Prediction Capability of Monsoon Depression in 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 monsoon depression over the Bay of Bengal during 8-11 June, 2017 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 long-wave 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 MLPSs. Srivastava et al. (2017) [1] 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) [2-3]. Monsoon is a global phenomenon. The southwest summer monsoon is perhaps the best defined and well organized amongst the monsoons of the world (Das, 2002) [4]. 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 (Debsarma, S. K., 2004) [5]. 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) [6]. 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. An explanation of the intensification of MLPSs has been investigated by many researchers (Sikka, 1977 [3] and P. Koteswarm, 1958; Saha and Chang, 1983; Warner, 1984) [7-9]. The intensification of the MLPSs occurs in association with the interaction between upper tropospheric divergence and lower tropospheric convergence (P. Koteswaram et al., 1958) [7]. 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) [10]. 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) [11-13].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) [14]. 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) [15]. 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) [15].

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) [16]; 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) [17-19], 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) [20] and studies of summer monsoon rainfall (Islam, 2008) [21]. The simulation of the Summer Monsoon regional climate was investigated by Srinivas et *al*. (2015) [22] 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) [23-29]. 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 using WRF model is analyzed by Mallik et al. (2015) [30]. 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., 2013) [31-32], tropical cyclones. Chawla et al. (2018) [33] recognized that the regional model performs considerably well over the region. Srinivas et al. (2015) [34] investigated the simulation of the Indian Summer Monsoon regional climate using advanced research WRF model. Sukrit et al. (2010) [35] 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. MD over the BoB during 08-11 June, 2017

In association with advance of southeast summer monsoon, a low pressure area formed over the North BoB in the morning of 10th June, 2017. It concentrated into a well-marked low pressure area over northern part of BoB on 11th June at morning and into a Depression in the evening of 11th June. At 1800 UTC of 11th June it intensified into a Deep-Depression. It moved north-northeastwards and crossed Bangladesh coast near Khepupara between 2300 UTC of 11th June and 0000UTC of 12th June, 2017.

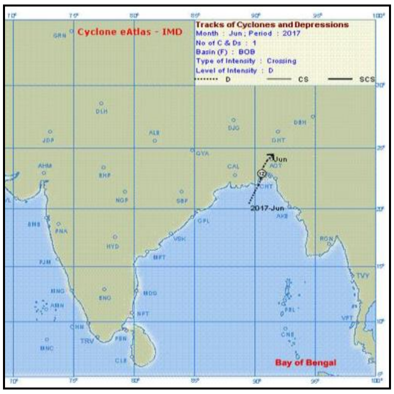

Fig. 1: Track of the MD of 11-12 June, 2017 (eAtlas, IMD)

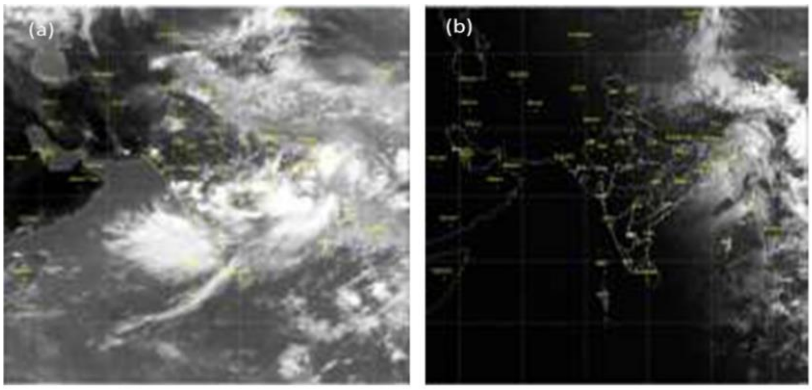

Fig.2 (a-b): INSAT 3D based IR imagery of deep depression of 11-12 June on (a) 1100 and (b) 0000 UTC, 2017 respectively.

It lay over coastal Bangladesh and neighborhood (latitude 22.5°N and latitude 90.5°E) at 0000 UTC of 12th June. Then it moved northeastwards across Bangladesh and weakened gradually into a depression at 1800 UTC of 12th June and further into a Well-marked Low pressure area over east Bangladesh and adjoining area at 0000 UTC of 13 June, 2017. It caused heavy rainfall over Bangladesh and adjoining area. This event is simulated by WRF model with evaluating different meteorological parameters are described briefly in the following section.

The observed track up to landfall of the foresaid depression and INSAT 3D based IR imagery is depicted in the Fig. 1 and Fig. 2(a-b) respectively.

Fig. 2 (a) Satellite KALPANA-1 imagery at 1100 UTC of 11 June, 2017 showing low and medium clouds with deep to very deep convection lay over north and adjoining west central BoB and adjoining coastal areas of West Bengal & Bangladesh and Fig.2 (b) satellite imagery at 0000 UTC of 12 June showing the convection further got organized associated broken low and medium clouds with embedded deep convection lay over northwest and adjoining northeast BoB. As the system was moving north- northeastwards, it was tracked by DWR Cox's Bazar on 11 June. Typical Radar imageries are presented in fig.3. DWR Cox's Bazar captured the location and associated rainfall due to monsoon depression reasonably well. It also captured the curved bands in different distances entering towards the center in a cyclonic rotation which enhanced the high impacts of the location specific rainfall.

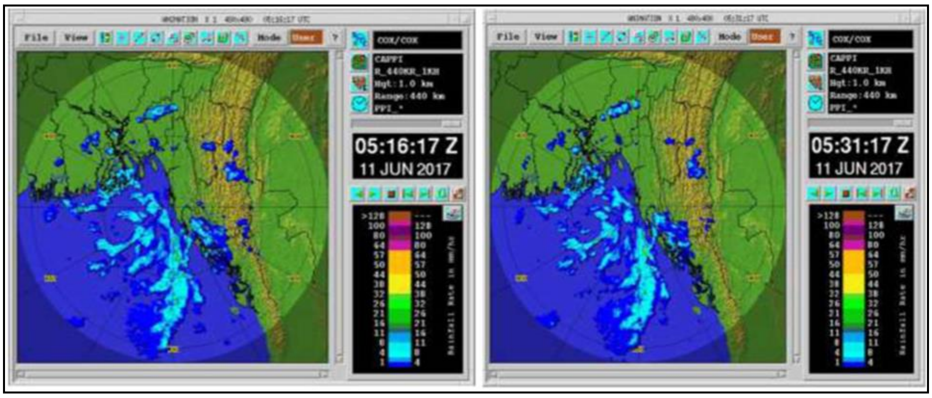

Fig.3 Typical Radar imageries of deep depression on 11 June, 2017 (source: BMD)

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 1. The initial condition of the model simulation is taken as 0000 UTC of 30 March 2016 and lateral boundary condition is taken for 48 hours.

