Simulation of Pre-monsoon Thunderstorm and its Thermodynamic Features over Bangladesh Using Weather Research and Forecasting Model

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Abstract

An attempt has been made to simulate the thunderstorm events of 15 May 2017 and its thermodynamic features using the WRF-ARW model in a single domain of 9 km horizontal resolution and 48 hours advance run was done using GFS dataset. The model performance was done by analyzing different meteorological parameters, for example, mean sea level pressure (MSLP), wind pattern at various pressure levels, two-meter height temperature, relative humidity (RH), vorticity, vertical wind shear, and convective available potential energy (CAPE) etc. For the validation of model-simulated different weather parameters have also been compared with the 3 hourly observed values of BMD. It is found that the model simulated result is good enough to predict thunderstorm events over Bangladesh particularly, Barisal, Khulna, Rajshahi, Bhola and Ishurdi. precisely well.

Keywords: Thunderstorm, WRF-ARW Model, Relative Humidity, MSLP and CAPE

1. Introduction

Nor'westers, locally known as 'Kalbaishakhi', are severe thunderstorms that form in the eastern and northwestern parts of Bangladesh and move from Northwest to Southeast direction during the pre-monsoon season (March to May). The Nor'westers produce heavy rainfall, lightning, showers, thunder, hail-storms, dust-storms, surface wind squalls, down-bursts and tornadoes. The nor'westers cause loss of human lives and damage to properties worth millions of dollars [1] through strong surface wind, squalls, large hail, lightening and occasional tornadoes accompanying them. Thunderstorms constitute a family of severe local storms, which comprises events such as tornadoes, hailstones, strong surface wind speed (gust) and squally winds and flash floods [2], which may also include wind shear and turbulence. These storms develop mainly due to merging of mid-tropospheric cold dry northwesterly winds and low level southerly warm moist winds from the Bay of Bengal. As the lifetime of these severe storms is only of few hours, prediction of these storms is a challenging task using any conventional forecasting technique.

Several studies have been performed for pre-monsoon thunderstorms over the Indian region (Mukhopadhyay, et al. 2009, Latha, R. & Murthy, B.S., 2011, Tyagi et al. 2011). Peterson and Dewan (2002) showed that TS (Thunderstorm) over the Indo-Bangla region are most common in the afternoon and overnight. Litta et al., [3] performed a simulation of a severe thunderstorm event using the WRF NMM model. Hu et al., [4] examined the sensitivity of the performance of the Weather Research and Forecast (WRF) model to the use of three different PBL schemes [MellorYamada-Janjic (MYJ), Yonsei University (YSU), and the asymmetric convective model, version 2 (ACM2)]. They found WRF simulations with different schemes over Texas in July-September 2005 shows that the simulations with the YSU and ACM 2 schemes give much less bias than with the MYJ scheme. Das et al., [5] conduct a coordinated field experiment on severe thunderstorm observations and regional modeling over the South Asian Region. Rahman et al., [6] examined the simulation of thermodynamic features of a thunderstorm event over Dhaka using the WRF-ARW model. Thunderstorm forecasting is very difficult task with accurate time and positions. The main objective of this research is to develop real time weather forecasting of TS events which can help the public sector and the people to reduce and minimize the repetitive losses of their properties and lives.

2. Model Setup and Methodology

In this study, the ARW dynamics solver of WRF version 3.9 has been used as the principal modeling tool. WRF model was set up by Bangladesh Meteorological Department (BMD) and all the technical support was also provided by BMD. The model was configured on a single domain with 10 km horizontal grid spacing. The domain has 167 and 223 grid points in the west-east and north-south directions respectively. The domain was configured to have the same vertical structure of 38 unequally spaced sigma (non-dimensional pressure) levels. The center (23.5°N, 90°E) of the domain was taken over Bangladesh. The physical parameterization schemes used in this study are Kessler scheme for microphysics, Kain-Fritsch (new Eta) scheme for cumulus parameterization, Yonsei

University scheme (YSU) for planetary boundary layer. Data at 0000 UTC 14 May 2017 were used as initial conditions. The model performance was evaluated by examining the different predicted parameters like mean sea level pressure, lower and upper level wind patterns, horizontal, temperature, vertical profile of relative humidity, vertical wind shear of the u-component of wind, lower and upper level relative vorticity, rainfall etc. Before describing the visualization tools, an overview of the configurations for the WRF model used in this study is given in Table 1.

