006). Krishnamurti, 1979 described that the monsoon climate is characterized by high amount of seasonal rainfall and U-turn of wind direction. In agricultural sector this rainfall is very important as a source of fresh water. Various weather systems such as tropical cyclones and weak disturbances contribute to monsoon rainfall (Ramage, 1971). Among these systems, the most efficient rain-producing system is known as the MLPSs. Due to geographical position, Bangladesh experiences many natural disturbances for example Tropical Cyclone (TC), MLPSs, storm surges, floods, droughts, nor'westers, tornadoes, heavy rainfall, cold wave, heat waves etc. Most of the rainfall events occur in monsoon months (JJAS). Among the MLPSs, MDs are synoptic scale cyclonic circulations that occur over the North

BoB and Indian subcontinent during the SW monsoon season and give copious rainfall [Rao et al, 1976 and Sikka, 1977].

An explanation of the intensification of MLPSs has been investigated by many researchers (Sikka, 1977 and P. Koteswarm, 1958; Saha and Chang, 1983; Warner, 1984). The intensification of the MLPSs occurs in association with the interaction between upper tropospheric divergence and lower tropospheric convergence (Koteswaram et al., 1958). Saha et al., 1981 studied the analysis of the daily changes of sea level pressure rather than the pressure itself, finding that most of the MLPSs that form at the head BoB were associated with pressure disturbances coming from the east. For the growth of MLPSs a reasonable easterly wind shear of the order of 20 ms-1 at 850 hPa level, large growth rates for horizontal scales of the order of 1000 to 2000 km are possible (Krishnamurti et al., 1984). The mesoscale prediction system like MLPSs requires the use of high resolution atmospheric mesoscale models and observations with a mesoscale system. Some studies of the numerical prediction of heavy rainfall using high resolution mesoscale models explain the predictability of events with rainfall less than 200 mm/day (Bhaskar et al., 2005, Routray et al., 2005 and Hatwar et al., 2005).Among the MLPSs, MD is critical for monsoon rainfall because: (i) it occurs about six times during each summer monsoon season, (ii) it propagates deeply into the continent and produces large amounts of rainfall along its track, and (iii) about half of the monsoon rainfall is contributed to by the MDs (Krishnamurti, 1979). For that reason understanding various properties of the MD is a key towards considerate of the accuracy of the SW monsoon and especially its hydrological process. Occasionally MDs form in the land as a land depression and cause heavy rainfall over the region where it lies (Raj, 2003). MDs are more intense than ML. From a low pressure area intensity into a depression there should be at least two closed isobars present within a 5° square (Raj, 2003). NWP models use in monsoon weather research and forecasting is new in Bangladesh. Though very recently, an attempt has been made to simulate and predict the HREs including MLPSs during summer monsoon season over Bangladesh using NWP mesoscale models like MM5, WRF etc. by many researchers (Prasad, 2005); high impact rainfall events of summer monsoon over Bangladesh, simulation of heavy rainfall event of 11 June 2007, synoptic analysis of heavy rainfall event over southeast region of Bangladesh (Ahsan et al., 2011, 2013a and 2013b), simulation of a very heavy rainfall event of 13 September, 2004 over Bangladesh due to monsoon land depression using WRF model (Mallik et al., 2014) and studies of summer monsoon rainfall (Islam, 2008). Das et al. (2002) studied skills of different mesoscale models over Indian region during monsoon season. They made a proposal that the WRF is able to produce best all India rainfall prediction in the day-1 forecast and, the MM5 is able to produce best all India rainfall forecasts in day-3. Kumar et al. (2001) studied the investigation of the 26 July, 2005 heavy rain event over Mumbai, India using the WRF model. Bhowmik and Durai (2010) conducted research on multi-model ensemble forecasting of rainfall over Indian monsoon region. Song et al. (2009) considered the assessment of the WRF model in reproducing a flash-flood heavy rainfall event over Korea. This study examined the ability of the cloud-resolving WRF model to reproduce the convective cells associated with the flash-flooding heavy rainfall near Seoul, South Korea, on 12 July, 2006.

The simulation of the Summer Monsoon regional climate was investigated by Srinivas et al. (2015) using advanced research WRF model. The model is configured with a single domain of horizontal resolution of 30 km. Sensitivity experiments were conducted with three convection schemes [Kain-Fritsch (KF), Betts-Miller-Janjic (BMJ), Grell-Devenyi (GD)]. Simulated regional climate was evaluated by comparison of precipitation with 0.5° India Meteorological Department (IMD) gridded rainfall data over land, Tropical Rainfall Measuring Mission (TRMM) rainfall data over the ocean and atmospheric circulation fields with 1° NCEP global final analysis (FNL) data. Though all the simulations showed spatial-temporal rainfall patterns, BMJ had least bias towards dryness whereas KF had moist bias and GD had higher dry bias. BMJ could simulate low, moderate and high rainfall reasonably well. The better performance of BMJ scheme is evident owing to better simulation of surface pressure, temperature, lower & upper atmospheric flow fields and geopotential. The simulation of a very heavy rainfall event of 17 June, 2011 over Bangladesh due to monsoon deep depression by using WRF model is analyzed by Mallik et al. (2015). The advanced research WRF model is a regional popular community model that is widely used for both studying as well as forecasting a variety of high-impact meteorological events, such as rainfall (Routray et al., 2010; Mohanty et al., 2012), tropical cyclones (Routray et al., 2016). Chawla et al. (2018) recognized that the regional model performs considerably well over the region. Srinivas et al. (2015) investigated the simulation of the Indian Summer Monsoon regional climate using advanced research WRF model. Sukrit et al. (2010) studied the mesoscale simulation of a very heavy rainfall event over Mumbai, using the WRF model. However, finding the best set of physics parameterization schemes to simulate heavy to extremely heavy rainfall events, and understanding the effect of the combination of different parameterization schemes on rainfall estimates over the BoB and adjoining Bangladesh is active area of research.

2. Details of Monsoon Depression on 13-16 June, 2008

A series convective cloud developed over the central Bay of Bengal (BoB) and adjoining area on 13 June 2008. The convection increased slowly and intensified over the region. The southwesterly winds over the BoB increased in intensity leading to growth of a lower level cyclonic circulation embedded with the monsoon trough over the North Bay of Bengal on 14 June. Under its influence, a low pressure area formed over the North BoB at 0300 UTC of 15 June. The mean Sea level pressure fell by about 2 hPa along Coastal area of Bangladesh, West Bengal and Orissa coasts at 1200 UTC of 15 June. The sufficient upper level divergence continued to support the deep convection over the area. Under the influence of the above favourable conditions, the low pressure area over the north BoB concentrated into a depression and lay centered at 0300 UTC of 16 June 2008 over the North BoB near lat. 21.5°N and long. 90.0°E. Moving in a north-northwesterly direction, it crossed Bangladesh coast near long 89.5°E between 1100 and 1200 UTC of 16 June. Under its influence widespread rainfall with scattered heavy to very rainfall and isolated extremely heavy rainfall occurred over Bangladesh. The observed track up to landfall of the foresaid depression, the INSAT imageries along with OLR distribution and DWR, Kolkata imageries at 1200 UTC of 16 June, 2008 is depicted in the Fig. 1. and Fig. 2 (a-c) respectively.
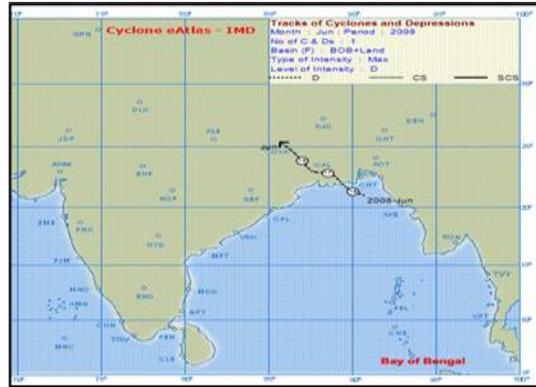

Fig.1: Track of the MD of 16 June, 2008 (eAtlas, IMD)
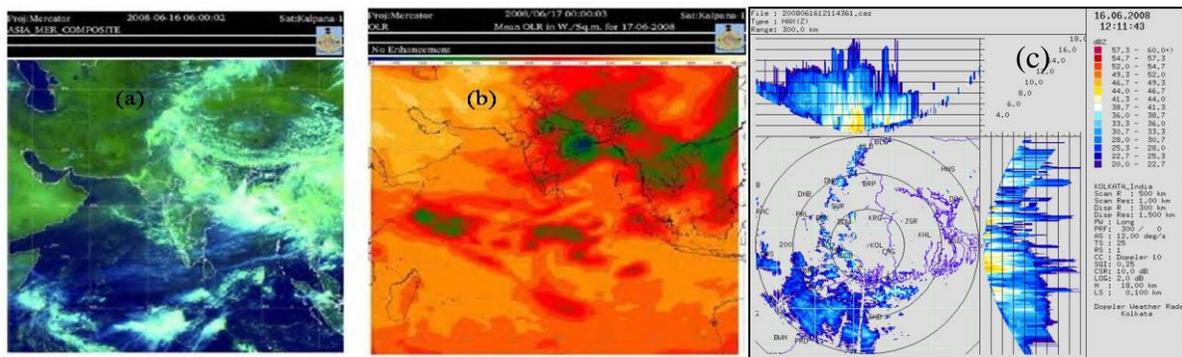

Fig.2 (a-c): INSAT imageries of MD at 0600 UTC and OLR at 0000 UTC and DWR imageries Kolkata at 1200 UTC of 16 June over Bangladesh and adjoining region.

