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Simulation of Monsoon Low Pressure System and its Associated Rainfall Over Bangladesh Using WRF Model

Deepa Roy[1], Md. Abdus Samad[1*] and S. M. Quamrul Hassan[2]

[1]*Department of Applied Mathematics, Dhaka University, Dhaka-1000, Bangladesh*

[2]*Bangladesh Meteorological Department, Agargaon, Dhaka-1207, Bangladesh*

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Abstract

In this paper an effort has been made to simulate the monsoon Low Pressure System (LPS) and its associated rainfall event of 16-20 August, 2013 using Weather Research and Forecasting (WRF) model. The model was run for 24-h, 48-h and 72-h in a single domain of 10 km horizontal resolution using The National Centre for Environmental Prediction (NCEP) high-resolution Global Final (FNL) Analysis 6-hourly data using initial and lateral boundary conditions. WRF double-moment 5 class micro physics scheme, Kain–Fritsch (new Eta) cumulus physics scheme,Yonsei University planetary boundary layer scheme, Revised MM5 surface layer physics scheme, Unified Noah LSM as land surface model, Rapid Radiative Transfer Model (RRTM) for long-wave and Dudhia scheme for short-wave scheme are used for the simulation. The performance of the model is evaluated analyzing Mean Sea Level Pressure (MSLP), Wind Pattern, Vorticity, Vertical Wind Shear and Rainfall Distribution. The model successfully captured the low pressure system, initial condition, propagation, landfall time and location reasonably well. The model simulated rainfall amount and associated areas sensibly well compared with the observed data by BMD and Tropical Rainfall Measuring Mission (TRMM).

Keywords: Monsoon,LPS, WRF Model, Rainfall.

I. Introduction

Bangladesh is a country situated in the northeastern part of South Asia within 88.01–92.41°E and 20.57–26.64°N. The area isabout 147,610 sq. km. The land of Bangladesh is very flat: Elevation is about 1–37 m above sea level except small portions in the southeast (elevation about 200 m) which is bordered with Myanmar and in the northeast (elevation about 100 m) which is bordered with Shilling hill of India. Due to this geographical position, Bangladesh experiences the highest amount of monsoon rainfall among SAARC region. The monsoon climate is traditionally characterized by large amount of seasonal rainfall and reversal of wind direction[1]. Most importantly this rainfall is the major source of water to various human activities such as agriculture, hydropower and drinking water. Various weather systems such as tropical disturbances, thunderstorms contribute to monsoon rainfall[2]. Among these systems, the most efficient rain-producing system is known as the Monsoon Depression (MD).

Heavy Rainfall Events (HREs) are known to occur during the southwest monsoon season over the Indian subcontinent as well as in Bangladesh. These HREs are different from the heavy rainfall associated with tropical cyclonic systems. Rainfall in our country varies greatly in space and time. Maximum rainfall occurs in the monsoon period extending from the month of June to September. Due to high temperature of summer, the moisture-laden south–west monsoon originates from the vast expanse of the Bay of Bengal. By June, this monsoon wind moves all over Bangladesh and precipitates heavily.

The prediction of these HREs is subjected to the limitations of synoptic forecasting methods, which only indicate probable occurrence of heavy rainfall but not the quantity. Although numerical models provide quantitative prediction of rainfall, they are subjected to the limitations of initial data, model dynamics and physics.

There are lots of research has been done in previous years based on numerical prediction model. All these literature reflects the simulation of rainfall estimation, characteristics, probabilities, forecasting. A previous study by Mooley[3] estimated that MDs could contribute about 11–16% of total summer monsoon rainfall using data from six stations (Calcutta, Allahabad, Delhi, Goplur, Nagpur, and Ahmadabad).Gamal[4] observed the heavy rainfall simulation over Sinai Peninsula using WRF model. Das[5] studied skills of different mesoscale models over Indian region during monsoon season. Song[6] studied the assessment of the WRF model in reproducing a flash-flood heavy rainfall event over Korea.Mallik[7] analyzed the simulation of a very heavy rainfall event of 17 June, 2011 over Bangladesh due to monsoon deep depression by using WRF model. Srinivas[8] investigated the simulation of the Indian Summer Monsoon regional climate using advanced research WRF model. Sukrit[9] studied the mesoscale simulation of a very heavy rainfall event over Mumbai, using the WRF model.

