Predictability of Monsoon Low Pressure Area over the Head Bay of Bengal and Its Associated Rainfall using Weather Research and Forecasting Model

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Abstract

An attempt has been made to simulate Monsoon Low Pressure Area over the Bay of Bengal (BoB) during 12-16 July, 2018 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 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 reasonably well. The model has simulated rainfall, wind and rh sensibly well compared with the observed data of BMD and Tropical Rainfall Measuring Mission (TRMM). It can be concluded that the WRF model with the accurate setup of the domain, horizontal resolution and the appropriate parameterization schemes is proficient to simulate and forecast the monsoon low over the BoB and its associated rainfall over Bangladesh up to 96-hours advance.

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. 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, monsoon low 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 monsoon lows (Krishnamurti, 1979) [14]. For that reason understanding various properties of the monsoon low is a key towards considerate of the accuracy of the SW monsoon and especially its hydrological process. Occasionally MONSOON LOWs form in the land as a land depression and cause heavy rainfall over the region where it lies (Raj, 2003) [15]. monsoon lows 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 (monsoon low) 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. Monsoon Low over the BoB on 12-16 July, 2018

A Low-pressure area formed over northwest Bay and adjoining area on 13 July, 2018 and laid over same area on 14 July. It was intensified into a well-marked low over the same area at 03 UTC at 15 July, 2018 and moved in a northwesterly direction. Under its influence steep pressure gradient persisted over North Bay and adjoining coastal area of Bangladesh. Then it moved slightly westward and lay over coastal Orissa and adjoining northwest Bay at 16 July, 2018.Then it moved in west/northwesterly direction further. On 17 July it moved northwestward and lay over Jharkhand of India and adjoining area. On 18 July, 2018 it moved northwestward and lay over Madhya Pradesh and adjoining Uttar Pradesh of India as a Low. . It caused heavy rainfall over Bangladesh and neighborhood. This event is simulated by WRF model with evaluating different meteorological parameters are described briefly in the following section.

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.

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.

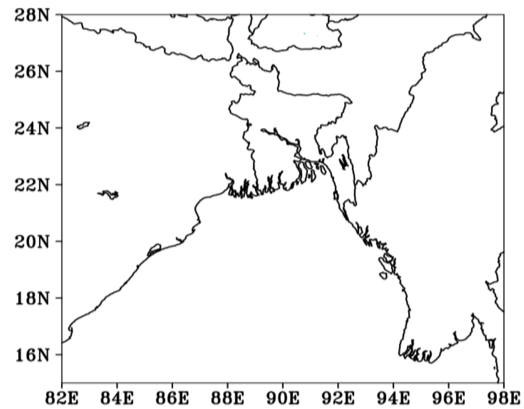

Figure 1: WRF model domain configuration

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 (Monsoon Low) 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 Yonsei University
PBL Parameterization -	(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 monsoon low event occurred over the BoB on 12-16 July 2018. Model was run using six hourly NCEP-GFS datasets from 0000 UTC of 11 July 2018 to 0000 UTC of 17 July 2018 as initial and lateral boundary condition. Hourly outputs of the model were analyzed for investigating the causes and mechanisms for the formation of the monsoon low 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 of monsoon low.

4. Case-04: Result and Discussions

4.1 Analysis of Mean Sea Level Pressure (MSLP)

The model simulated mean sea level pressure (hPa) at 850 hPa level valid for 0000 UTC of 15 July, 2018 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 14 July, 13 July, 12 July and 11 July respectively are shown in Fig.4.1.1(a-d).

The model simulated central pressure is about 989, 987, 984 and 985 hPa at 0000 UTC of 15 July, 2018 for 24-h, 48-h, 72-h and 96-h model run respectively. Whereas the lowest estimated central pressure by Monsoon Low is 994 hPa at 0000 UTC of 15 July, 2018 at Khepupara station. The steep pressure gradient lies over the Bay of Bengal. The number of isobars which travels from the Bay of Bengal towards Bangladesh is about 2 - 4 and it is very much supportive for carrying huge amount of moisture towards Bangladesh and adjoining area. It is also favorable for the formation of convective and non-convective clouds and positive approach for the occurring of extreme rainfall and gusty or squally wind over Bangladesh and adjoining area.

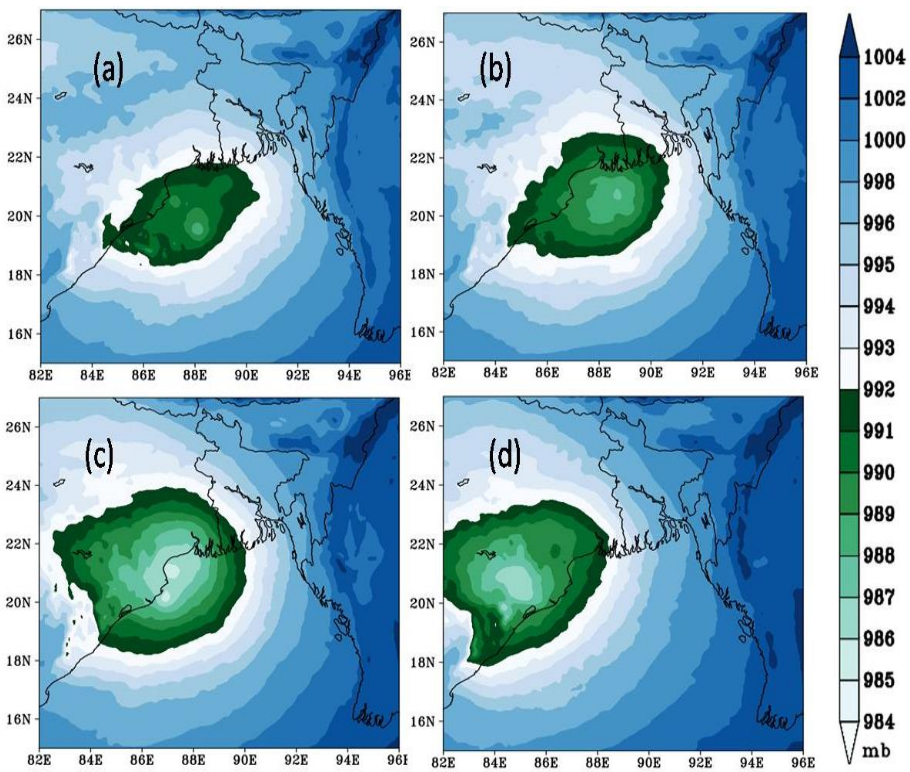

Fig. 4.1.1 (a-d): Model simulated MSLP analysis at 850 hPa level valid for 0000 UTC of 15 July, 2018 for 24-h, 48-h, 72-h and 96-h respectively.