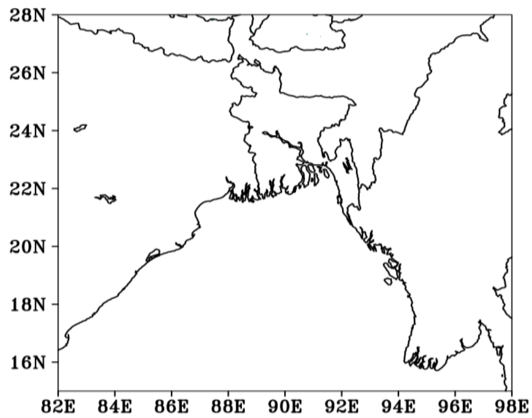

Figure 3.1: WRF model domain configuration

3.1 Data used

The Global Forecast System (GFS) dataset run by the National Centre for Environmental Prediction (NCEP) with the 1°×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.

3.2 Methodology

The WRF-ARW Model has been used for the study of the selected MD event occurred over the BoB on 08-11 June 2017. Model was run using six hourly NCEP-GFS datasets from 0000 UTC of 08 June 2017 to 0000 UTC of 11 June 2017 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.

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 Yonsei
PBL Parameterization -	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

4. Results and Discussion

The analysis of the model output is discussed in this section. Comparison of the model outcome with observed output is also included here.

4.1 Analysis of Mean Sea Level Pressure (MSLP)

The model simulated mean sea level pressure (hPa) at 850 hPa level valid for 1500 UTC of 11 June, 2017 at the time of landfall for 24-h, 48-h, 72-h and 96-h advance model run based on the initial conditions of 0000 UTC of 11 June, 10 June, 09 June and 08 June respectively are shown in Fig.4 (a-d). The formation of low pressure area is an important initial condition for possible weather disturbances which may intensify into a tropical depression when the favorable conditions prevail. This low pressure is the important factor which signifies the genesis to intensity level by the optimum values of pressure drop.The model simulated central pressure of the depression at 1500 UTC of 11 June, 2017 for 24-h, 48-h, 72-h and 96-h advanced are about 987, 978, 974 and 972 hPa respectively. The model simulated center of the system at the time of landfall is about lat. 22° N and

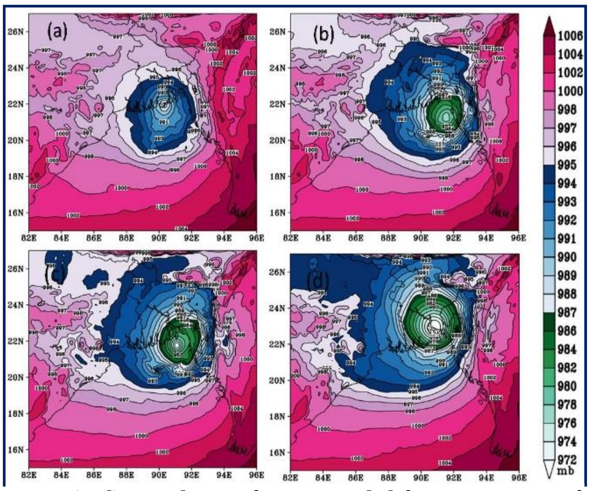

Fig.4 (a-d): Analysis of MSLP valid for 1500 UTC of 11 June, 2017 for 24-h, 48-h, 72-h and 96-h respectively.

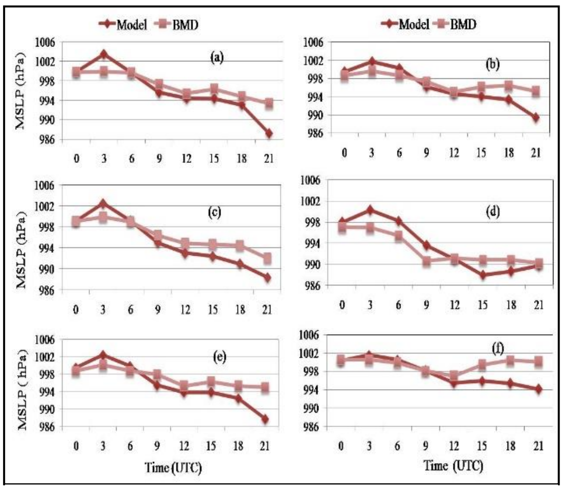

Fig. 5 (a-f): Validation of 3 hourly model simulated MSLP (hPa) of MD of 11 June, 2017 with BMD observed data of the stations a) Chattogram (b) Cox's Bazar (c) Hatiya (d) Khepupara (e) Kutubdia & (f) Teknaf long.90.2°E. Whereas the lowest estimated central pressure by RSMC of India is 988 hPa at 1500 UTC of 11 June, 2017. The mean sea level pressure over Tibet is very high and its central pressure varies from 997 hPa to above 1004 hPa at 1500 UTC of 11 June, 2017.

The depression remains stationary over southwestern part of Bangladesh and adjoining areas for long time may be due to this high pressure over Tibetan plateau. The depression did not move towards further east or southeast due to very high pressure prevailing over northeast India and southern part of Myanmar regions respectively. From the model simulated mean sea level pressure analysis it can be concluded that the model simulated the mean sea level pressure reasonably well.

Validation of 3 Hourly Model simulated MSLP of MD of 11 June, 2017 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. 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.

4.2 Analysis of Wind Flow of 850, 500 & 200 hPa Level

Wind flow (ms^{-1}) distribution of 850 hPa, 500 hPa and 200 hPa level valid for 1500 UTC of 11 June, 2017 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 11 June, 10 June, 09 June and 08 June respectively are shown in Fig. 6 (a-d), Fig. 7 (a-d) and Fig. 8 (a-d). It is found that a cyclonic circulation lies over the southeastern part of Bangladesh and adjoining areas at 850 hPa and 500 hPa level of wind patterns [Fig. 6 (a-d) & 7 (a-d)]. The center of the circulation at 850 hPa is located over south-western part of Bangladesh and adjoining areas (22º N, 90.2º E). The center of the circulation at 500 hPa is located over southeastern part of Bangladesh and adjoining areas which is northeast of 850 hPa position.