For case study, heavy rainfall event of 16-20 August, 2013 have been selected. The model performance was evaluated by examining the different predicted parameters like mean sea level pressure, lower and upper level wind patterns, vertical profile of relative humidity, vertical wind shear of the u-component of wind, upper level vorticity, rainfall etc.

II. Data and Methodology

The Weather Research and Forecasting (WRF) model, a Numerical Weather Prediction (NWP) system, is designed for both atmospheric research and operational forecasting needs. The model serves a wide range of meteorological applications across scales from tens of meters to thousands of kilometers[10]. ARW (version 3.8.0) developed by the National Center for Atmospheric Research (NCAR)[11] is implemented during this study. Global Final Analysis (FNL) data have been used as input to the WRF model.WRF model

[*] Author for correspondence. e-mail: samad@du.ac.bd

was set up by Bangladesh Meteorological Department (BMD) and all the technical supports were also provided by BMD.In this study, The National Centre for Environmental Prediction (NCEP) high-resolution Global Final Analysis (FNL) data on 1.0°×1.0° grids covering the entire globe every 6-h were taken as the initial and lateral boundary conditions. The observed rainfall data of BMD were used to compare the model predicted rainfall. The Tropical Rainfall Measuring Mission (TRMM) daily rainfall data were also used to further compare with the model derived rainfall amounts at different stations. The model domain (18° N to 28.5° N and 84° E to 96° E) of this study is shown in Fig. 1. The center of the domain wastaken to be 23.5° N & 90° E. The details of the

model configuration is given in Table 1.

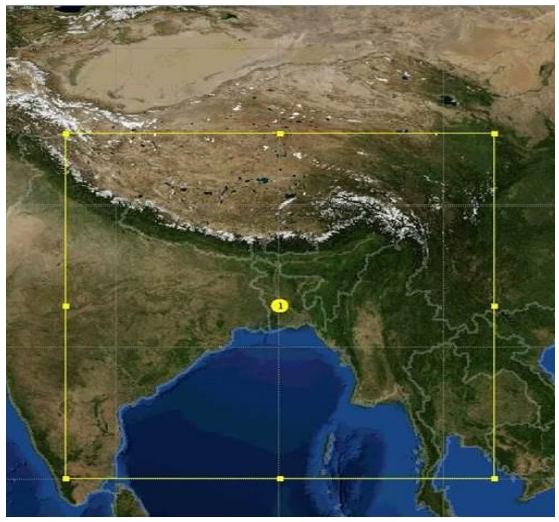


Fig.1. Domain considered for this case study.

Table 1. Overview of WRF model configurations.

Model Dynamics	
WRF core	ARW
Data	NCEP-FNL
Input Data Interval	6-h
Output Data Interval	3-h
Number of Domain	1
Central point of the domain	23.5° N, 90° E
Horizontal grid distance	10 km
Integration time step	50s
Grid Points	167× 223 × 38 (total 1415158 grid points at each time step)
Covered area	18°– 28.5° N and 84°– 98° E
Map projection	Mercator
Vertical Coordinate	Pressure Coordinate
Time integration scheme	3^{rd} order Runge-Kutta
Spatial differencing Scheme	6^{th} order centered differencing
Model Physics	
Microphysics	WDM-5 class scheme
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

III. Governing Equations

The ARW dynamics solver integrates the compressible, non-hydrostatic Euler equations. The equations are cast in flux form using variables that have conservation properties, following the philosophy of Ooyama[12] and formulated using a terrain-following mass vertical coordinate[13]. Then they are extended to include the effects of moisture, Coriolis and curvature terms and further augmented to include projections to the sphere. Finally, before constructing the discrete solver, the governing equations are recast to perturbation form using perturbation variables to reduce truncation errors in the horizontal pressure gradient calculations and machine rounding errors in the vertical pressure gradient and buoyancy calculations.