3. Experimental Setup

In this study, the WRF model is run on a single domain at 10 km horizontal resolution. The domain is centered (23°N, 90°E) over Bangladesh to represent the regional-scale circulations and to solve the complex flows of this region. The domain configuration of the model in the present study is depicted in Figure 3. The initial condition of the model simulation is taken as 0000 UTC of 12 June 2008.
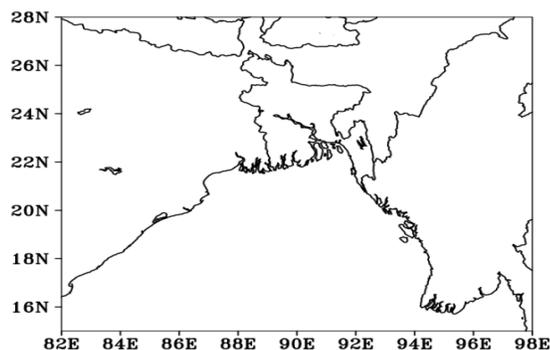

Figure 3: WRF model domain configuration

3.1 Data used

The global final (FNL) dataset run by the National Centre for Environmental Prediction (NCEP) with the $1° \times 1°$ horizontal and 6 hour temporal resolution were used as the initial and lateral boundary condition in this study. The WRF-ARW model has the availability of a good number of schemes for the examination of different physics such as microphysics, planetary boundary layer (PBL) physics, surface layer physics, radiation physics and cumulus parameterization. The physics and dynamics employed in the model in this study are summarized in Table 1. Three-hourly observed data of MSLP, Temperature, RH and rainfall have been collected from Bangladesh Meteorological Department (BMD) for the validation of model performance.

Table 1: Overview of the WRF model configuration

Domain & Dynamics	
WRF core -	ARW
Data -	NCEP–GFS
Interval -	6 h
Number of domain -	1
Central point of the domain -	23° N, 90° E
Resolution -	10 km × 10 km
Grid size -	222 × 222 × 38
Covered area -	15.5°– 28.5° N and 82°– 98° E
Map projection -	Mercator
Integration time step -	30 s
Vertical coordinates -	Pressure coordinate
Time integration scheme -	3rd order Runge-Kutta
Spatial differencing scheme -	6th order centered difference
Physics	
Microphysics -	Morrison 2-moment microphysics
PBL Parameterization -	Yonsei University (YSU) scheme
Surface layer physics -	Revised MM5 scheme
Land-surface model -	Unified Noah LSM
Short wave radiation -	Dudhia scheme
Long wave radiation -	RRTM scheme
Cumulus parameterization -	Kain–Fritsch (new Eta) scheme

3.2 Methodology

The WRF-ARW Model has been used for the study of the selected MD event occurred over the BoB on 13-16 June 2008. Model was run using six hourly NCEP-GFS datasets from 0000 UTC of 12 June 2008 to 0000 UTC of 17 June 2008 as initial and lateral boundary condition. Hourly outputs of the model were analyzed for investigating the causes and mechanisms for the formation of the MD event. Various parameters such as: mean sea level pressure, wind speed at 850 hPa and 200 hPa pressure level, two meter height temperature, relative humidity, vorticity, vertical wind shear, heat flux, MCAPE, rainfall have been investigated. For the validation of the model performance, values of several parameters were compared with the observed value collected from BMD.

4. Results and Discussions

4.1 Analysis of Mean Sea Level Pressure (MSLP)

The mean sea level pressure at 850 hPa level valid for 1200 UTC of 16 June, 2008 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 16 June, 15 June, 14 June, and 13 June respectively are shown in Fig. 4 (a-d). The model has simulated the convergence zone over the southeastern part of Bangladesh at the time of landfall. It is favorable for the incursion of moisture flux towards the convergence zone from the vast area of the BoB. The model has simulated the landfall center very well using different initial conditions and it is remarkable that the convergence zone slightly varies with the lead time.
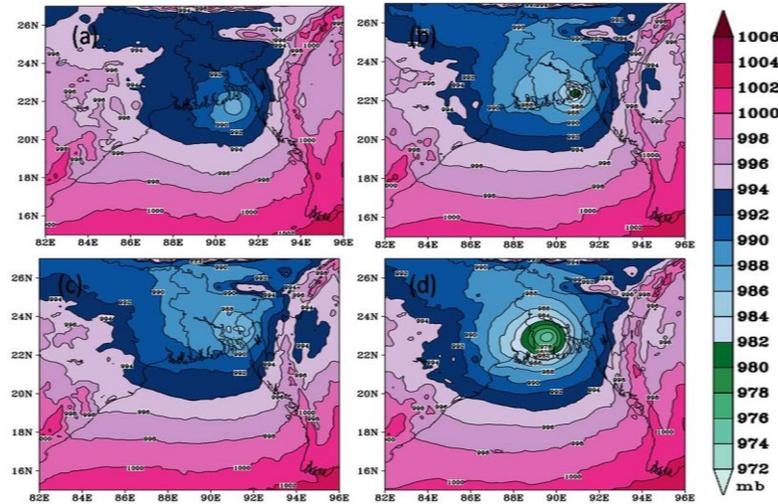
Fig. 4 (a-d): Analysis of model simulated MSLP at 850 hPa (or mb) level valid for 1200 UTC of 16 June, 2008 for 24-h, 48-h, 72-h and 96-h respectively.
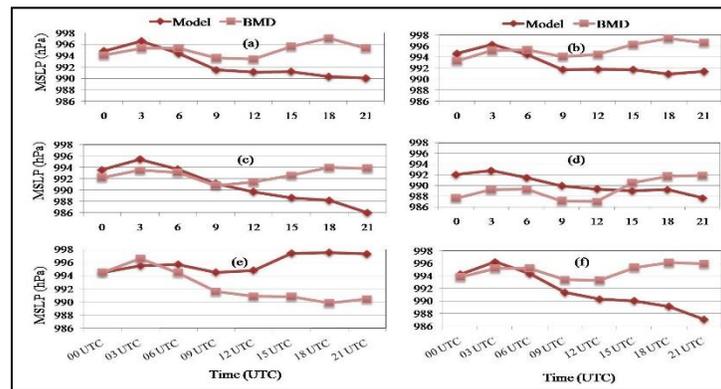

Fig. 5 (a-f): Validation of 3 hourly model simulated MSLP (hPa) of MD of 16 June, 2008 with BMD observed data of the stations a) Chattogram (b) Cox's Bazar (c) Hatiya (d) Khepupara (e) Kutubdia & (f) Sandwip

Fig. 4 shows that the system can be predicted even 96-h advance though the landfall position varies slightly according to the lead time. For this system it is found that the depression intensity increased before the landfall of the system, it keeps its intensity same till landfall and the system predicted by the WRF model reasonably well. The isobaric lines are in circular pattern around the center of the system. Closed isobar and Minimum Central pressure (MCP) of a monsoon depression is very important as it helps to measure the intensity of the system. Fig. 4 shows the model simulated MCP of MD gradually decreases with time and attains peak intensity before the landfall of the system and after that pressure increase with time. The model simulated MCP is found 986 hPa, 982 hPa, 984 hPa & 976 hPa at 24-h, 48-h, 72-h & 96-h model run respectively and the number of closed isobar is about 4-6. Steep pressure gradient is found at the southeast sector of the system center and as well as to the southwest sector which is the favorable condition for occurring of high impact rainfall to the both sectors. The lowest estimated central pressure by Regional Specialized Meteorological Centre (RSMC) of India [RSMC-2008] is 988 hPa at 1200 UTC of 16 June. On the other hand BMD observed MCP at 1200 UTC of 16 June is 987 hPa. Therefore, the model underestimated the minimum central pressure by 3 hPa for 24h simulation.