Therefore, the vertical axis of the depression at the time of landfall is slightly tilted northeastward with height. A narrow belt of maximum wind is found to the southeast sector of the system which carries high amount of moisture from the BoB and it is very much supportive for the formation of cumuli and strati-form of clouds which is accountable for occurring high impact rainfall. The maximum sustained wind is found in different bands and a little bit far away from the system center where actually deep convection occurs with high thundering and lightning flashes. The maximum gusty or squally wind is found in the southeast and southwest sector of the system center. The WRF model has captured this primary (occurring regions of maximum wind) and secondary (occurring regions of less maximum wind) gusty wind well enough. At both 850 hPa and 500 hPa level, convergence zone is formed in a very organized way whereas at higher level of atmosphere (200 hPa) the circulation pattern is not well-organized. Actually, a divergence zone is found at that level (Fig. 8 (a-d)).

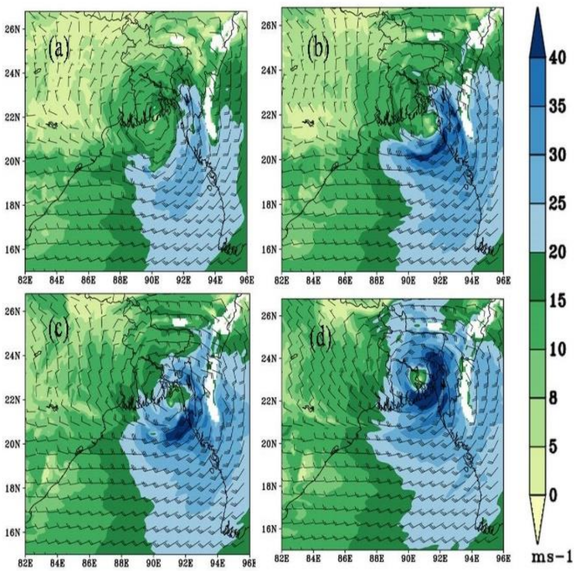

Fig.6 (a-d): Analysis of wind flow distribution at 850 hPa level valid for 1500 UTC of 11 June, 2017 for 24-h, 48-h, 72-h and 96-h respectively.

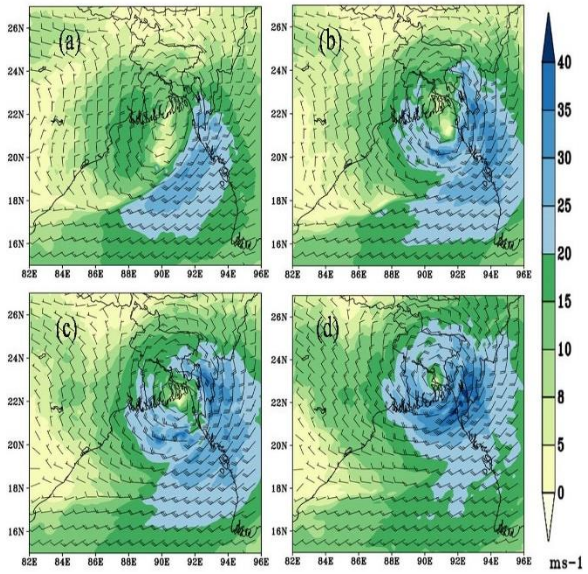

Fig.7 (a-d): Analysis of wind flow distribution at 500 hPa level valid for 1500 UTC of 11 June, 2017 for 24-h, 48-h, 72-h and 96-h respectively.

This model simulated wind speed is favorable for the intensification of monsoon depression over south-eastern part of Bangladesh and adjoining areas. The area of convergence (i.e., zone of high convective activity) observed over Sandwip, Sitakunda, Maijdi Court, Hatiya, Kutubdia, Chattogram, Bhola, Patuakhali and neighborhood i.e., southeastern and southwestern sectors of the depression. So, it can be assumed that due to this constructive condition, high amount of rainfall is occurred over south-eastern part and southwestern part of Bangladesh and adjoining areas which is validated with the observed rainfall of BMD and TRMM. Validation of 3 Hourly Model simulated wind speed (ms^{-1}) of MD of 11 June, 2017 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.

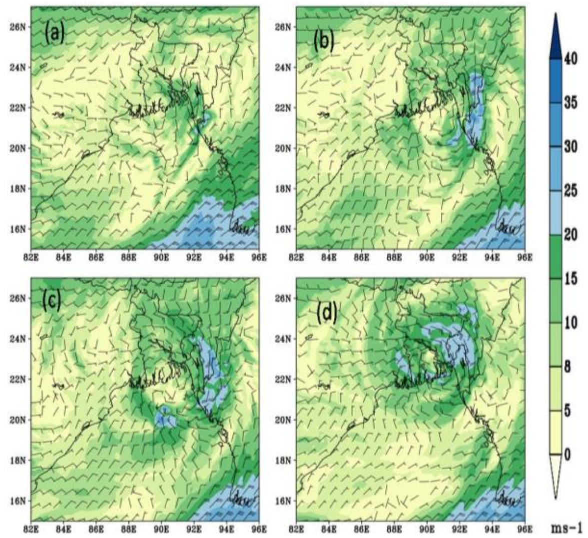

Fig.8 (a-d): Analysis of wind flow distribution at 200 hPa level valid for 1500 UTC of 11 June, 2017 for 24-h, 48-h, 72-h and 96-h respectively.

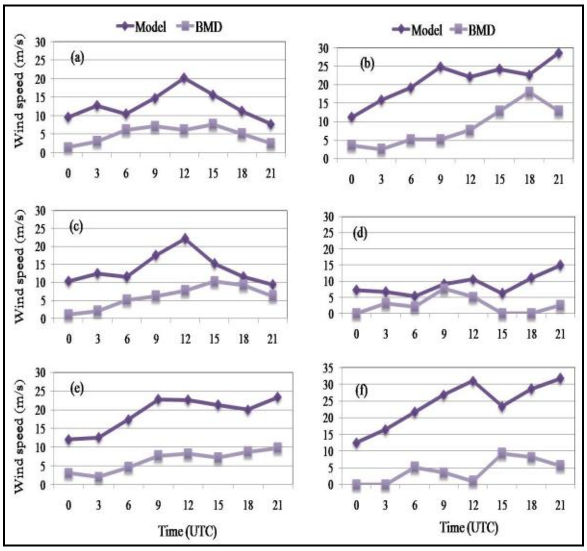

Fig. 9 (a-f): Validation of 3 hourly model simulated Wind speed (ms-1) of MD of 11 June, 2017 with BMD observed data of the stations a) Chattogram (b) Cox's Bazar (c) Hatiya (d) Khepupara (e) Kutubdia & (f) Teknaf

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 minor biases. It is also mentionable that model overestimated the wind flow. 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.