Validation of 3 Hourly Model simulated MSLP of Monsoon low of 14 June, 2018 with observed data of different stations are depicted in fig. 4.1.2 (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.

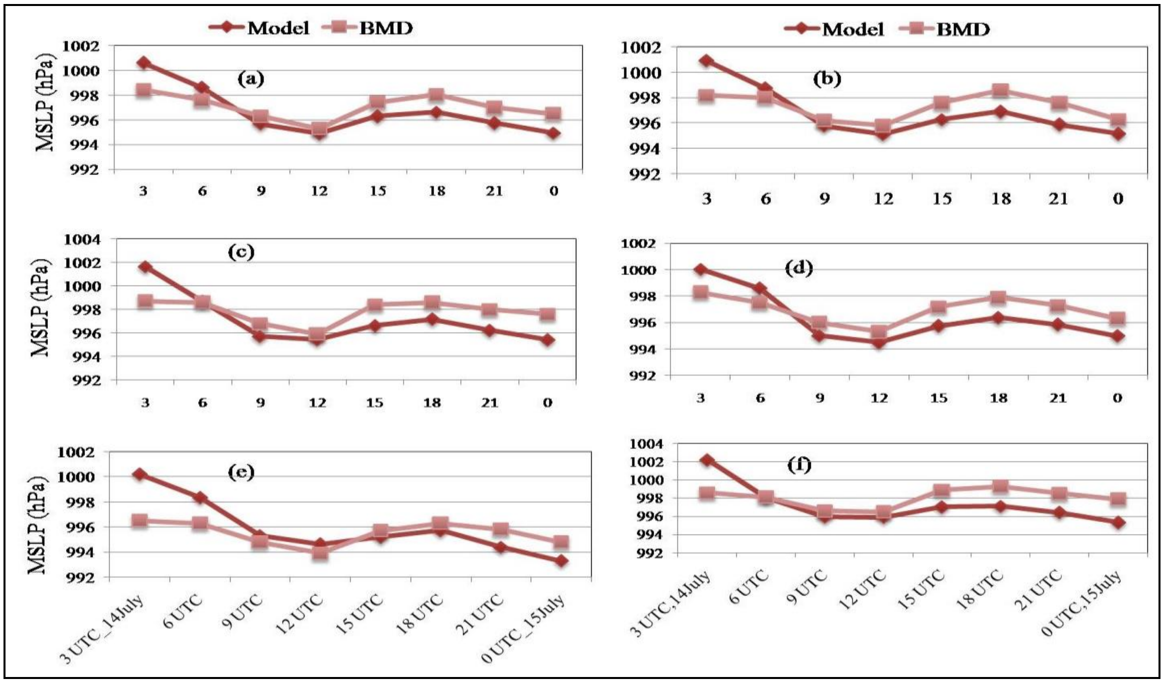

Fig. 4.1.2 (a-f): Validation of 3 hourly model simulated MSLP (hPa) of Monsoon lowof 14 June, 2018 with observed data of the stations (a) Barisal (b) Bhola (c) Hatiya (d) Jashore (e) Khepupara & (f) Kutubdia

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

Wind flow (ms^{-1}) of 850 hPa, 500 hPa and 200 hPa level valid for 0000 UTC of 15 July, 2018 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 14 July, 13 July, 12 July and 11 July respectively are shown in Fig. 4.2.1 (a-d), Fig. 6.4.2.2(a-d) and Fig. 4.2.3 (a-d).

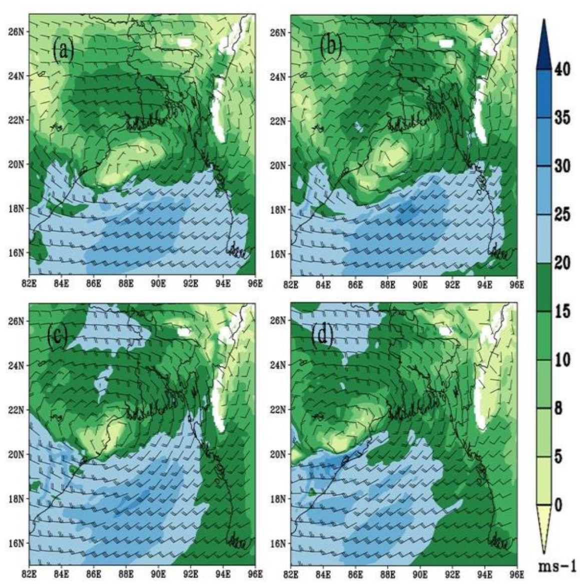

Fig.4.2.1 (a-d): Analysis of wind flow distribution at 850 hPa level valid for 0000 UTC of 15 July, 2018 for 24-h, 48-h, 72-h and 96-h respectively

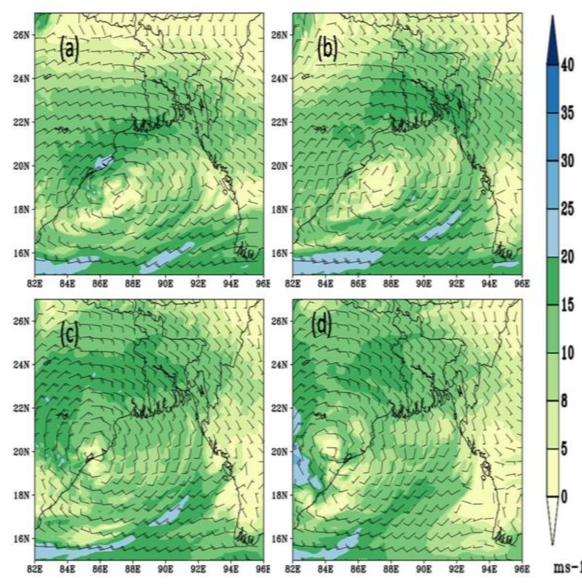

Fig.4.2.2 (a-d): Analysis of wind flow distribution at 500 hPa level valid for 0000 UTC of 15 July, 2018 for 24-h, 48-h, 72-h and 96-h respectively.