Validation of 3 Hourly Model simulated MSLP of MD of 16 June, 2008 with BMD observed data of different stations are depicted in fig. 5 (a-f) at the time of or near at the time of landfall for checking the performance or capturing ability of the model. Randomly coastal six stations are chosen for computational analysis to validate the model performance and it is found that the three hourly model simulated MSLP is very close to the observed value of BMD with very minor biases. It is also mentionable that model sometimes overestimated or sometimes underestimated the MSLP. This is very significant for predicting the MSLP for the less bias corrections.

4.2 Analysis of wind flow at 850, 500 and 200 hPa levels

Wind flow (ms^{-1}) of 850 hPa, 500 hPa and 200 hPa level valid for 1200 UTC of 16 June, 2008 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 16 June, 15 June, 14 June and 13 June respectively are shown in Fig. 6 (a-d), Fig. 7 (a-d) and Fig. 8 (a-d). The pattern of wind field distributions is symmetric in every stage of the MD. At 1200 UTC of 16 June, at the time of landfall, there is a strong wind bands in the peripheral sector of system with cyclonic flow where convergence occurs strongly and enhanced thunder activity and lightning flashes. Maximum wind is approximately 15-20 ms-1 in the outer band of the system. All simulation captured the well-organized circulation pattern varying the position and time. At 1200 UTC of 16 June i.e. at the time of landfall maximum intensity, strongest wind bands found around the center of the depression and the wind is above 15 ms-1 in the south- east, northwest and southwest sectors.

The average maximum wind speed simulated by 24-h, 48-h, 72-h and 96-h model run is about 15 ms-1 at 850 hPa level which very close to the estimated maximum sustained surface wind of 13 ms-1 by RSMC and found that the model overestimated the maximum sustained wind. It is also seen that the maximum gusty wind is found in a distance from the convergence zone which enhanced severe convection. The maximum wind is also found in some bands which is the indication of deep thunder activity in band wise of the system.
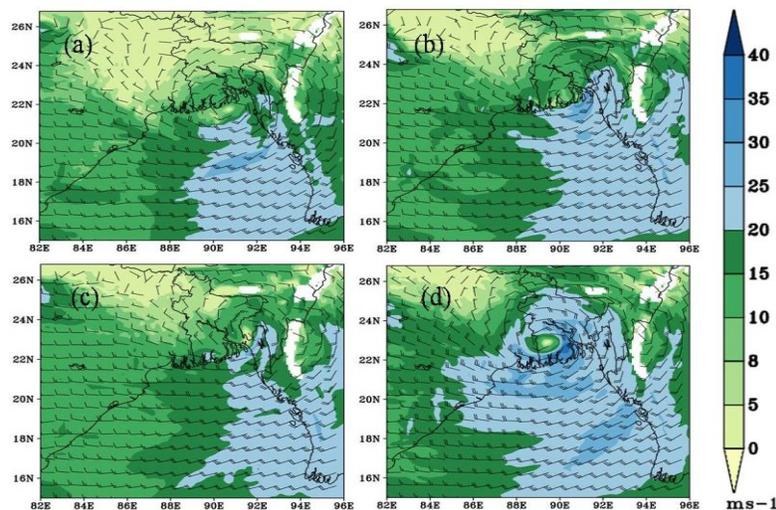

Fig.6 (a-d): Analysis of wind flow distribution at 850 hPa level valid for 1200 UTC of 16 June, 2008 for 24-h, 48-h, 72-h and 96-h respectively.
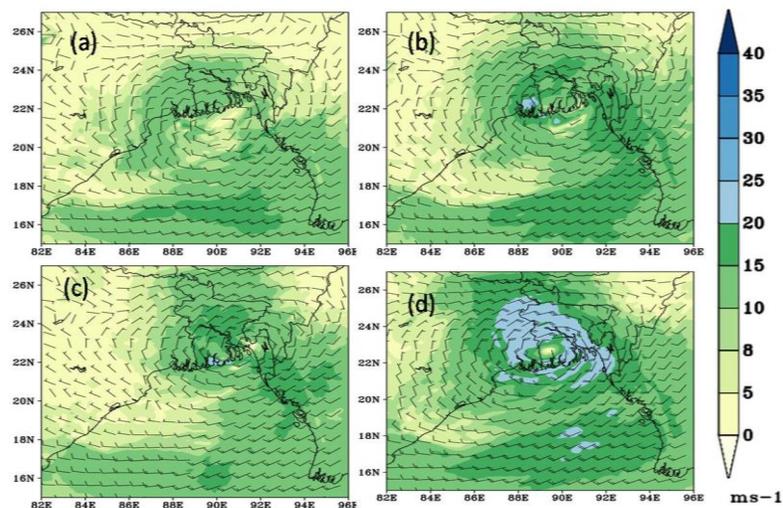

Fig. 7 (a-d): Analysis of wind flow distribution at 500 hPa level valid for 1200 UTC of 16 June, 2008 for 24-h, 48-h, 72-h and 96-h respectively.

The distribution of 500 hPa wind flow (ms-1) valid for 1200 UTC of 16 June, 2008 of model simulation for 24-h, 48-h, 72-h and 96-h are shown in Fig. 7(a-b) respectively. It is found that a cyclonic circulation lies over the southwestern part of Bangladesh and adjoining area and tilted southwestwards with height.

The model simulated area average wind speed is calculated and found 15-20 ms-1. It is also mentionable that the circulation pattern extends up to 500 hPa level and the maximum gusty wind is found from surface to mid-tropospheric level which is favorable for the system intensification. At both 850 hPa and 500 hPa level, convergence zone is well organized   whereas at higher level (200 hPa levels) the circulation pattern is not well-organized. Convergence starts to break and an initiation of divergence zone is found at that level (Fig. 8 (a-d)). This is the strong supportive condition for the deactivation of the system. This divergence condition is the main reasons for not allowing the MD to convert into cyclonic stage. These model simulated wind speeds are favorable for the intensification of MD over southwestern part of Bangladesh and adjoining area. The narrow belt of high winds carries huge amount of moisture towards southeast and southwest sector of the system from surface level to 500 hPa level which is favorable for convective cloud formation and system intensification.
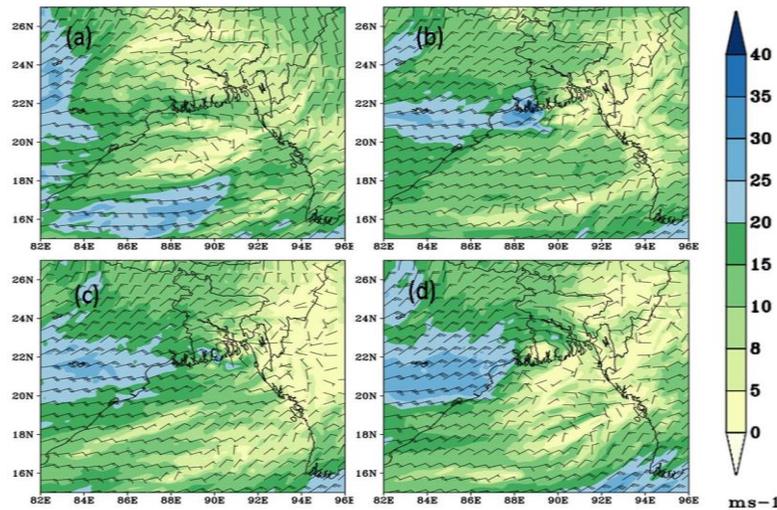

Fig. 8 (a-d): Analysis of wind flow distribution at 200 hPa level valid for 1200 UTC of 16 June, 2008 for 24-h, 48-h, 72-h and 96-h respectively.
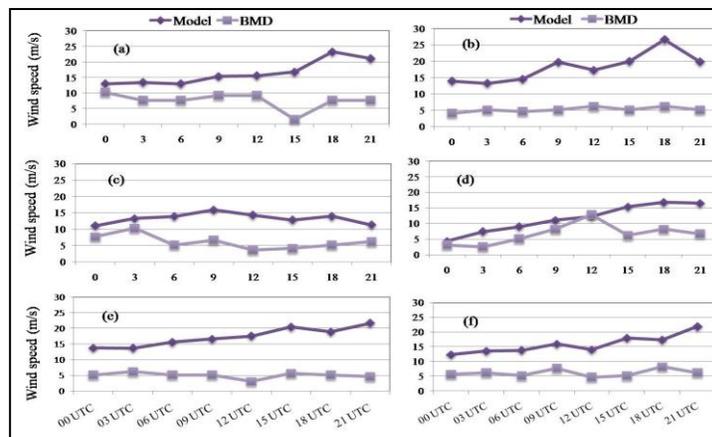

Fig. 9 (a-f): Validation of 3 hourly model simulated Wind speed (ms-1) of MD of 16 June, 2008 with BMD observed data of the stations a) Chattogram (b) Cox's Bazar (c) Hatiya (d) Khepupara (e) Kutubdia & (f) Sandwip

So, it can be concluded that due to this favorable condition, high amount of rainfall is occurred over south-eastern part of Bangladesh and adjoining areas which is validated with the observed rainfall of BMD. Validation of 3-hourly model simulated wind speed (ms-1) of MD of 16 June, 2008 with BMD observed data of different stations are depicted in fig. 9(a-f) at the time of or near at the time of landfall for checking the performance or capturing ability of the model. Randomly coastal six stations are chosen for computational analysis to validate the model performance and it is found

that the three hourly model simulated wind speed is almost close to the observed value of BMD with less errors. It is also noticeable that model overestimated the wind flow. The model predicted wind pattern is very good enough at the time or near the time of landfall.