The basic forms of the atmospheric governing equations are as follows:

$$\frac{d\boldsymbol{V}}{dt} = -\frac{1}{\rho}\boldsymbol{\nabla}p + \boldsymbol{g} + \boldsymbol{F} - 2\boldsymbol{\Omega}\times\boldsymbol{U} \tag{1}$$

$$\frac{\partial\rho}{\partial t} = -\boldsymbol{\nabla}\cdot(\rho\boldsymbol{U}) \tag{2}$$

$$p = \rho RT \tag{3}$$

$$c_p\frac{d\ln T}{dt} - R\frac{d\ln p}{dt} = \frac{J}{T} = \frac{ds}{dt} \tag{4}$$

$$\frac{dq}{dt} = E - C \tag{5}$$

Equation (1) is the vectorial form of the momentum equation that states Newton's second law for motion relative to a rotating coordinate frame. Here, $\boldsymbol{V} = (u, v, w)$ is the velocity vector relative to the rotating frame, ρ is the density, p denotes pressure, $\boldsymbol{g}$ is the acceleration due to gravity, $\boldsymbol{F}$ represents the frictional force and centrifugal force combinedly and $\boldsymbol{\Omega}$ is the angular velocity of the rotating frame. This equation states that the acceleration following the relative motion in the rotating frame equals the sum of the Coriolis force, the pressure gradient force, gravity, frictional and centrifugal force. In case of spherical coordinate system, equation (1) leads to the following three component equations:

$$\frac{du}{dt} - \frac{uv\tan\phi}{a} + \frac{uw}{a} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + 2\Omega v\sin\phi - 2\Omega w\cos\phi + F_x \tag{6}$$

$$\frac{dv}{dt} + \frac{u^2\tan\phi}{a} + \frac{vw}{a} = -\frac{1}{\rho}\frac{\partial p}{\partial y} - 2\Omega u\sin\phi + F_y \tag{7}$$

$$\frac{dw}{dt} - \frac{u^2+v^2}{a} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g + 2\Omega u\cos\phi + F_z \tag{8}$$

In these equations, a is the mean radius of Earth while ϕ denotes the latitude. Equations (6), (7) and (8) are respectively the eastward, northward and vertical component of momentum equation(1).Equation (2) is the continuity equation which expresses the conservation of mass. It states that the local rate of change of density is equal to minus the mass divergence.Equation (3) is called the equation of state (or ideal gas law) for dry air. In this equation, T denotes the temperature while R is the gas constant whose value for dry air is 287 J kg^{-1} K^{-1}.In equation(4), c_p is the specific heat at constant pressure, s designates entropy and J is the rate of heating per unit mass due to radiation, conduction and latent heat release. This equation is a modified form of the thermodynamic energy equation (TDE):

$$c_v\frac{dT}{dt} + p\frac{d\alpha}{dt} = J \tag{9}$$

Here c_v is the specific heat at constant volume and $\alpha = \frac{1}{\rho}$ is the specific volume (or 'inverse density'). The TDE (9) states that change in internal (thermal) energy of dry air ($c_v\frac{dT}{dt}$) plus the rate of work ($p\frac{d\alpha}{dt}$) done by the fluid system (per unit mass) on its environment by thermal processes (due to vertical motion and the consequent expansion or contraction of a parcel; for example, a rising parcel expands and does work on its environment, so it cools) equals the rate of heating (J). The modified form of equation (9) indicates that vertical motion in the atmosphere changes the thermodynamic state in a reversible way. A parcel moving vertically will change temperature due to compression or expansion with pressure change, but when returned to its original level, it will have done no work on its environment. If $J = 0$, then its temperature will return to the original temperature.Equation (5) is the simplified form of the conservation of moisture. It states that the rate of change of moisture following the motion of an air parcel ($\frac{dq}{dt}$) is equal to the difference between evaporation (E) and condensation (C).

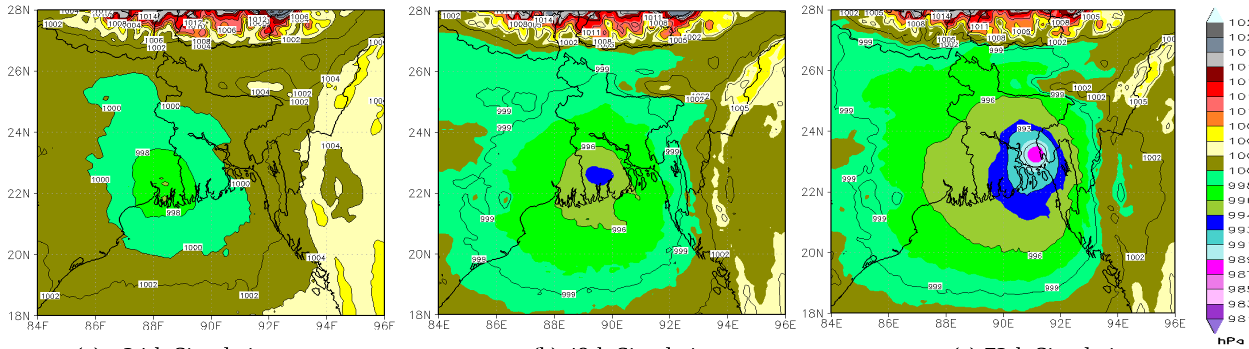
IV. Results and Discussions

The results and discussion of the study are outlined in the following sections.