4.3 Analysis of Meridional and Zonal Wind

The meridional wind at 1500 UTC of 11 June, 2017 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 11 June, 10 June, 09 June and 08 June respectively are presented in Fig.10 (a-d). From the analysis of meridional wind **(**longitude 90.2^o E**)** it can be seen that at the system center, the wind flow is at 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 system center 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 0900 UTC of 11 June, 2017 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 11 June, 10 June, 09 June and 08 June respectively are presented in Fig. 11 (a-d). Similar to the analysis of meridional wind it has been seen from the zonal wind **(**latitude is 22.5^o 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 is found to the south-east sector of the system center and it extends up to 300 hPa level. The secondary maximum wind (15-30) ms^{-1} is found at the right side of the system center.

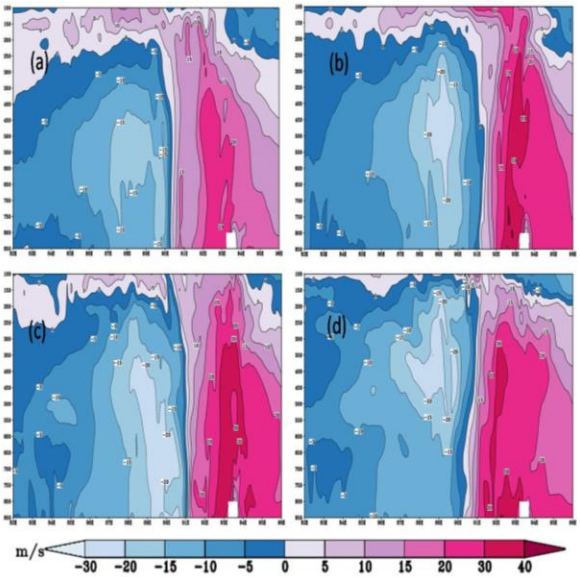

Fig.10 (a-d): Analysis of meridional wind valid for 1500 UTC of 11 June, 2017 for 24-h, 48-h, 72-h & 96-h respectively.

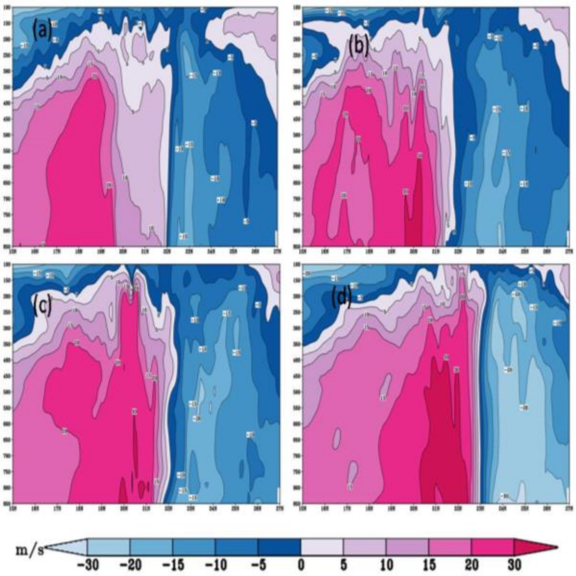

Fig.11 (a-d): Analysis of zonal wind valid for 1500 UTC of 11 June, 2017 for 24-h, 48-h, 72-h & 96-h respectively.

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

The relative humidity at 850 hPa level at 1500 UTC of 11 June, 2017 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 11 June, 10 June, 09 June and 08 June respectively are presented in Fig. 12 (a-d). The high amount of relative humidity is an important environmental variable associated with cloud and rain formation.

From the analysis of relative humidity, it is found that the strong southwesterly flow transports a high amount of moisture of the order of 80-100% to the plain of central and southeastern part of Bangladesh and adjoining areas 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 22º N at 1500 UTC of 11 June, 2017 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 11 June, 10 June, 09 June and 08 June respectively are presented 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. Validation of 3 hourly model

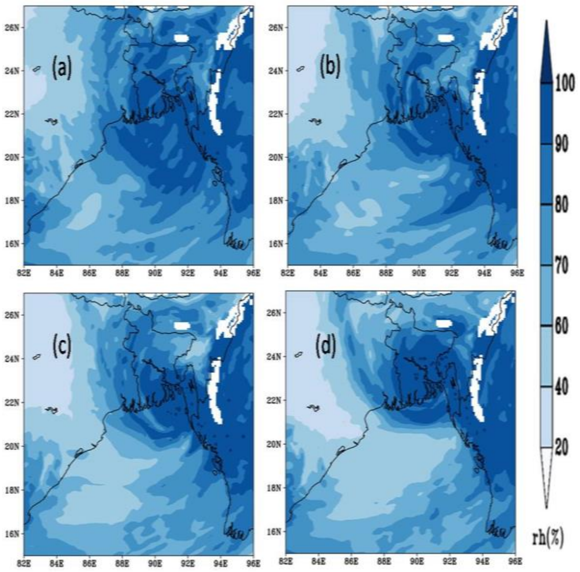

Fig.12 (a-d): Analysis of relative humidity (%) distribution valid for 1500 UTC of 11 June, 2017 for 24-h, 48-h, 72-h & 96-h respectively

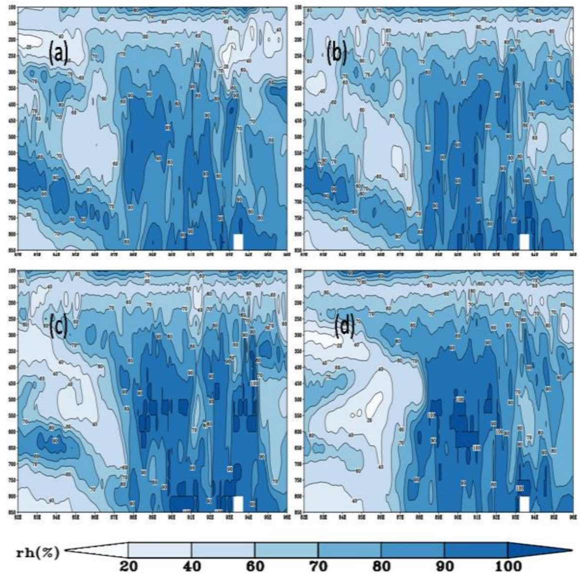

Fig.13 (a-d): Analysis of vertical cross-section of relative humidity valid for 1500 UTC of 11 June, 2017 for 24-h, 48-h, 72-h & 96-h respectively.

simulated RH (%) of MD of 11 June, 2017 with BMD observed data of Different stations are depicted in fig.14. The model simulated RH is very close to the observed values of BMD. The WRF model predicted this parameter very well compared to BMD data. The RH is responsible for providing latent heat flux for system intensification and also for the formation of different species of clouds and afterwards occurring of rainfall and the model performance is good enough for predicting the rainfall over Bangladesh. Here only four stations are chosen for model validation but applicable for all stations.