It is found that a well-organized cyclonic circulation lies over the northwestern Bay of Bengal and adjoining areas at 850 hPa and 500 hPa level of wind patterns [Fig. 4.2.1 (a-d) & 4.2.2 (a-d)]. The center of the circulation at 850 hPa is located over northwestern BoB. The center of the circulation at 500 hPa is located slightly south of 850 hPa position. Therefore, the vertical axis of the depression at the time of landfall is slightly tilted southward with height. A narrow belt of maximum wind (>15 ms^{-1}) is found to the southeast sector of the system which carries high amount of moisture from the Bay of Bengal towards Bangladesh and it is very much supportive for the formation of stratus and convective clouds which produce high impact rainfall. At both 850 hPa and 500 hPa level, convergence zone is formed where at higher level of 200 hPa the circulation pattern is not well-organized. Actually a divergence zone is found at that level (Fig. 4.2.3 (a-d)).

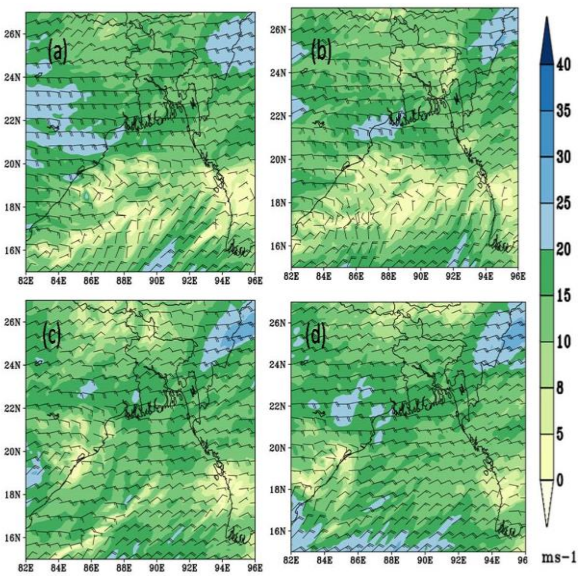

Fig. 4.2.3 (a-d): Analysis of wind flow distribution at 200 hPa level valid for 0000 UTC of 15 July, 2018 for 24-h, 48-h, 72-h and 96-h respectively.

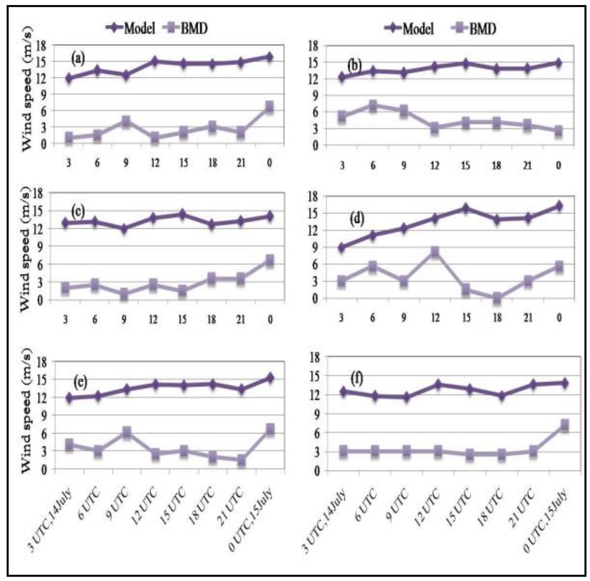

Fig. 4.2.4 (a-f): Validation of 3 hourly model simulated wind speed (ms-1) of Monsoon low of 14 June, 2018 with BMD observed data of the stations (a) Barishal (b) Bhola (c) Hatiya (d) Jashore (e) Khepupara & (f) Kutubdia

This model simulated wind speed is favorable for the intensification of monsoon depression over southwest Bangladesh and adjoining areas. So, it can be concluded that due to this favorable condition convective activity may strengthen, which is very much supportive to form high amount of rainfall over south-eastern and northeastern part of Bangladesh and adjoining areas which is validated with the observed rainfall data of BMD. Validation of 3 Hourly Model simulated wind speed (ms^{-1}) of Monsoon low of 14 June, 2018 with BMD observed data of different stations are depicted in fig. 6.4.2.4 (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 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 model simulated the meridional wind of 15 July, 2018 at 0000 UTC for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 14 July, 13 July, 12 July and 11 July respectively are shown in Fig. 4.3.1 (a-d). From the analysis of meridional wind (along long.88.1^{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 (10-30) ms^{-1}. The model simulated the gusty or squally wind to the right side of the system center and the peak gust is found at least 100 km away from the center and these is the region where highest convective activity occurs. 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 blowing 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.

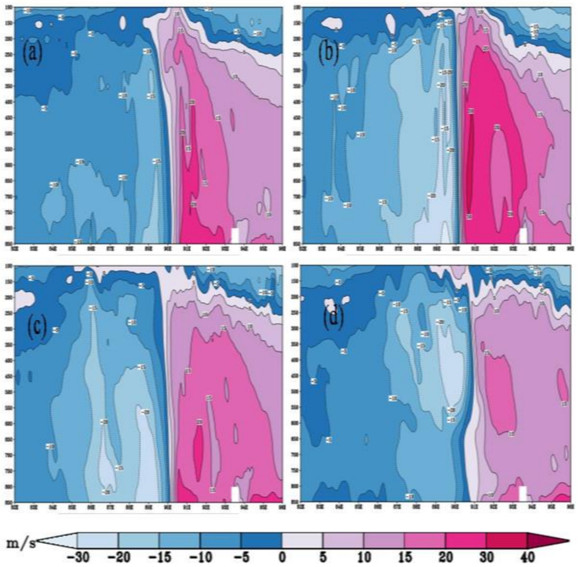

Fig. 4.3.1 (a-d): Analysis of meridional wind valid for 0000 UTC of 15 July, 2018 for 24-h, 48-h, 72-h & 96-h respectively.