4.3 Analysis of Meridional and Zonal Wind Pattern

The model simulated meridional wind of 16 June, 2008 at 1200 UTC for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 16 June, 15 June, 14 June and 13 June respectively are shown in Fig. 10 (a-d). From the analysis of meridional wind (along long. 90.5° E) it can be seen that at the system center, the wind flow is in a calm condition (≤ 2 ms^{-1}). At the right side of the system center (along higher longitude) the wind speed is positive, that is the wind flow is from the south to north direction. Primary high amount of maximum wind is found at the right side of the MD and it is about (15-30) ms^{-1}. Again, secondary maximum wind is found at the left side (along lower longitude) of the system center and its value is negative due to its direction from north to south. From this analysis it is also found that the well-circulation of wind is simulated by the model and the high amount of maximum wind (15-30) ms^{-1} is found from surface up to 300 hPa level. The zonal wind at 1200 UTC of 16 June, 2008 of model simulation
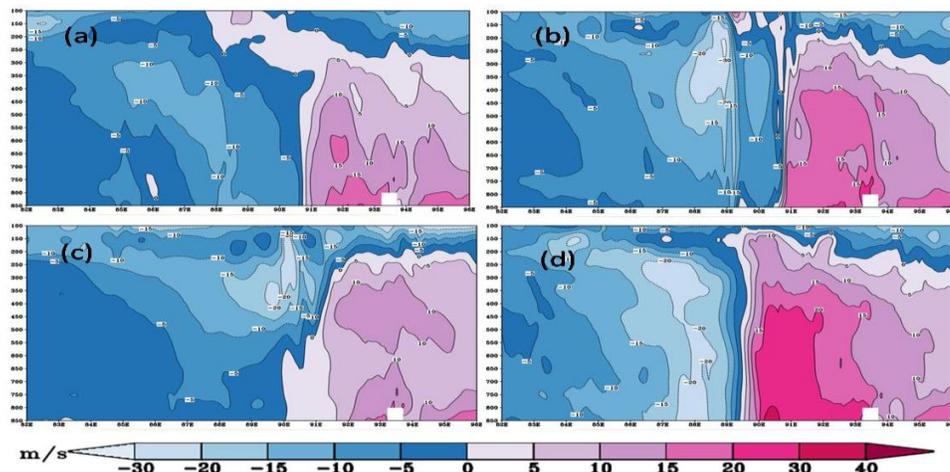

Fig. 10 (a-d): Analysis of meridional wind valid for 1200 UTC of 16 June, 2008 for 24-h, 48-h, 72-h & 96-h respectively.

for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 16 June, 15 June, 14 June and 13 June respectively are shown in Fig. 11 (a-d).
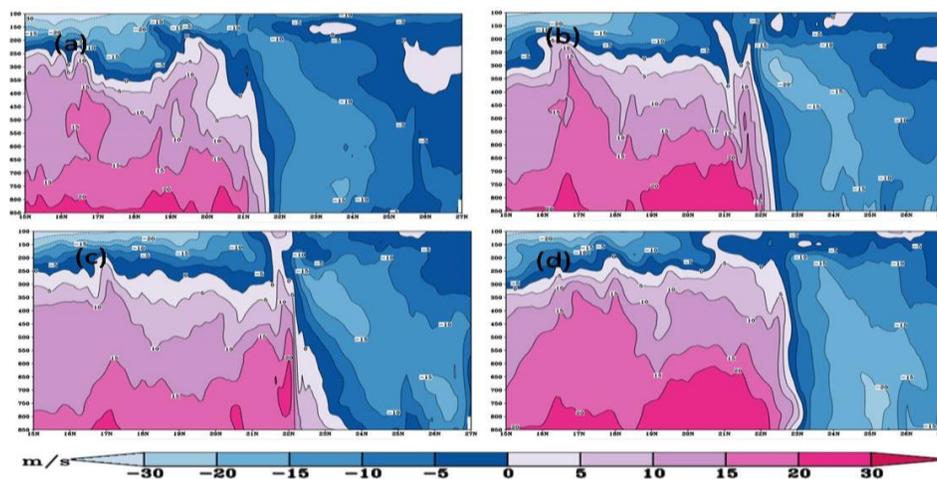

Fig. 11 (a-d): Analysis of zonal wind valid for 1200 UTC of 16 June, 2008 for 24-h, 48-h, 72-h & 96-h respectively.

Similar to the analysis of meridional wind it has been seen from the zonal wind (along lat. 21.8° N) analysis that at the left side (along lower latitude) of the system center the wind speed is positive where at the right side (along higher

latitude) it is negative. Positive value indicates the wind is travelling from the west to east and the negative value from east to west. From this analysis we have found that the primary maximum wind (20-30) ms^{-1} is found to the southeast sector of the system center and it extends up to 300 hPa level. The secondary maximum wind (15-20) ms^{-1} is found at the right side of the system center. From the analysis of meridional and zonal wind it can be concluded that the well-organized circulation of the depression extended up to 300 hPa level.

4.4 Analysis of Relative Humidity (850 hPa) and its Vertical Cross-Section

The relative humidity at 850 hPa level at 1200 UTC of 16 June, 2008 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions of 0000 UTC of 16 June, 15 June, 14 June and 13 June respectively are shown in Fig. 12 (a-d).
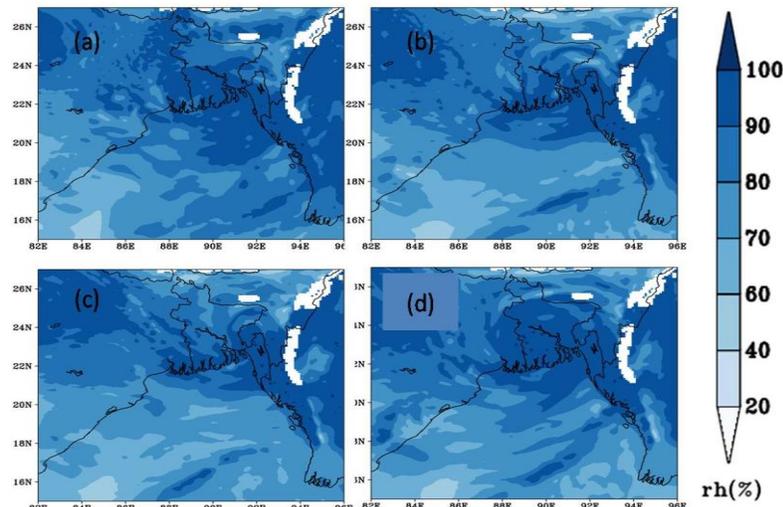

Fig. 12 (a-d): Analysis of relative humidity valid for 1200 UTC of 16 June, 2008 for 24-h, 48-h, 72-h & 96-h respectively.
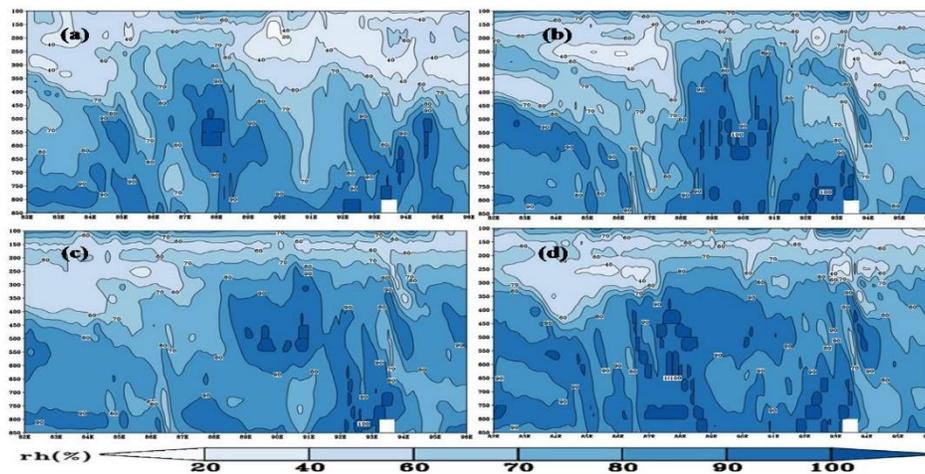

Fig. 13 (a-d): Analysis of vertical cross-section of relative humidity valid for 1200 UTC of 16 June, 2008 for 24-h, 48-h, 72-h & 96-h respectively.