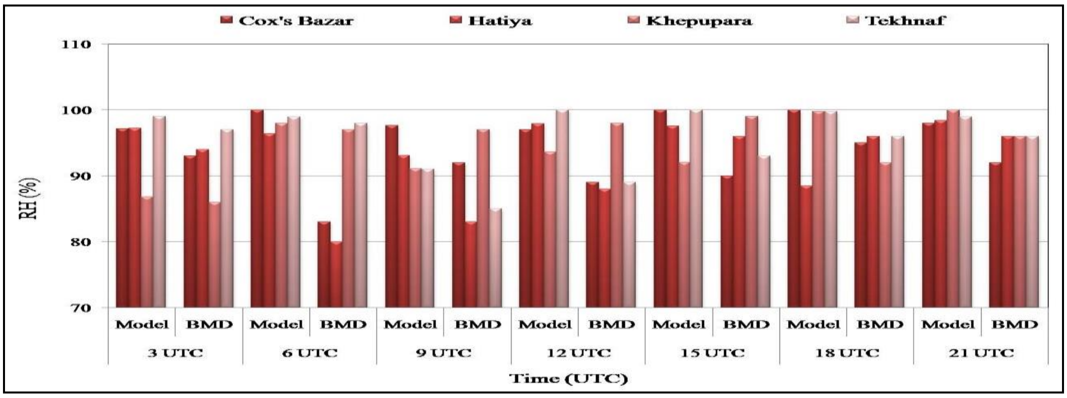

Fig. 14: Validation of 3 Hourly Model simulated RH (%) of MD of 11 June, 2017 with BMD observed data of the stations a) Cox's Bazar (b) Hatiya (c) Khepupara & (d) Teknaf.

4.5 Analysis of Relative Vorticity at 850 and 500 hPa Level

The model simulated 850 hPa level relative vorticity ($\times 10^{-5}\ s^{-1}$) valid for 1500 UTC of 11 June, 2017 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 11 June, 10 June, 09 June and 08 June respectively are presented in Fig.15 (a-d) and in Fig.16 (a-d) the 500hPa level vorticity valid for 1500 UTC of 11 June, 2017 are presented respectively.

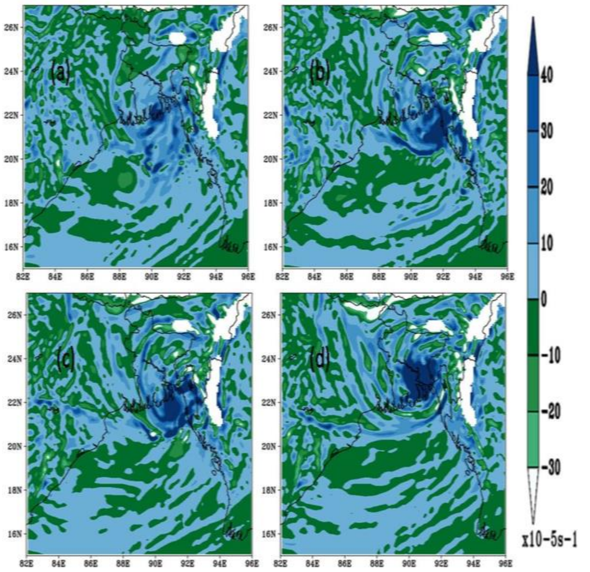

Fig.15 (a-d): The model simulated relative vorticity (unit: $\times 10^{-5} s^{-1}$) at 850 hPa valid for 1500 UTC of 11 June, 2017 for 24-h, 48-h, 72-h & 96-h respectively.

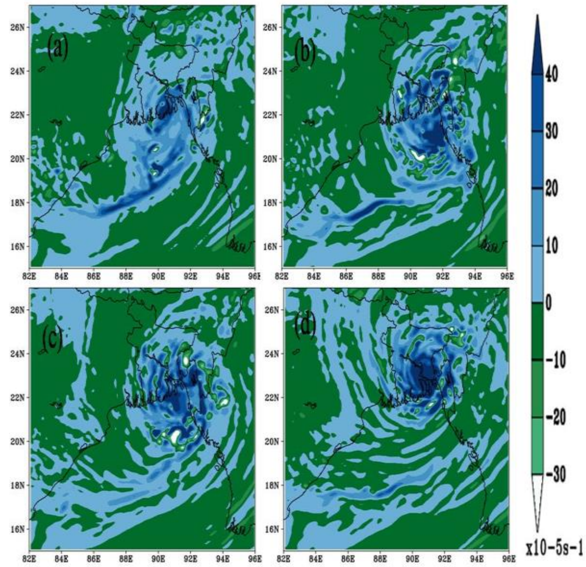

Fig.16 (a-d): The model simulated relative vorticity (unit: $\times 10^{-5} s^{-1}$) at 500 hPa valid for 1500 UTC of 11 June, 2017 for 24-h, 48-h, 72-h & 96-h respectively.

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 [(10-40) $\times 10^{-5}\ s^{-1}$] which is very much supportive for the formation of deep convective clouds and its associated rainfall. From the analysis of upper level (500 hPa) relative vorticity, it has been found that positive vorticity is found at the surroundings of the system center and also negative value of vorticity is found. This positive value is very much supportive for the updraft and the negative value for downdraft simultaneously. When vigorous updraft occurs then associative sinking also occurs and the respective wind pattern also changes. This results to heavy to very heavy rainfall in these associated areas. From model simulation it has been observed that heavy rainfall occurs in southeastern and southwestern part of Bangladesh.