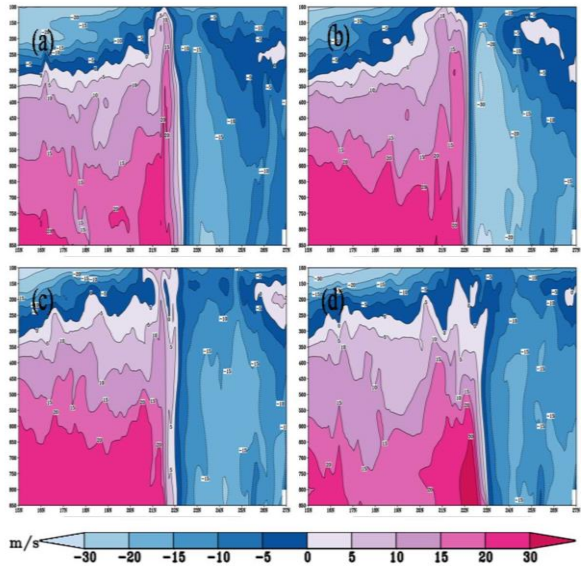

Fig. 4.3.2 (a-d): Analysis of zonal wind valid for 0000 UTC of 15 July, 2018 for 24-h, 48-h, 72-h & 96-h respectively.

The zonal wind at 0000 UTC of 15 July, 2018 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 14 July, 13 July, 12 July and 11 July respectively are shown in Fig. 4.3.2 (a-d). Similar to the analysis of meridional wind it has been seen from the zonal wind (along lat.19.6° N) analysis that at the left side (along lower latitude) of the system center the wind speed is positive whereas 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 (10-30) ms^{-1} is found to the south-east sector of the system center and it extends up to 300 hPa level. The secondary maximum wind (10-20) ms^{-1} is found at the right side of the system center i.e., along lower latitudes. So, the system is rotating column started surface to 300 hPa level which is very favorable condition for the monsoon depression and the WRF model has captured this three-dimensional structure reasonably well.

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

The relative humidity at 850 hPa level at 0000 UTC of 15 July, 2018 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions of 0000 UTC of 14 July, 13 July, 12 July and 11 July respectively are shown in Fig. 4.4.1 (a-d). 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% over Northwest Bay and adjoining Bangladesh. The contents of high magnitude of moisture play an important role for the formation of the severe convective clouds over these regions. This high amount relative humidity may form strati-form of precipitation and cumuli-form of precipitation in the lower and upper tropospheric level. The model captured this moisture amount over Bangladesh precisely even in 96-h advance. The high amount of relative humidity is an important environmental variable associated with cloud and rain formation.

The vertical cross-section of relative humidity analysis along the 19.6°N on 15 July, 2018 at 0000 UTC of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions of 0000 UTC of 14 July, 13 July, 12 July and 11 July respectively are shown in Fig. 4.4.2 (a-d). It is found that the relative humidity of the order of 80-100% 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. The model has also simulated the high amount of relative humidity in the peripheral band of the system where thunder activity predominantly occurs.

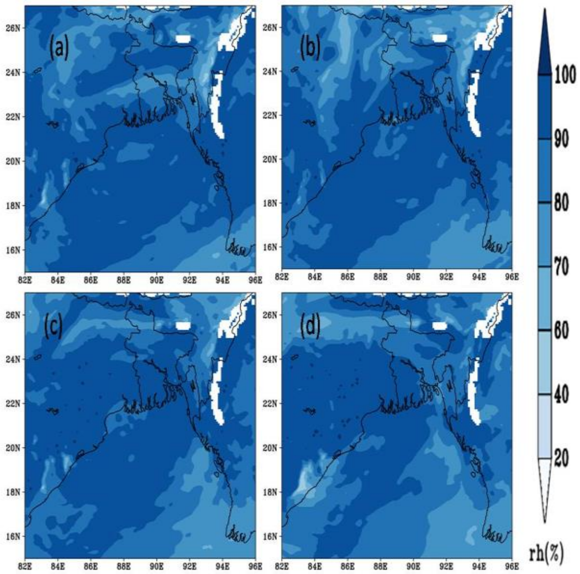

Fig. 4.4.1 (a-d): Analysis of relative humidity valid for 0000 UTC of 15 July, 2018 for 24-h, 48-h, 72-h & 96-h respectively.

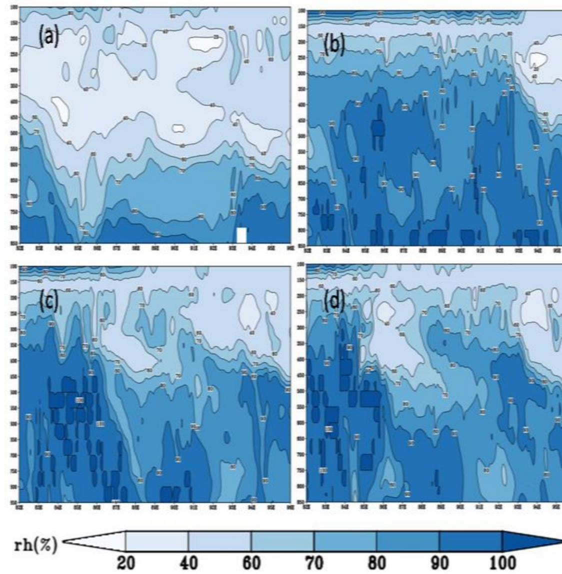

Fig. 4.4.2(a-d): Analysis of vertical cross-section of relative humidity valid for 0000 UTC of 15 July, 2018 for 24-h, 48-h, 72-h & 96-h respectively.

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 Monsoon low of 03 UTC of 14 July, 2018 to 00 UTC of 15 July, 2018 with BMD observed data of Different stations are depicted in fig. 4.4.3.