The high amount of relative humidity is an important environmental variable associated with cloud formation and rainfall processes. From the analysis of relative humidity, it is seen that the strong southwesterly flow transports a high amount of moisture of the order of 90-100% to the plain of central and southeastern part of Bangladesh and adjoining area from the Bay of Bengal. The contents of high magnitude of moisture play an important role for the formation of the severe convective activities over these regions. The vertical cross-section of relative humidity analysis along the 21.8º N on 16 June, 2008 at 1200 UTC of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions of 0000 UTC of 16 June, 15 June, 14 June and 13 June respectively are shown in Fig. 13 (a-d).

It is found that the relative humidity of the order of 90-100% vertically extended up to 400 hPa level and 60-70% vertically extended up to 200 hPa levels. It is a favorable condition for cloud formation and later precipitation over these regions.
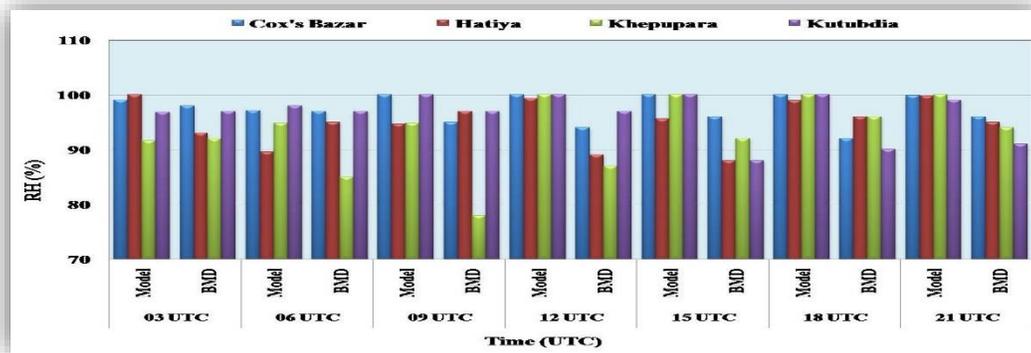

Fig. 14: Validation of 3 hourly model simulated RH (%) of MD of 16 June, 2008 with BMD observed data of the stations a) Cox's Bazar (b) Hatiya (c) Khepupara & (d) Kutubdia.

The model has also simulated the high amount of relative humidity in the peripheral band of the system where thunder activity predominantly occurs. The model simulated surface relative humidity is compared with that of observed data of BMD of 96% that has a good signature. Validation of 3 Hourly Model simulated RH (%) of MD of 16 June, 2008 with BMD observed data of Different stations are depicted in fig. 14. Model simulated RH overestimated the observed values of BMD with small difference. Otherwise, the WRF model performed well compared to BMD data in capturing the RH values over the selected four stations.

4.5 Analysis of Relative Vorticity at 850 and 500 hPa Levels

The model simulated 850 hPa level relative vorticity ($\times 10^{-5}$ s^{-1}) valid for 1200 UTC of 16 June, 2008 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions of 0000 UTC of 16 June, 15 June, 14 June and 13 June respectively are shown in Fig. 15 (a-d) and in Fig. 16 (a-d), the 500 hPa level vorticity valid for 1200 UTC of 16 June, 2008 are presented respectively.
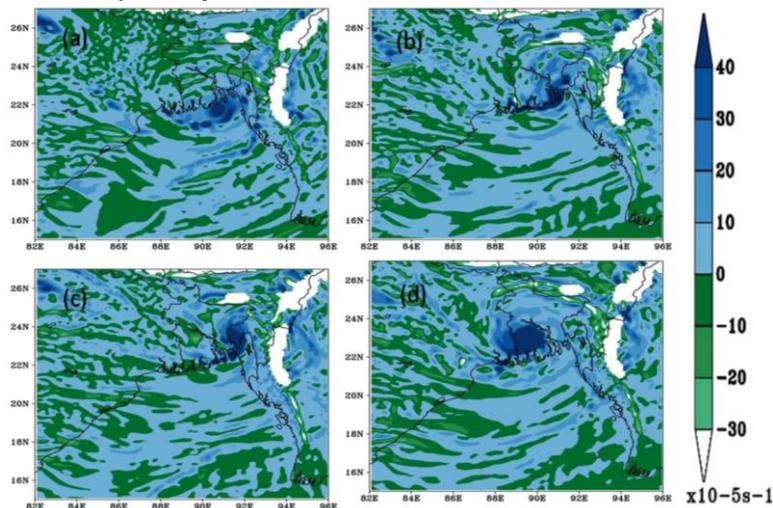

Fig. 15 (a-d): The model simulated relative vorticity (unit: $\times 10^{-5}$s^{-1}) at 850 hPa valid for 1200 UTC of 16 June, 2008 for 24-h, 48-h, 72-h & 96-h respectively.'

The positive vorticity of wind flow denotes cyclonic flow while negative vorticity supports anti-cyclonic flow. It is found that at the surroundings of the system center the vorticity is positive [(20-40) $\times 10^{-5}$ s^{-1}] at lower level and [(10-30) $\times 10^{-5}$ s^{-1}] at upper level which is very much supportive for system intensification and the formation of deep convective clouds. From the analysis of lower and upper level relative vorticity, it has been found that positive vorticity of order of (20-30) $\times 10^{-5}$ s^{-1} is found at the surroundings of the system center and also negative value of vorticity of order of –(10-30) $\times 10^{-5}$ s^{-1} is found away from the center.
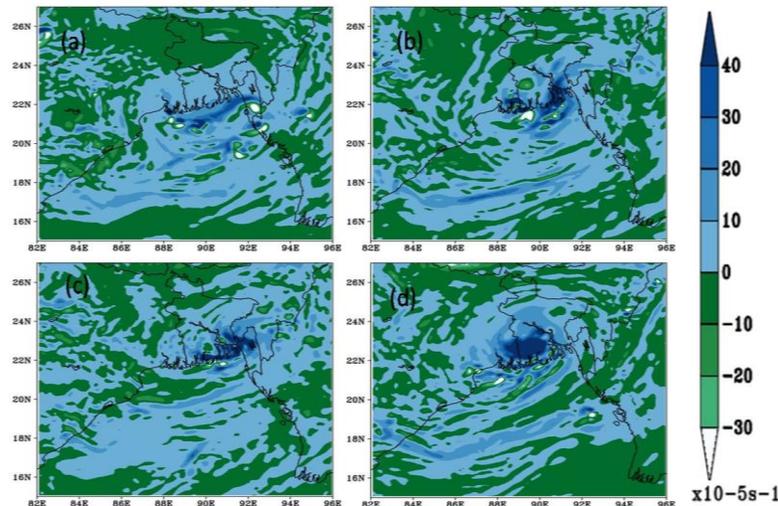
Fig. 16 (a-d): The model simulated relative vorticity (unit: $\times 10^{-5}\text{s}^{-1}$) at 500 hPa valid for 1200 UTC of 16 June, 2008 for 24-h, 48-h, 72-h & 96-h respectively.

4.6 Analysis of Vertical Wind Shear

The model simulated vertical wind shear (ms^{-1}) of the u-component of wind between 500 hPa and 850 hPa level (u_{500}-u_{850}) valid for 1200 UTC of 16 June, 2008 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions of 0000 UTC of 16 June, 15 June, 14 June and 13 June respectively are shown in Fig.17 (a-d).
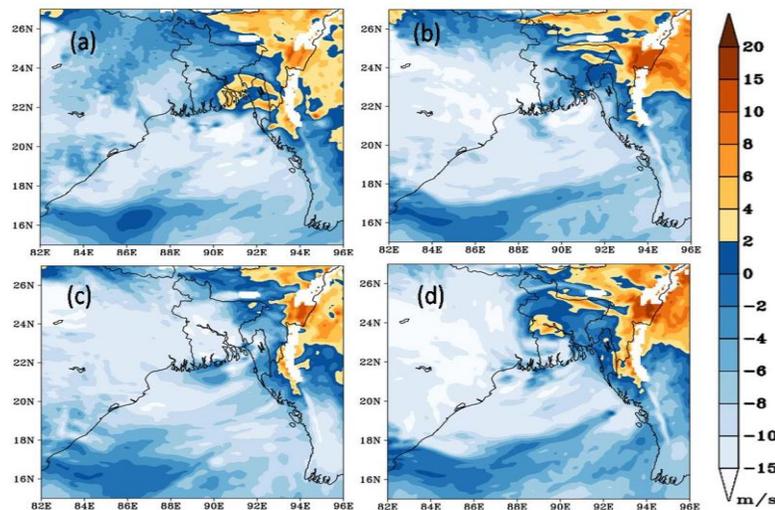

Fig.17 (a-d): Fig. 18 (a-d): The model simulated vertical wind shear (ms-1) between the 500 and 850 hPa level valid for 1200 UTC of 16 June, 2008 for 24-h, 48-h, 72-h & 96-h respectively.