4.6 Analysis of Vertical Wind Shear and Reflectivity

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 1500 UTC of 11 June, 2017 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 11 June, 10 June, 09 June and 08 June respectively are presented in Fig. 17 (a-d). It is found from the vertical wind shear analysis that at the system center the value of the vertical wind shear is negative because at the system center the wind is in a calm condition. But at the surrounding areas of the system center, the value of the vertical wind shear starts to increase.

Due to this positive value, the system can't be intensified to a tropical cyclone rapidly because at the upper level the wind speed is more than at the lower level wind speed and it thus supports to vertical breakdown of the system. These values of wind shear help to develop monsoon depression and heavy to very heavy rainfall over these regions of Bangladesh and very much non-supportive condition of forming tropical cyclone.

The model simulated reflectivity (dBZ) 850 hPa level valid for 1500 UTC of 11 June, 2017 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 11 June, 10 June, 09 June and 08 June respectively are presented in Fig. 18 (a-d). The reflectivity factor is an important parameter for the formation of convective clouds and severe thunder storms with strong lightning flashes. The model simulated reflectivity is found 30-60 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.

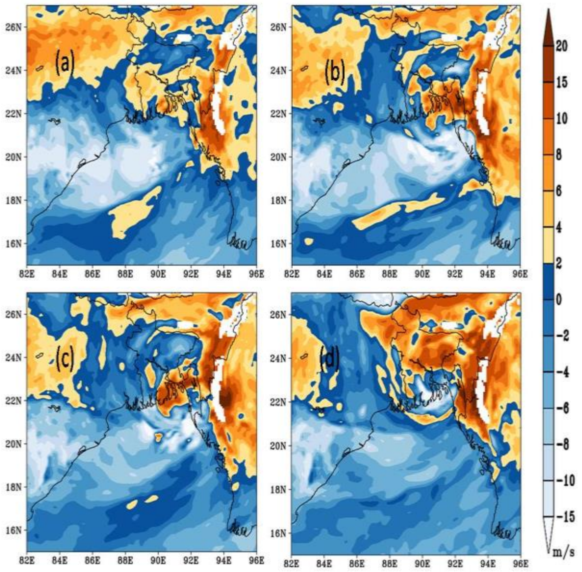

Fig.17 (a-d): The model simulated vertical wind shear (ms^{-1}) between the 500 and 850 hPa level valid for 1500 UTC of 11June, 2017 for 24-h, 48-h, 72-h & 96-h respectively.

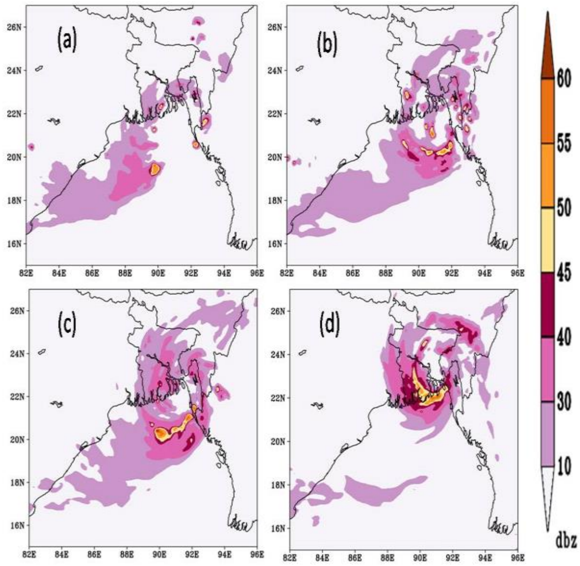

Fig. 18 (a-d): The model simulated radar reflectivity (unit: dBZ) valid for 1500 UTC of 11 June, 2017 for 24-h, 48-h, 72-h & 96-h respectively

4.7 Analysis of Temperature at 2m Height

The model simulated temperature (o C) at 2m height valid for 1500 UTC of 11 June, 2017 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions of 0000 UTC of 11 June, 10 June, 09 June and 08 June respectively are shown in Fig. 19 (a-d). From the temperature analysis it is found that the model simulated temperature is about (28-30) ^{o} C at the system center which is very much prior supportive condition for deep cloud formation and later high amount of precipitation over these regions. The 24-h run predicted value is more accurate than that of others higher lead-time run.

Validation of 3 Hourly Model simulated temperature (^{0}C) of MD of 11 June, 2017 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.

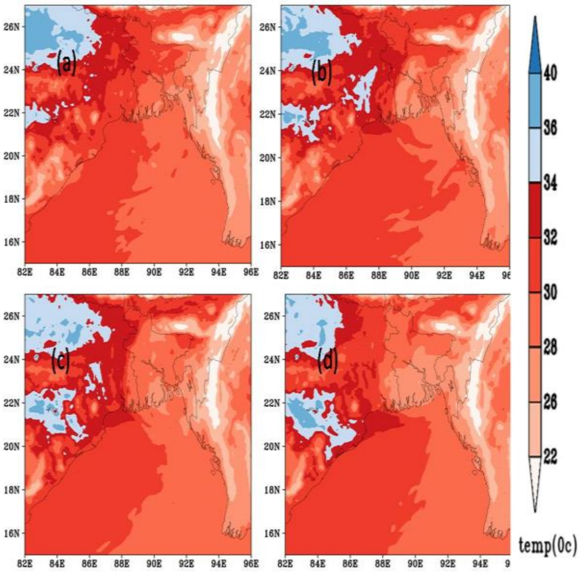

Fig. 19 (a-d): Analysis of temperature at 2 m height valid for 1500 UTC of 11 June, 2017 for 24-h, 48-h, 72-h & 96-h respectively.

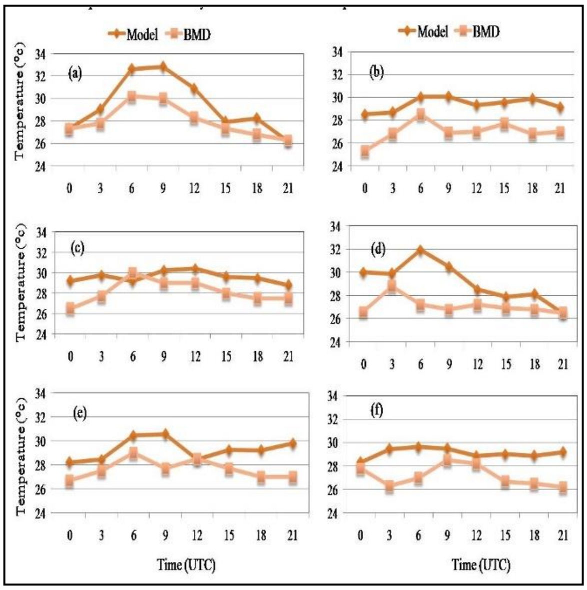

Fig. 20 (a-f): Validation of 3 hourly model simulated temperature (0C) of MD of 11 June, 2017 with BMD observed data of the stations a) Chattogram (b) Cox's Bazar (c) Hatiya (d) Khepupara (e) Kutubdia & (f) Teknaf

4.8 Analysis of Maximum Convective Available Potential Energy (MCAPE) and Outgoing Long wave Radiation (OLR)

The model simulated Maximum Convective Available Potential Energy (Jkg^{-1}) 850 hPa level valid for 1500 UTC of 11 June, 2017 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 11 June, 10 June, 09 June and 08 June respectively are presented in Fig. 21 (a-d).