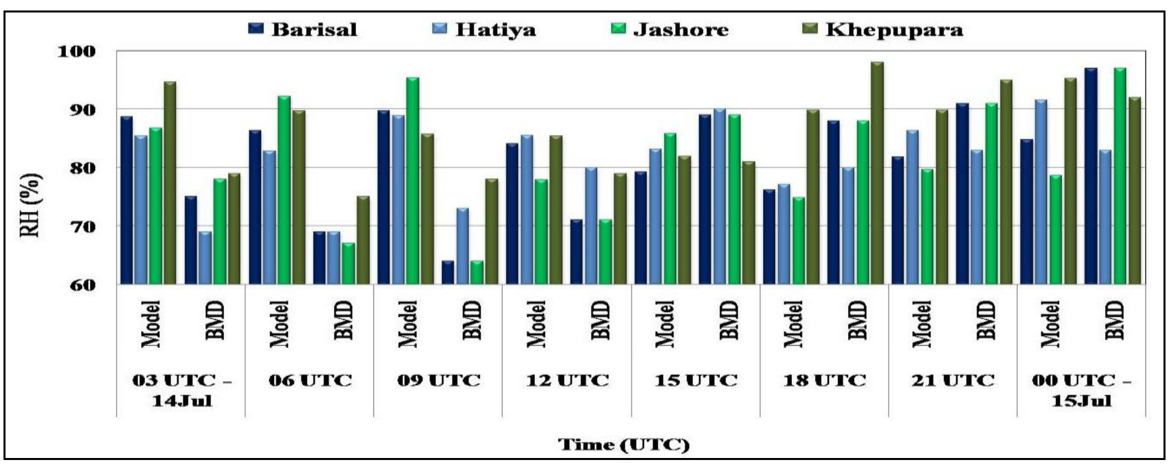

Fig. 6.4.4.3: Validation of 3 hourly model simulated relative humidity (%) of Monsoon low of 03 UTC of 14 July, 2018 to 00 UTC of 15 July, 2018 with BMD observed data of the stations a) Barisal (b) Hatiya (c) Jashore & (d) Khepupara

4.5 Analysis of Relative Vorticity at 850 and 500 hPa Level

The model predicted 850 hPa level and 500 hPa level relative vorticity ($\times 10^{-5}$ s^{-1}) valid for 0000 UTC of 15 July, 2018 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions of 0000 UTC of 14 July, 13 July, 12 July and 11 July respectively are shown in Fig. 6.4.5.1 (a-d) and in Fig. 6.4.5.2 (a-d) respectively.

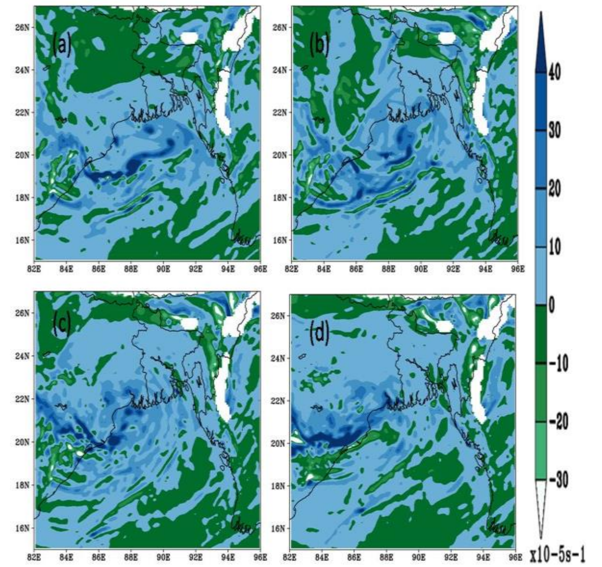

Fig. 4.6 (a-d): The model simulated vertical wind shear (ms-1) between the 500 and 850 hPa level valid for 0000 UTC of 15July, 2018 for 24-h, 48-h, 72-h & 96-h respectively.

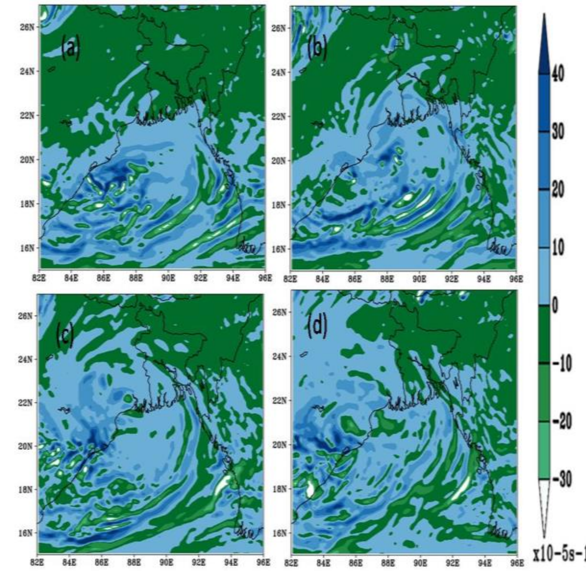

Fig. 4.6.1 (a-d): The model simulated radar reflectivity (unit: dBZ) valid for 0000 UTC of 15 July, 2018 for 24-h, 48-h, 72-h & 96-h respectively.

From the analysis of lower and upper-level relative vorticity, it has been found that positive vorticity of order of (10-30) $\times10^{-5}$ s^{-1} is found at the surroundings of the system center and also negative value of vorticity of order of (-10 to -20) $\times10^{-5}$ s^{-1} is found away from the system center. 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 rainfall in these associated areas. The positive vorticity of wind flow also denotes cyclonic flow while negative vorticity supports anti-cyclonic flow which is very much supportive for the formation of deep convective clouds related to monsoon depression.

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 0000 UTC of 15 July, 2018 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions of 0000 UTC of 14 July, 13 July, 12 July and 11 July respectively are shown in Fig. 4.6.1 (a-d).

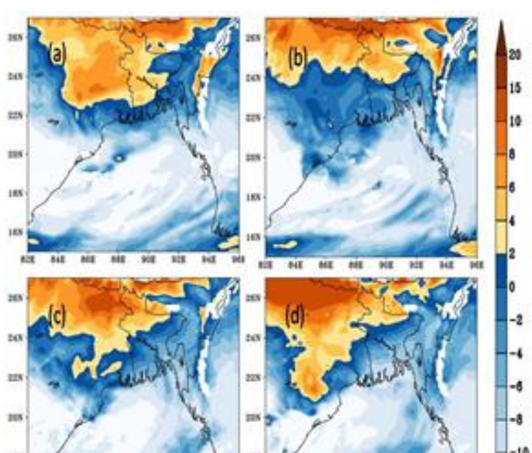

Fig. 4.6 (a-d): The model simulated vertical wind shear (ms-1) between the 500 and 850 hPa level valid for 0000 UTC of 15July, 2018 for 24-h, 48-h, 72-h & 96-h respectively.