It is found from the vertical wind shear analysis that at the system center the value of the vertical wind shear is lower. But at the surrounding areas of the system center, the value of the vertical wind shear starts to increase and the area average value is in the order of 8-15 ms^{-1}. Due to this higher positive value, the system can't be intensified to a tropical cyclone because at the upper level the wind speed is more than at the lower level wind speed and it thus supports the formation of a low pressure system like MD. These values of wind shear help to develop MD and heavy to very heavy rainfall over these regions of Bangladesh which lies at the southeast sector of the system.

4.7 Analysis of Reflectivity

The model simulated reflectivity (dBZ) 850 hPa level valid for 1200 UTC of 16 June, 2008 of model simulation for 24-h, 48-h, 72-h and 96-h run based on the initial conditions 0000 UTC of 16 June, 15 June, 14 June and 13 June respectively are presented in Fig. 18 (a-d). The reflectivity is an important parameter for the formation of convective clouds and severe thunder storms. The model simulated radar reflectivity is found 30-55 dBZ. When the magnitude is

> 50 dBZ, it is associated with severe thunder activity (Mallik et al, 2016). The maximum value is found at a certain distance of the system which represents that the thunder activity occurs at some outer bands of the system. It is also clear from the simulation that the SW sector is the region where the chance of severe thunder activity lies.
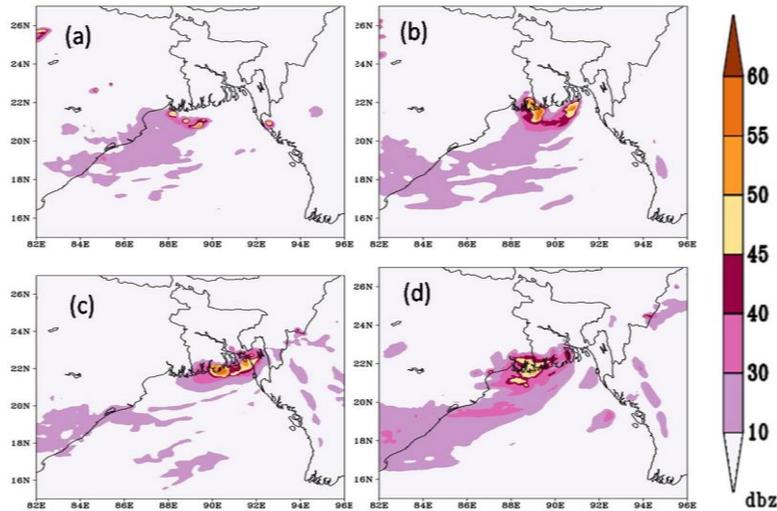

Fig. 18 (a-d): The model simulated radar reflectivity (unit: dBZ) valid for 1200 UTC of 16 June, 2008 for 24-h, 48-h, 72-h & 96-h respectively.

4.8 Analysis of Temperature at 2m Height

The model simulated temperature (°C) at 2m height valid for 1200 UTC of 16 June, 2008 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions of 0000 UTC of 16 June, 15 June, 14 June and 13 June respectively are shown in Fig. 19 (a-d).
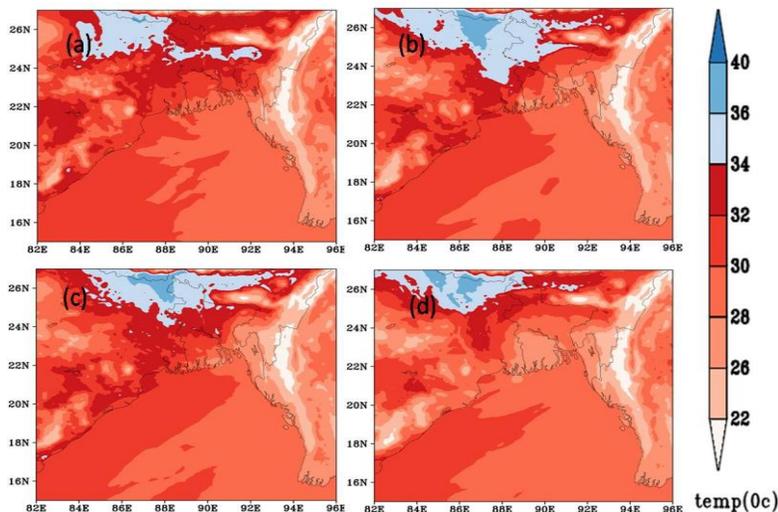

Figure 19 (a-d): Analysis of temperature at 2 m height valid for 1200 UTC of 16 June, 2008 for 24-h, 48-h, 72-h & 96-h respectively.

From the temperature analysis it is observed that the temperature is about (28-30)°C at the system center. But away from the system center to the south-east sector, the temperature fall by 2 to 4°C. It is very much supportive for high amount of rainfall because due to rainfall the temperature suddenly falls down in those sectors. The model simulated area average temperature of 28°C is compared with the observed area average temperature of 29°C which matched with high precision. The 24-h run is more accurate than that of others run.

Validation of 3 Hourly Model simulated temperature (°C) of MD of 16 June, 2008 with BMD observed data of different stations are depicted in fig. 20 (a-f) at the time of or near at the time of landfall for checking the performance or capturing ability of the model. Randomly coastal six stations are chosen for computational analysis to validate the

model performance and it is found that the three hourly model simulated temperature is very close to the observed value of BMD with minor biases. It is also mentionable that model overestimated the temperature. It is also significant that the model captured the location of the probable rainfall area though it contains less predictability for the simulation of high impact rainfall.
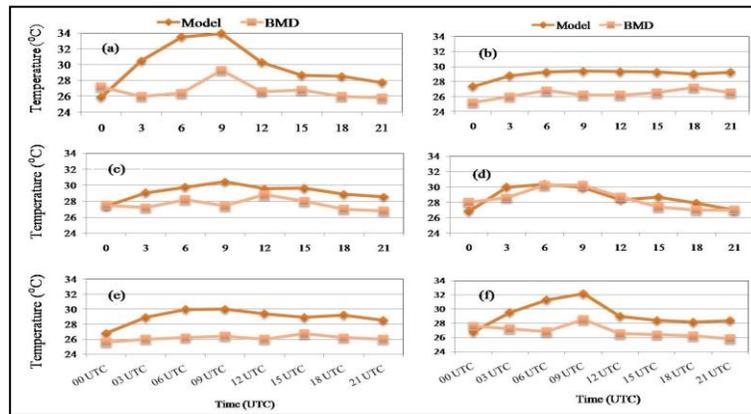

Figure 20 (a-f): Validation of 3 hourly model simulated temperature (^{o}C) of MD of 16 June, 2008 with BMD observed data of the stations a) Chattogram (b) Cox's Bazar (c) Hatiya (d) Khepupara (e) Kutubdia & (f) Sandwip

4.9 Analysis of Maximum Convective Available Potential Energy (MCAPE)

The model simulated Convective Available potential Energy (Jkg^{-1}) 850 hPa level valid for 1200 UTC of 16 June, 2008 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 16 June, 15 June, 14 June and 13 June respectively are presented in Fig. 21 (a-d).
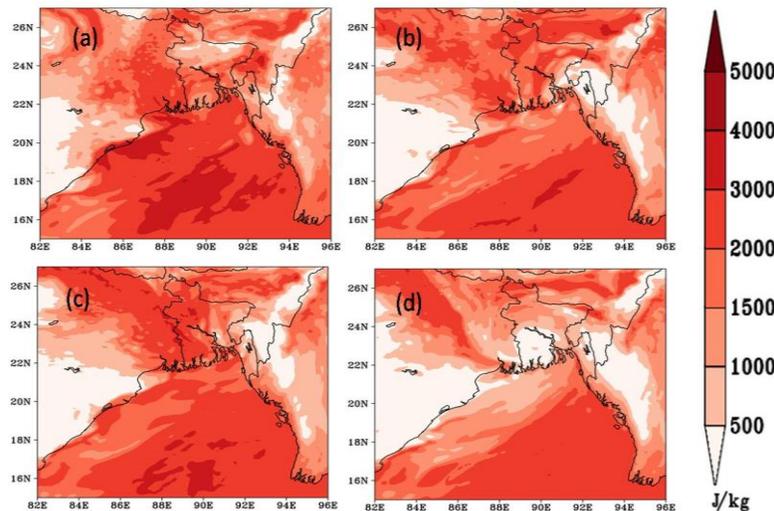

Figure 21 (a-d): The model simulated MCAPE (unit: J/kg) valid for 1200 UTC of 16 June, 2008 for 24-h, 48-h, 72-h & 96-h respectively.