From the analysis the MCAPE is found in the order of < 500 Jkg^{-1} at the center of the system which lies over southeast side of Bangladesh but in the outer shell of the monsoon depression especially in the southeast and southwestern part the MCAPE 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

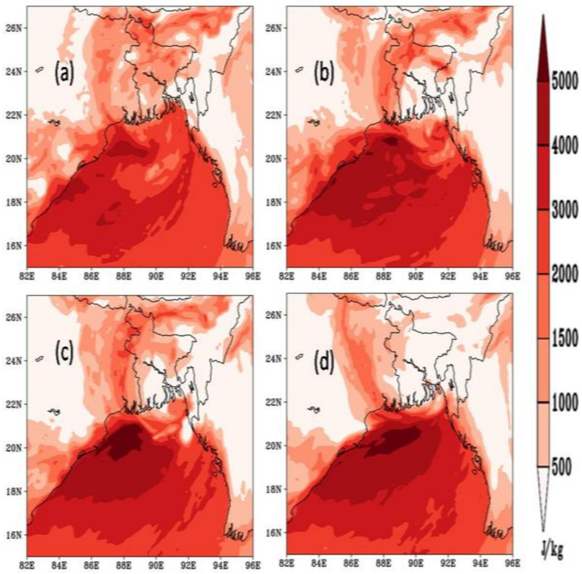

Fig. 21 (a-d): The model simulated MCAPE (unit: J/kg) valid for 1500 UTC of 11 June, 2017 for 24-h, 48-h, 72-h & 96-h respectively.

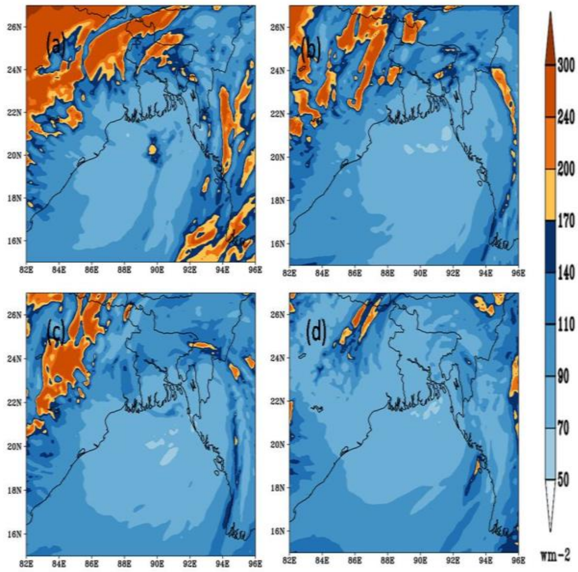

Fig. 22 (a-d): The model simulated outgoing long wave radiation (olr) valid for 1500 UTC of 11 June, 2017 for 24-h, 48-h, 72-h & 96-h respectively.

of the system. The possibility of the formation of maximum thunder activity is to the southwest and southeast sector of the monsoon depression due to its greater value. The model performance is good enough.

The model simulated outgoing long wave radiation valid for 1500 UTC of 11 June, 2017 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 11 June, 10 June, 09 June and 08 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 Wm^{-2}), because above the system center the sky was partly cloudy. So the model captures the lower value of olr which is also supportive condition for formation of the system.

4.9 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 11 June, 10 June, 09 June and 08 June, 2017 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.

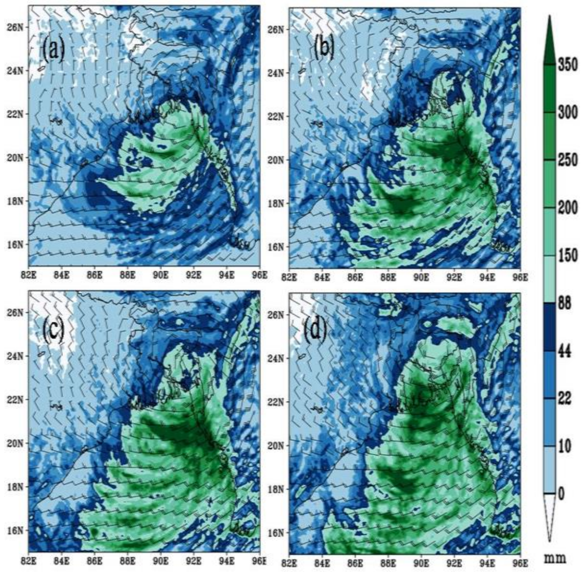

Fig. 23 (a-d): The model simulated 24-h, 48-h, 72-h & 96-h accumulated rainfall based on the initial condition 0000 UTC of 11, 10, 09, 08 June, 2017 respectively.

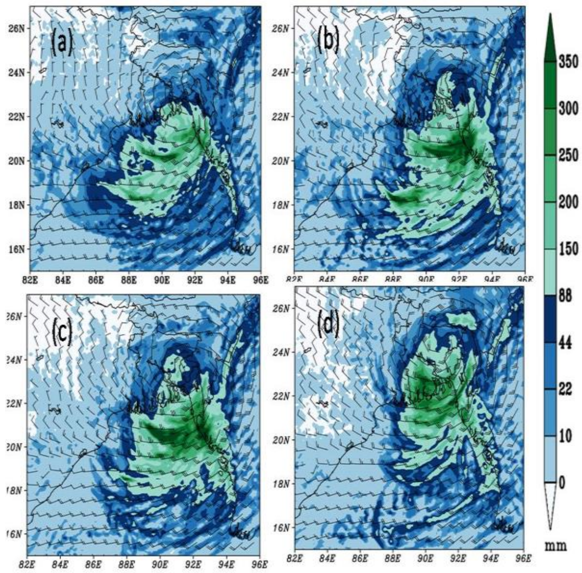

Fig.24 (a-d): Comparison of 24-h accumulated rainfall analysis valid for 11 June, 2017 simulated by 24-h, 48-h, 72-h, 96-h advanced model run respectively