Analysis of MSLP

The model simulated MSLP at 850 hPa level valid for 0300 UTC of 19 August, 2013 of model simulation for 24-h, 48-h and 72-h based on the initial conditions 0000 UTC of 19 August, 18 August and 17 August respectively are shown in Fig.2. (a-c).

The central pressure of the depression at 0300 UTC of 19 August, 2013 for 24-h, 48-h and 72-h advanced are about 998, 996 and 993 hPa respectively. The model simulated center of the system at the time of landfall is about lat. 22.5° N and long. 88.5° E. The lowest value of central pressure of the depression is about 993 hPa at 0300 UTC of 19 August, 2013for 72-h advanced. The model simulated isobar over the North Bay of Bengal have almost south to north orientation. The mean sea level pressure over Tibet is very high and its central pressure varies from 1002 hPa to above 1011 hPa at 0300 UTC of 19 August, 2013. The depression remains stationary over southwestern part of Bangladesh and adjoining area 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 intense high pressure prevailing over northeast India and southern part of Myanmar region respectively.

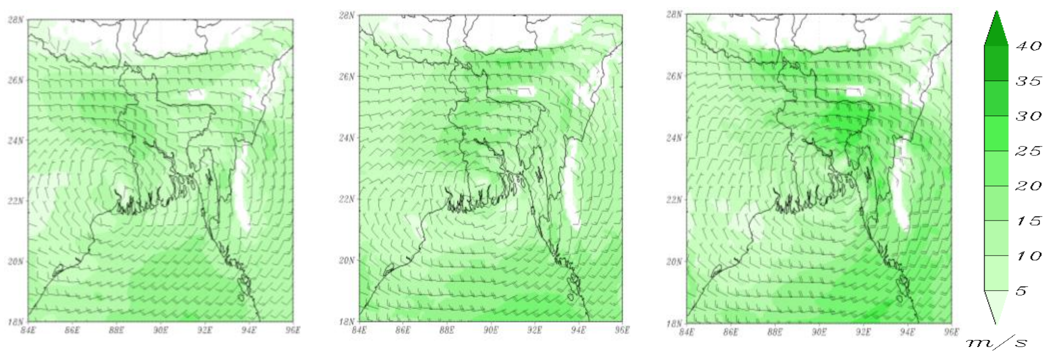


(a) 24-h Simulation (b) 48-h Simulation (c) 72-h Simulation

Fig. 2. (a-c): Model simulated MSLP at 850 hPa level valid for 0300 UTC of 19 August, 2013 for 24-h, 48-h and 72-h respectively.

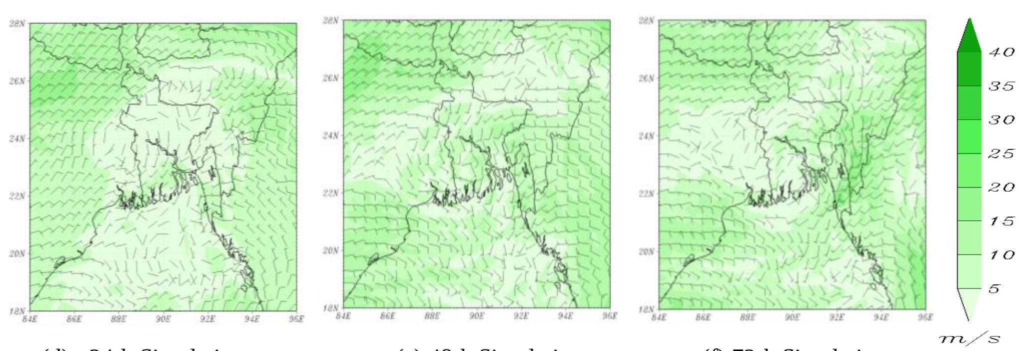
Analysis of Wind Pattern at 850 & 200 hPa level