From the analysis the MCAPE is found in the order of < 500 Jkg^{-1} at the center of the system which lies over southwest side of Bangladesh but in the outer shell of the MD, the CAPE is in the order of 1000-3000 jkg-1 for 24-h, 48-h, 72-h and 96-h model run. This magnitude of this thermodynamic parameter is very much supportive for the formation of thunder activity and lightning flashes in the out shell of the system. The possibility of the formation of maximum thunder activity is to the southwest and southeast sector of the MD.

4.10 Analysis of Outgoing Long Wave Radiation (OLR)

The model simulated outgoing long wave radiation valid for 1200 UTC of 16 June, 2008 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 16 June, 15 June, 14 June and 13 June respectively

are presented in Fig. 22 (a-d). The OLR is dependent on the temperature of the radiating body. It is affected by the Earth's skin temperature, skin surface emissivity, atmospheric temperature, water vapor profile, and cloud cover. Near the center of the depression value of the outgoing long wave radiation was less (70-110), because above the system center the sky was overcast. So, the model captures the lower value of OLR which is also supportive condition for formation of the system.
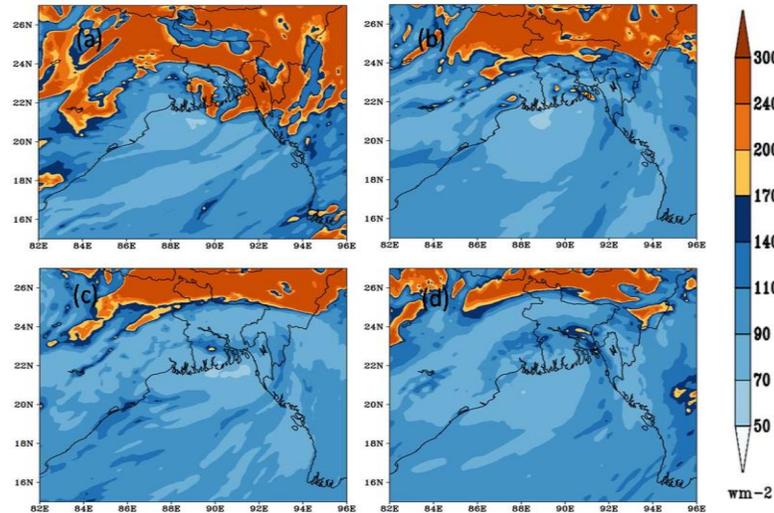

Figure 22 (a-d): The model simulated outgoing long wave radiation (olr) valid for 1200 UTC of 16 June, 2008 for 24-h, 48-h, 72-h & 96-h respectively.

4.11 Rainfall Analysis

The model simulated 24-h, 48-h, 72-h & 96-h accumulated rainfall (model run) based on the initial condition 0000 UTC of 16 June, 15 June, 14 June and 13 June, 2008 respectively are shown in Fig. 23 (a-d). From the analysis it is found that the simulated high amount of rainfall over southern part of Bangladesh where the convergence zone lies. It is also found that in the 2nd and 3rd quadrant the model predicted the highest amount of rainfall and comparatively less amount of rainfall predicted in the rest part of the country.
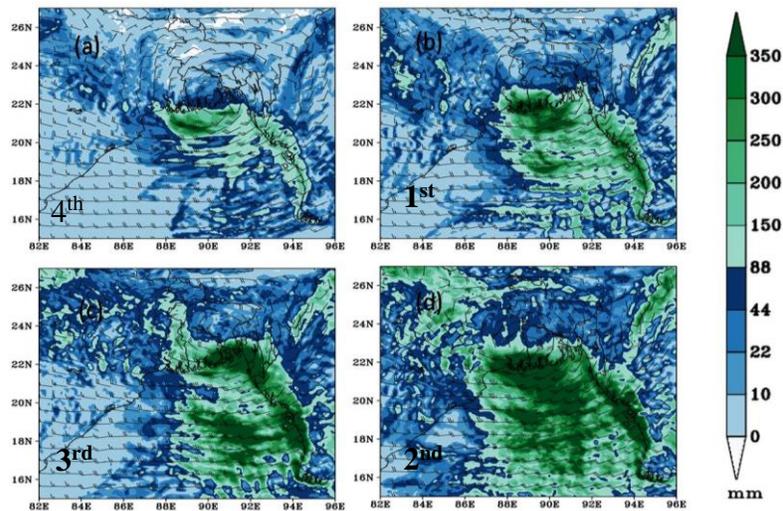

Figure 23 (a-d): The model simulated 24-h, 48-h, 72-h & 96-h accumulated rainfall based on the initial condition 0000 UTC of 16, 15, 14, 13 June, 2008 respectively.

The model simulated 24-h accumulated rainfall distribution valid for 16 June, 2008 simulated for 24-h, 48-h, 72-h and 96-h based on the initial conditions of 0000 UTC of 16 June, 15 June, 14 June and 13 June respectively are shown in Fig. 24 (a-d).
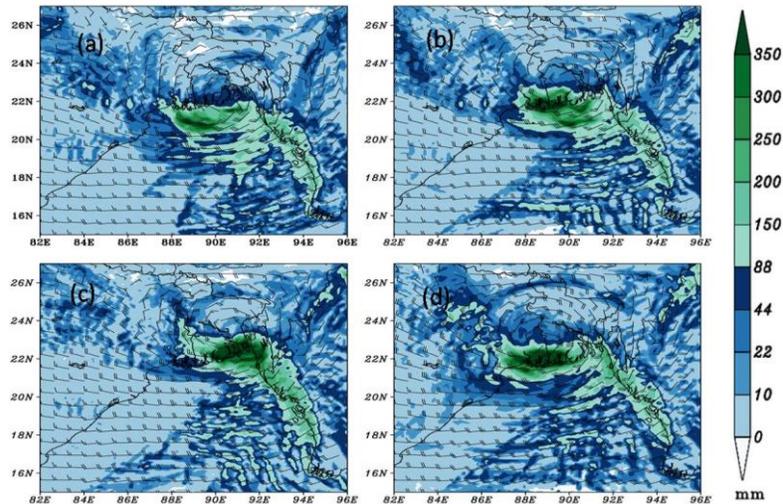
Figure 24 (a-d): Comparison of 24-h accumulated rainfall analysis valid for 16 June, 2008 simulated by 24-h, 48-h, 72-h, 96-h advanced model run respectively
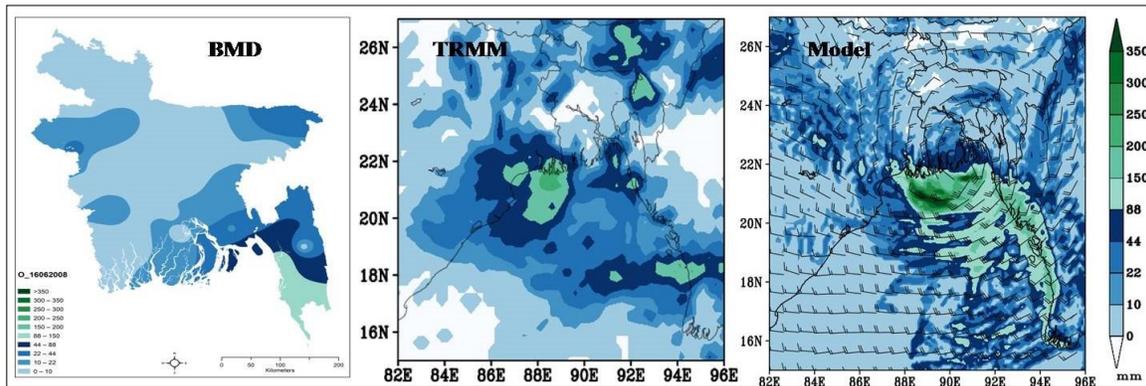