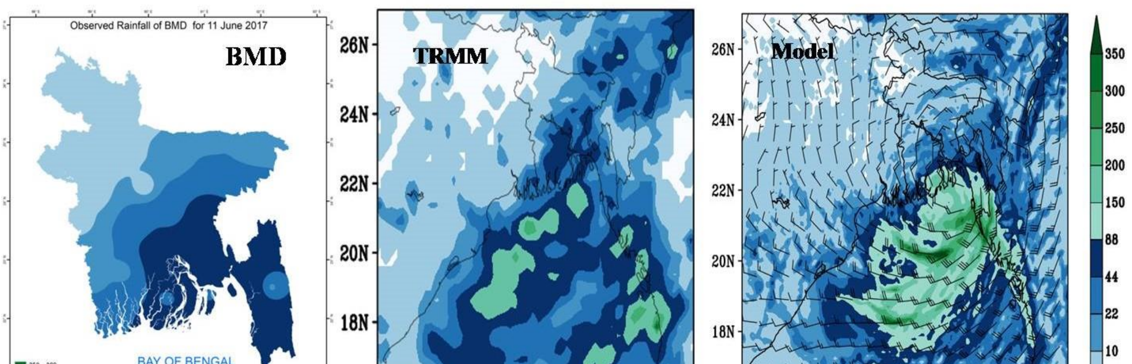

Fig.25: Comparison for spatial validation of WRF model simulated rainfall with BMD observed and TRMM predicted rainfall of MD of 11 June, 2017 (24h rainfall).

The model simulated 24-h accumulated rainfall distribution valid for 11 June, 2017 simulated for 24-h, 48-h, 72-h and 96-h based on the initial conditions of 0000 UTC of 11 June, 10 June, 09 June and 08 June respectively are shown in Fig. 24 (a-d). The model 24-h 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.

From the computational analysis of rainfall analysis it is mentionable that the model is simulate the high amount of rainfall over Cox's Bazar, Teknaf, M. Court, Mongla, Satkhira Patuakhali, Dhaka and Hatiya. The location and the time of the occurring of rainfall is captured by the model with good signature. Finally, comparison of WRF model simulated 24h accumulated rainfall and BMD observed rainfall of MD of 11 June, 2017 is shown in fig.26.

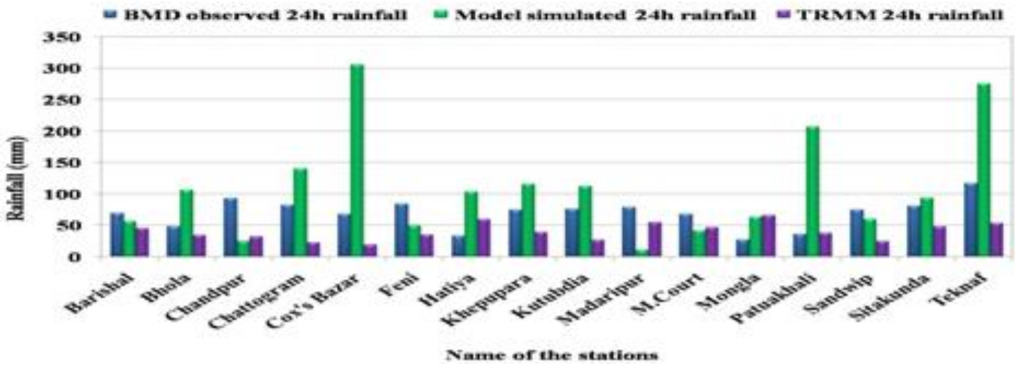

Fig. 26: Computational validation of model simulated rainfall with BMD observed & TRMM rainfall of various stations of 11 June, 2017 (24h accumulated rainfall)

Validation of Model simulated 3 hourly rainfall of 11 June, 2017 with BMD observed rainfall are shown in fig.27.

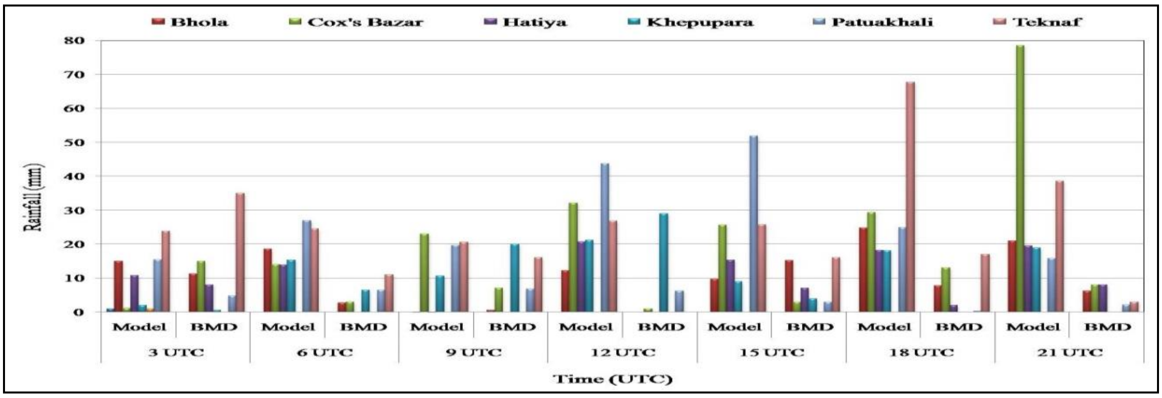

Fig.27: Computational validation of model simulated 3 hourly rainfall of MD of 11 June, 2017 with BMD observed rainfall data of the stations a) Bhola (b) Cox's Bazar (c) Hatiya (d) Khepupara (e) Patuakhali & (f) Teknaf

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.
- The model simulated lowest central pressure of the MD is 987, 978, 974 and 972 hPa at 1500 UTC of 11 June, 2017; for 24h, 48-h, 72-h and 96-h model run respectively. The observed central pressure was 988 hPa for 1500 UTC of 11 June, 2017. 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) x10^{-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 (15─20) 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 Sitakunda, Sandwip, Hatiya, Kutubdia, Maijdi Court, Teknaf, Bhola, Khulna, Sylhet, 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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