The model simulated Wind Patterns at 850 & 200 hPa levels (unit: ms^{-1}) valid for 0300 UTC of 19 August, 2013 of model simulation for 24-h, 48-h and 72-h based on the initial conditions 0000 UTC of 19 August, 18 August and 17 August respectively are shown in Fig.3.(a-c) & Fig.4.(d-f) respectively. At 850 hPa level, convergence zone is formed where at higher level of atmosphere (200 hPa) the circulation pattern is not well-organized. Actually a divergence zone is found at that level. This model simulated wind speed is favorable for the intensification of monsoon depression over south-eastern part of Bangladesh and adjoining areas. A narrow belt of maximum wind (30-35) ms^{-1}, is found southeast sector of the system which carries high amount of relative humidity from the Bay of Bengal and it is very much supportive for the formation of high impact rainfall. The area of convergence (i.e., zone of high convective activity) observed over Kutubdia, Sandwip, Hatiya, Teknaf, Bhola and neighborhood i.e., southeastern sector of the depression.



(a) 24-h Simulation (b) 48-h Simulation (c) 72-h Simulation

Fig. 3. (a-c): Model simulated Wind Pattern at 850 hPa level valid for 0300 UTC of 19 August, 2013 for 24-h, 48-h and 72-h respectively.



(d) 24-h Simulation (e) 48-h Simulation (f) 72-h Simulation

Fig. 4. (d-f): Model simulated Wind Pattern at 850 hPa level valid for 0300 UTC of 19 August, 2013 for 24-h, 48-h and 72-h respectively.

Analysis of lower level Vorticity (850 hPa level)

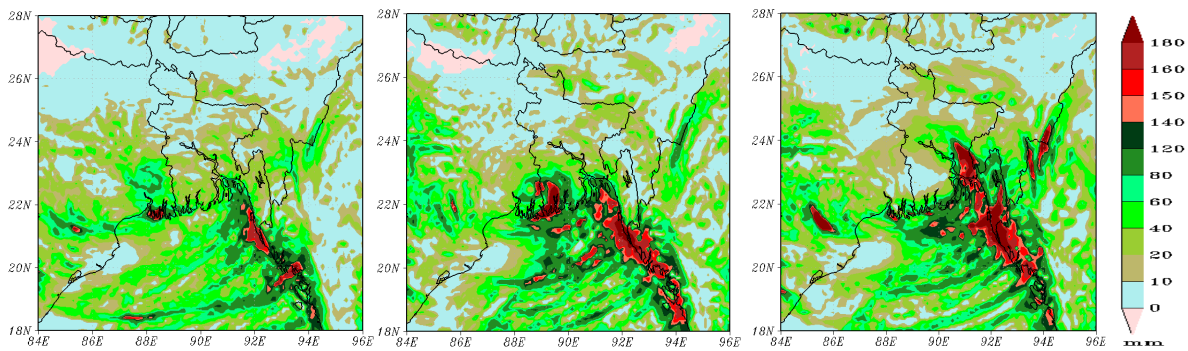
Vorticity is a measure of the spin of air parcels. Meteorologists are mostly concerned with the spin of horizontally flowing air about a vertical axis. So, the term 'vorticity' usually refers to the vertical component of the curl of the wind. From the analysis of lower level (850 hPa) vorticity, it has 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 rainfall in these associated areas.

Analysis of Vertical Wind Shear

Vertical wind shear is the difference, at the same geographical coordinates, but at different altitudes, in the direction or strength of winds.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 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. These values of wind shear help to develop monsoon depression and heavy to very heavy rainfall over these regions of Bangladesh.

Analysis of Rainfall Distribution

The model simulated 24-h rainfall distribution valid for 19 August, 2013 of model simulation for 24-h, 48-h and 72-h based on the initial conditions 0000 UTC of 19 August, 18 August and 17 August respectively are presented in Fig.5.(a-c)



(a) 24-h Simulation (b) 48-h Simulation (c) 72-h Simulation

Fig. 5. (a-c): Model simulated 24-h rainfall of 19 August, 2013 for 24-h, 48-h and 72-h simulation respectively.

Table 2. Comparison between WRF simulated and BMD observed rainfall of 19 August, 2013.