Figure 25: Spatial validation of WRF model simulated rainfall with BMD observed and TRMM rainfall of MD of 16 June, 2008 (24h rainfall)
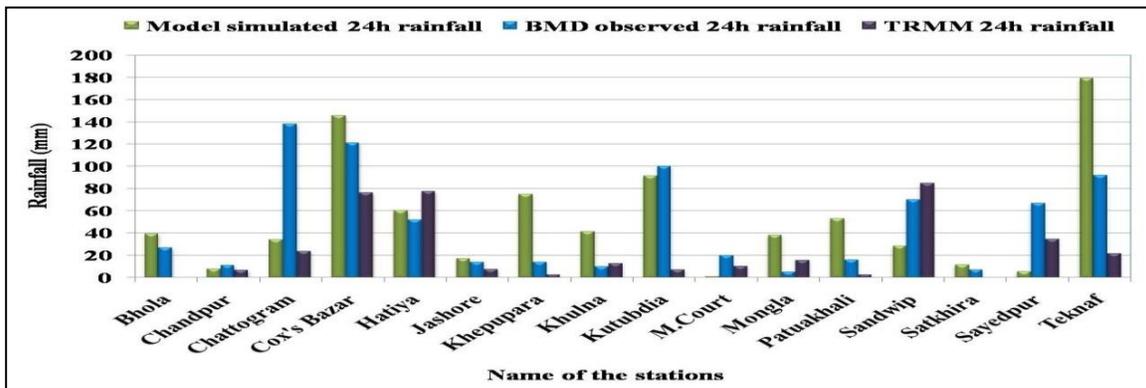
Figure 26: Computational validation of model simulated rainfall with BMD observed & TRMM rainfall of various stations of 16 June, 2008

The distribution of BMD observed data shows good rainfall over the belt of southern and southeastern part of Bangladesh, but low rainfall over the rest part of the country. It is found that model sometimes overestimates the rainfall and sometimes underestimates compared to that of BMD observed and the model simulated rainfall always underestimates the TRMM rainfall.

Figure 27: Comparison of WRF model simulated rainfall and BMD observed 24h accumulated rainfall of MD of 16 June, 2008.

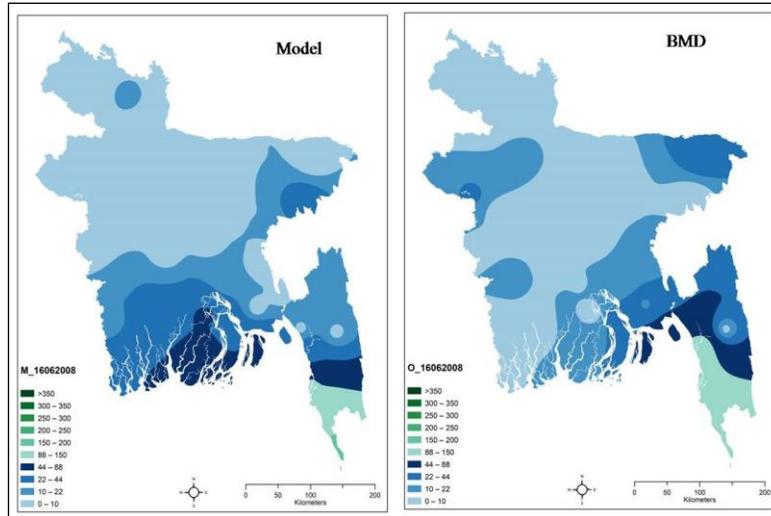From the computational analysis of rainfall analysis it is mentionable that the model simulates the high amount of rainfall over Cox's Bazar, Teknaf, Chattogram, Kutubdia, Khepupara and Hatiya. The location and the time of the occurring of rainfall are captured by the model with a good signature. 24-h model simulated rainfall has been compared with the observed data of Bangladesh Meteorological Department (BMD) and TRMM rainfall for the spatial and computational validation which is shown in Fig. 25 and 26 respectively.

Finally, comparison of WRF model simulated 24h accumulated rainfall and BMD observed rainfall of MD of 16 **June, 2008 is shown in fig.27.**

For model validation 3 hourly model simulated rainfall of 16 June, 2008 is computed with BMD observed rainfall and are shown in fig.28. From the computational analysis it is also clear that the model sometimes overestimates and sometimes underestimates. It is the good indication of capturing the rainfall over Bangladesh due to the monsoon depression over the BoB. So, the WRF model has the capability to predict the rainfall in association to MD reasonably well and the pattern of rainfall is in a good agreement.
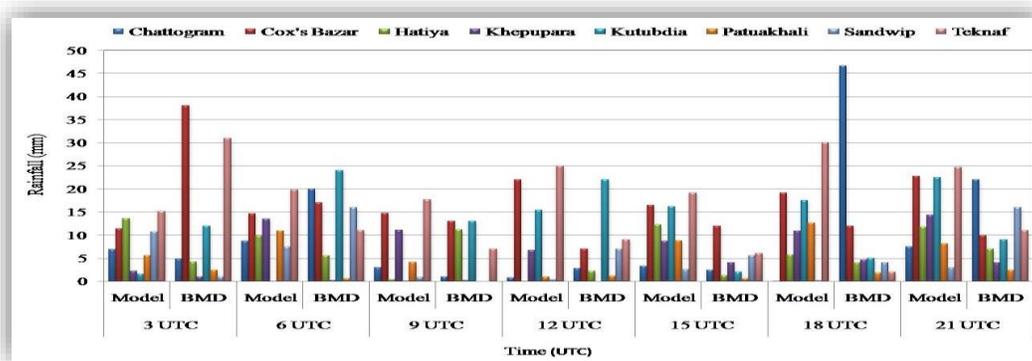
Figure 28: Computational validation of model simulated 3 hourly rainfall of 16 June, 2008 with BMD observed rainfall

5. Conclusion

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

- It has been concluded that the Morrison 2-mom with Kain-Fritsch and Yonsei University schemes options produce precisely realistic results from simulation and this combination is good for the simulation of MD over the BoB and associated rainfall over Bangladesh.

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- The model simulated lowest central pressure of the MD is 986 hPa, 982 hPa, 984 hPa & 976 hPa at 1200 UTC of 16 June, 2008; for 24h, 48-h, 72-h and 96-h model run respectively. The observed central pressure was 987 hPa for 1200 UTC of 16 June, 2008. So, if we reduce lead time forecast accuracy increases.

- The convergence of strong southwesterly flow transports high amount of moisture (90-100) % from the vast area of the Bay of Bengal towards the eastern and southeastern part of Bangladesh and neighborhood which is the supportive condition of system intensification, formation of strati- and cumuli-type of cloud and thence responsible for extreme rainfall. The model captured this meteorological parameter very well up to 300 hPa level which enhances the supply of latent heat and it is very much supportive for convective activity and lightning flashes.

- It is found that the model simulated Vorticity at 850 hPa levels is the order of $(20-40) \times 10^{-5}$ s^{-1} for all cases for 24-h, 48-h, 72-h and 96-h model run which is supportive for the formation of deep convective clouds related to the monsoon Depression and it is very close to the observation.

- The model simulated vertical wind shear is of order (8-15) ms^{-1} of all MD, observed over Sandwip, Hatiya and neighborhoods. These values of wind shear help to sustain monsoon depression for three which is the main cause of heavy to very heavy rainfall over these regions of Bangladesh.

- The areas of Cox's Bazar, Teknaf, Chattogram, Kutubdia, Khepupara and Hatiya. and neighborhoods where heavy to very heavy rainfall observed were characterized by the high amount of relative humidity, positive vorticity, radar reflectivity of >50 dBz, CAPE value >1500 j/kg and strong vertical wind shear which were very favorable for the formation of deep depression and these meteorological parameters are very much supportive for moist air updrafts and formation of clouds which consists of water droplets and enhanced the generation of raindrops within the clouds. These meteorological parameters related to all MD simulated by the WRF model with good accuracy.

- The model simulated rainfall amount and associated areas are sensibly well compared with the data observed by Bangladesh Meteorological Department (BMD) and Tropical Rainfall Measuring Mission (TRMM).

- The analysis of the wind field as obtained from the model shows that the high impact rainfall areas exhibit strong convergence of low level monsoon circulation. In some cases, the strong southwesterly wind was found to exist up to 300 hPa level. A low level jet streak varying in the range 25-28 ms^{-1} in the neighborhoods of the southeast Bangladesh and is a prominent feature marking the strong vertical wind shear in the lower troposphere for all MD.

Finally, it can be concluded that the WRF model with the   right combination of the domain, horizontal resolution and the suitable parameterization schemes is capable to simulate and predict the M LPS over the Bay of Bengal and associated rainfall over Bangladesh up to 96-hours advance reasonably well.

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