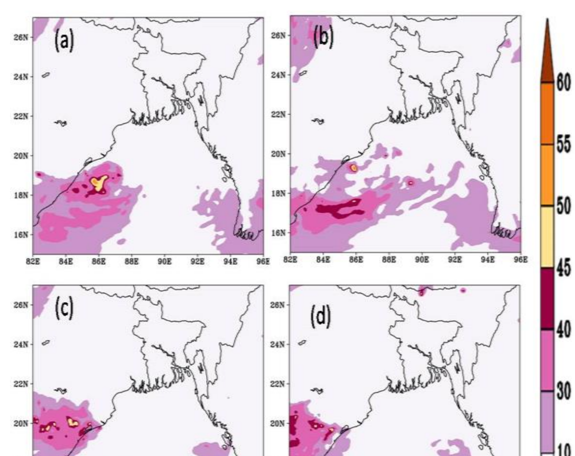

Fig. 4.6.1 (a-d): The model simulated radar reflectivity (unit: dBZ) valid for 0000 UTC of 15 July, 2018 for 24-h, 48-h, 72-h & 96-h respectively.

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 6-15 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 monsoon depression. These values of wind shear help to develop monsoon depression and heavy to very heavy rainfall over these regions of Bangladesh and adjoining area which lies at the southeast sector of the system. The model simulated radar reflectivity (dBZ) 850 hPa level valid for 0000 UTC of 15 July, 2018 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 14 July, 13 July, 12 July and 11 July respectively are presented in Fig..4.7(a-d). The radar reflectivity is an important parameter for the formation of convective clouds and severe thunder storms. The model simulated radar reflectivity is found 30 - 50 dBZ. When the magnitude is > 50 dBZ it is associated with severe thunder activity. 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 moderate thunder activity lies.

4.7 Analysis of Temperature at 2m Height

The model simulated temperature (^{o} C) at 2m height valid for 0000 UTC of 15 July, 2018 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions of 0000 UTC of 14 July, 13 July, 12 July and 11 July respectively are shown in Fig. 4.7.1(a-d).

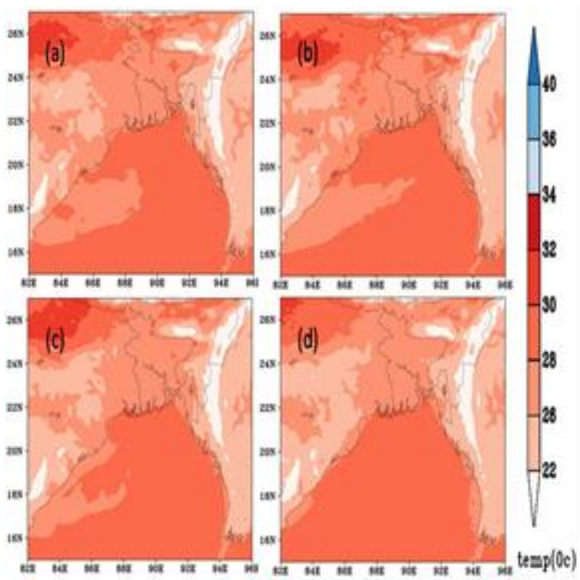

Fig. 4.7.1(a-d): Analysis of temperature at 2 m height valid for 0000 UTC of 15 July, 2018 for 24-h, 48-h, 72-h & 96-h respectively.

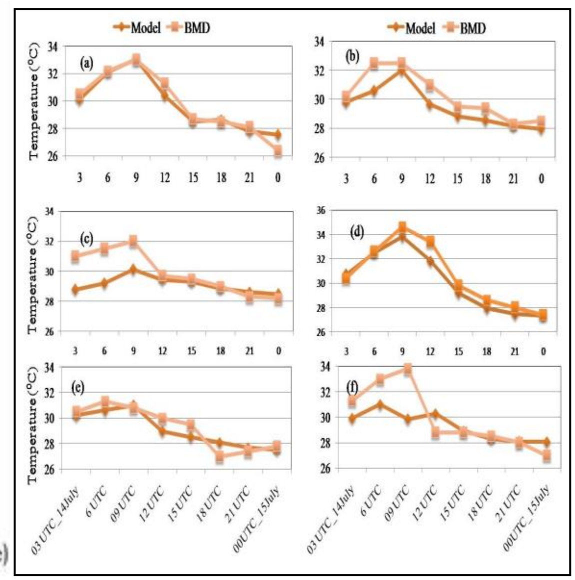

Fig. 4.7.2 (a-f): Validation of 3 hourly model simulated temperature (o C) of Monsoon lowof 03 UTC of 14 July, 2018 to 00 UTC of 15 July, 2018 with BMONSOON LOWobserved data of the stations (a) Barisal (b) Bhola (c) Hatiya (d) Jashore (e) Khepupara & (f) Kutubdia

From the temperature analysis it is observed that the temperature is about (26-28) ^{o} C at the system center which is very much supportive for cloud formation and later precipitation over these regions the 24-h run is more accurate than that of others run. Validation of 3- hourly model simulated temperature (^{0}C) of ML of 14 July, 2018 with BMD observed data of different stations are depicted in fig. 4.7.2 (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 very minor biases. It is also mentionable that model sometimes overestimated or sometimes underestimated the temperature. This is very significant for predicting the temperature for the less bias corrections.

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

The model simulated Convective Available potential Energy (Jkg^{-1}) 850 hPa level valid for 0000 UTC of 15 July, 2018 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 14 July, 13 July, 12 July and 11 July respectively are presented in Fig. 4.8.1 (a-d).