Position	WRF Rainfall (mm)	BMD Rainfall (mm)
Hatiya	78.06	62
Cox's Bazar	88.40	71
Kutubdia	77.54	66
Teknaf	90.67	86
Sandwip	82	14

The model simulated rainfall indicates high values over Hatiya, Cox's Bazar, Kutubdia, Teknaf and Sandwip than the observations produced by BMD rain gauges. The observed data by BMD shows good rainfall over the belt of southern and southeastern part of Bangladesh, but the rest part of the country has low rainfall. It is found that model simulated and BMD observed rainfall over the country overestimates the rainfall compared to that of TRMM observed rainfall, where TRMM shows comparatively low amount of rainfall. It is to mention in this regard that the network of rain-gauge stations of Bangladesh is not dense enough to capture the realistic picture of mesoscale processes unless one or more stations are located on the passage of convective systems. However, the WRF model overestimated the rainfall amount than the observed values of BMD. The model simulated rainfall has been compared with the Tropical Rainfall Measuring Mission (TRMM) and Bangladesh Meteorological Department (BMD) rain gauges observed rainfall which are shown in Fig. 6.

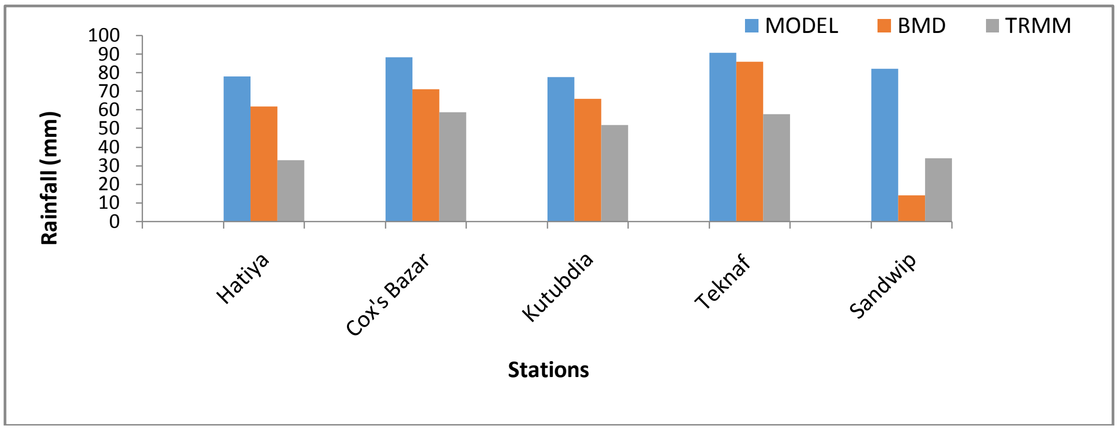


Fig. 6. Comparison of observed rainfall amounts among model, TRMM and BMD at different stations.

V. Conclusion

From the analysis we reach the following conclusions:

(1) From the WRF model observation, this very heavy rainfall event over Hatiya, Cox's Bazar, Kutubdia, Teknaf and Sandwip might be the results of interaction of monsoon land depression with the active phase of large scale southwest summer monsoon weather systems.

(2) The model simulated the center of depression over the southwestern part (22.5^{0}N, 88.5^{0}E) of Bangladesh having lowest surface pressure at 993 hPa reasonably well. The depression remains stationary over the same areas of Bangladesh for longer time and do not move further north due to the existence of intense high pressure area over Tibetan plateau and further northeast due to very high pressure over Myanmar and adjoining northeast Bay of Bengal.

(3) The convergence of strong southwesterly flow transports high amount of moisture from the vast area of the Bay of Bengal towards the narrow belt of eastern and southeastern part of Bangladesh and neighborhoods. The vertical profile of humidity along 22.50^{0}N shows that the humidity extended up to 200 hPa level which enhances the convective activity.

(4) The areas having heavy to very heavy rainfall wereHatiya, Cox's Bazar, Kutubdia, Teknaf, Sandwip and neighborhoods characterized by the positive vorticity, strong vertical wind shear, high amount of relative humidity were very favorable for the formation of land depression and these parameters are very much supportive for moist air updrafts.

Finally, we can conclude that the Mesoscale Model WRF (version 3.8) is able to simulate the very heavy rainfall event due to land depression over Hatiya, Cox's Bazar, Kutubdia, Teknaf, Sandwip and neighborhoods, and associated dynamical and thermo-dynamical features reasonably well.

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