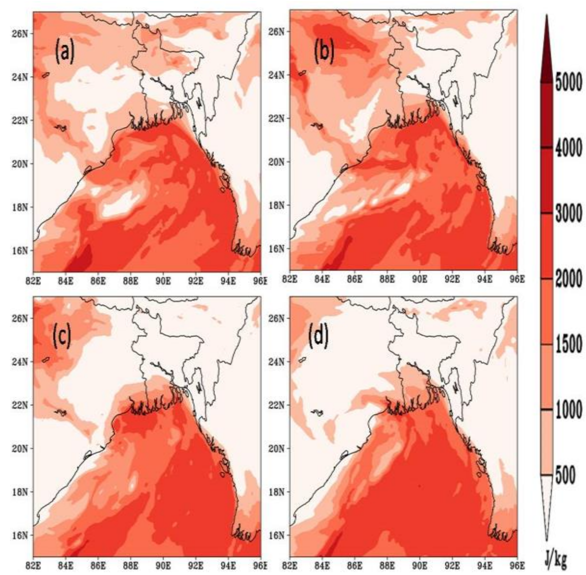

Fig.4.8.1 (a-d): The model simulated MCAPE (unit: j/kg) valid for 0000 UTC of 15 July, 2018 for 24-h, 48-h, 72-h & 96-h respectively.

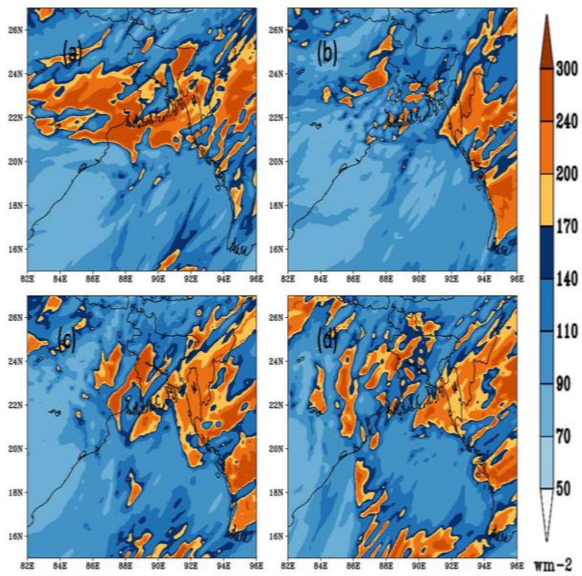

Fig. 4.8.2 (a-d): The model simulated outgoing long wave radiation (OLR) valid for 0000 UTC of 15 July, 2018 for 24-h, 48-h, 72-h & 96-h respectively.

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 monsoon depression 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 monsoon depression. The model simulated outgoing long wave radiation valid for 0000 UTC of 15 July, 2018 of model simulation for 24-h, 48-h, 72-h and 96-h based on the initial conditions 0000 UTC of 14 July, 13 July, 12 July and 11 July respectively are presented in Fig. 4.8.2 (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 overcast. 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 14 July, 13 July, 12 July and 11 July, 2018 respectively are shown in Fig. 4.9.1 (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. 4.10.3 and 4.10.4 respectively. The distribution of BMD observed data shows good rainfall over the belt of southeastern part of Bangladesh, but low rainfall over the rest part of the country.

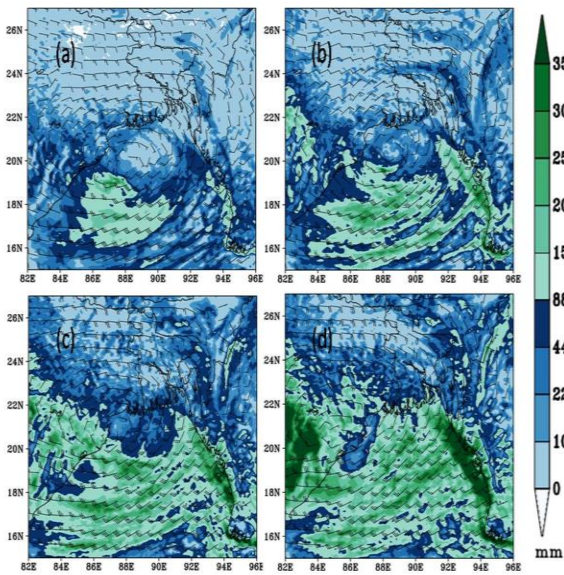

Fig. 4.9.1 (a-d): The model simulated 24-h, 48-h, 72-h & 96-h accumulated rainfall based on the initial condition 0000 UTC of 14, 13, 12, 11 July, 2018 respectively.

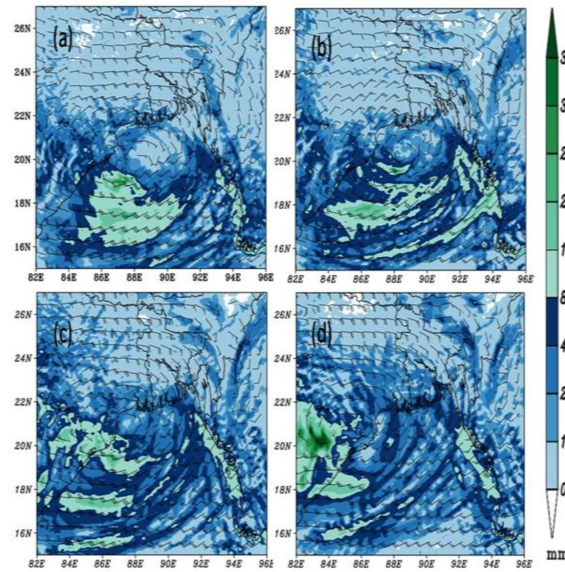

Fig. 4.9.2 (a-d): Comparison of 24-h accumulated rainfall analysis valid for 14 July, 2018 simulated by 24-h, 48-h, 72-h, and 96-h advanced model run respectively

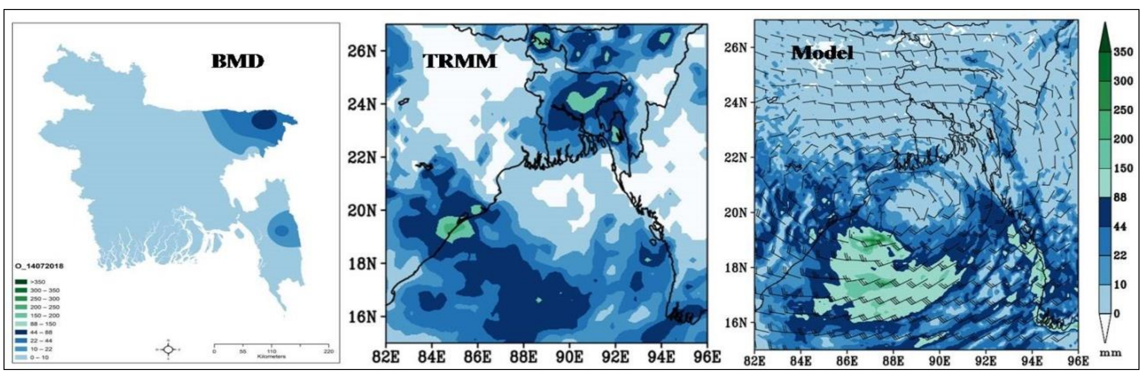

Fig.4.10.3 Comparison for spatial validation of WRF model simulated rainfall with BMD observed and TRMM rainfall of Monsoon low of 14 July, 2018 (24h rainfall)

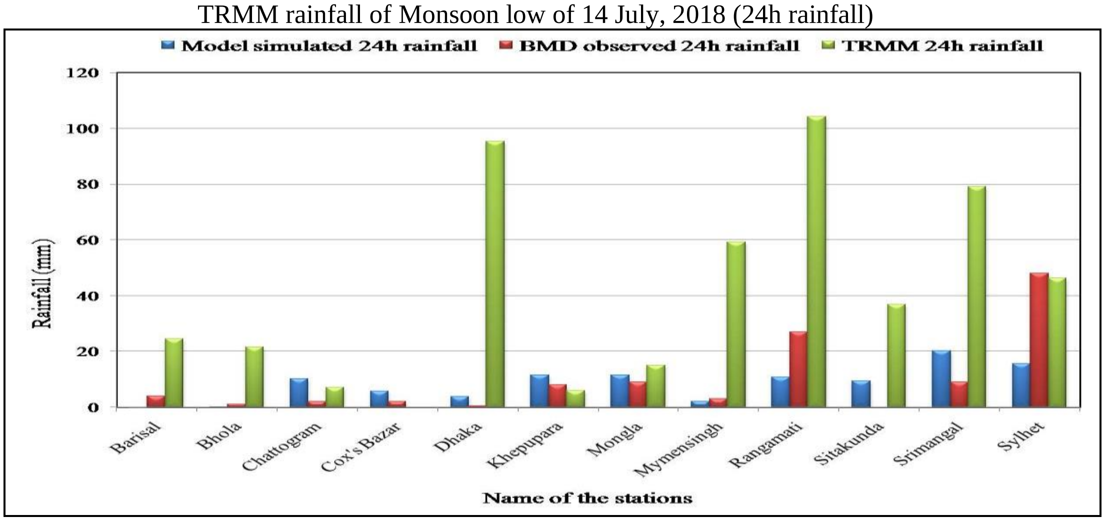

Fig. 4.10.4 Computational validation of model simulated rainfall with observed & TRMM rainfall of various stations of 14 July, 2018 (24h accumulated rainfall)

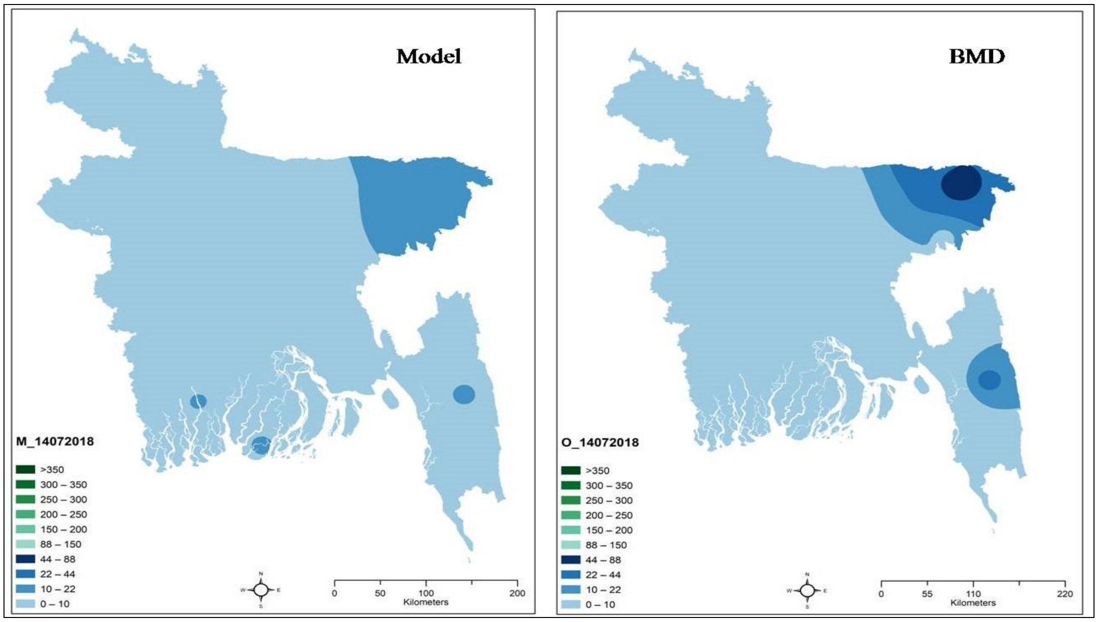

Fig.4.10.5: Comparison of WRF model simulated rainfall and BMD observed 24h accumulated rainfall of Monsoon low on14 July, 2018.

It is found that model underestimates the rainfall compared to that of observed and TRMM rainfall. From the computational analysis of rainfall analysis, it is mentionable that the model is simulate the moderate rainfall over Chattogram, Khepupara, Mongla, Rangamati, Srimangal, Sylhet. 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 rainfall of Monsoon low of 14 July, 2018 is shown in fig.6.4.10.5.

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 monsoon low over the BoB and associated rainfall over Bangladesh.
- The model simulated lowest central pressure of the monsoon low 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 MONSOON LOW, 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 monsoon low 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 (Monsoon Low) 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 monsoon low.

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 MLPS over the Bay of Bengal and associated rainfall over Bangladesh up to 96-hours advance reasonably well.

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