Table 1: WRF model and domain configurations

Domain & Dynamics	
WRF core	ARW
Data	NCEP-FNL
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	50 s
Number of grid points	X-direction 167 points, Y-direction 223 points
Covered area	18°– 28.5°N and 84°– 98°E
Map projection	Mercator
Vertical Coordinate	Pressure coordinate
Time integration scheme	3rd order Runge-Kutta
Spatial differencing scheme	6th order centered differencing
Physics	
Microphysics	Kessler 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

3. Result and Discussion

A remarkable number of meteorological parameters, such as mean sea level pressure, temperature, relative humidity, wind pattern, amount of rainfall etc. play an important role in the formation and development of thunderstorms. The behavior of these parameters during thunderstorm events on 15 May 2017 over Bangladesh are discussed below:

3.1 Mean Sea Level Pressure (MSLP)

One of the most important ingredients for the formation of thunderstorms in the development of the low-pressure area. So the analysis of MSLP is very important for the simulation of any thunderstorm events. Model-simulated MSLP of 15 May 2017 from 1700 UTC to 2100 UTC at ½ hour interval based on the initial condition 0000 UTC of 14 May 2017 are shown in Fig. 1. It is found that an active elongated trough of low pressure over the Gangetic plains of India which intrude towards Bangladesh through the middle of the country. The lowest surface pressure in the center of the trough is below 1001 hPa which is very low during this season. The formation of a low-pressure area over the Gangetic plains and intrude towards Bangladesh is the very common characteristics for the development of convective activities over the country. The lowest pressure of magnitude of 1001 hPa is found in the West Bengal and adjoining area. So, the model simulates the westerly trough very well which is the supportive condition for the formation of thunderstorms. thunderstorm events. Model-simulated MSLP of 15 May 2017 from 1700 UTC to 2100 UTC at ½ hour interval based on the initial condition 0000 UTC of 14 May 2017 are shown in Fig. 1. It is found that an active elongated trough of low pressure over the Gangetic plains of India which intrude towards Bangladesh through the middle of the country. The lowest surface pressure in the center of the trough is below 1001 hPa which is very low during this season. The formation of a low-pressure area over the Gangetic plains and intrude towards Bangladesh is the very common characteristics for the development of convective activities over the country. The lowest pressure of magnitude of 1001 hPa is found in the West Bengal and adjoining area. So, the model simulates the westerly trough very well which is the supportive condition for the formation of thunderstorms.

For the validation of model-simulated MSLP, a comparison is made with three hourly observed MSLP recorded by BMD over Barisal, Khulna, Rajshahi, Bhola and Ishurdi on 15 May 2017. This comparison is shown in Fig. 2(a-e). From the simulation result, a sharp fall of MSLP from 1002.67 hPa to 1000.62 hPa, 1001.54 hPa to 1000.10

hPa, and 1002.48 hPa to 998.94 hPa are found over Barisal, Khulna and Rajshahi, respectively on 15 May 2017 between 0600 UTC and 1200 UTC. Likewise, it is found that observed data shows a drop of MSLP between 1004 hPa and 1001 hPa, 1003.30 hPa and 1000.10 hPa and 1003.00 hPa and 999.20 hPa over Barisal, Khulna, and Rajshahi, respectively during the same period. Moreover, the fluctuation of MSLP over Bhola is not perfect, however, Ishurdi experienced the least variation between model data and observation data throughout the time. So, it can be concluded that model captures the sharp decrease of MSLP very well that confirm the validity of our model.

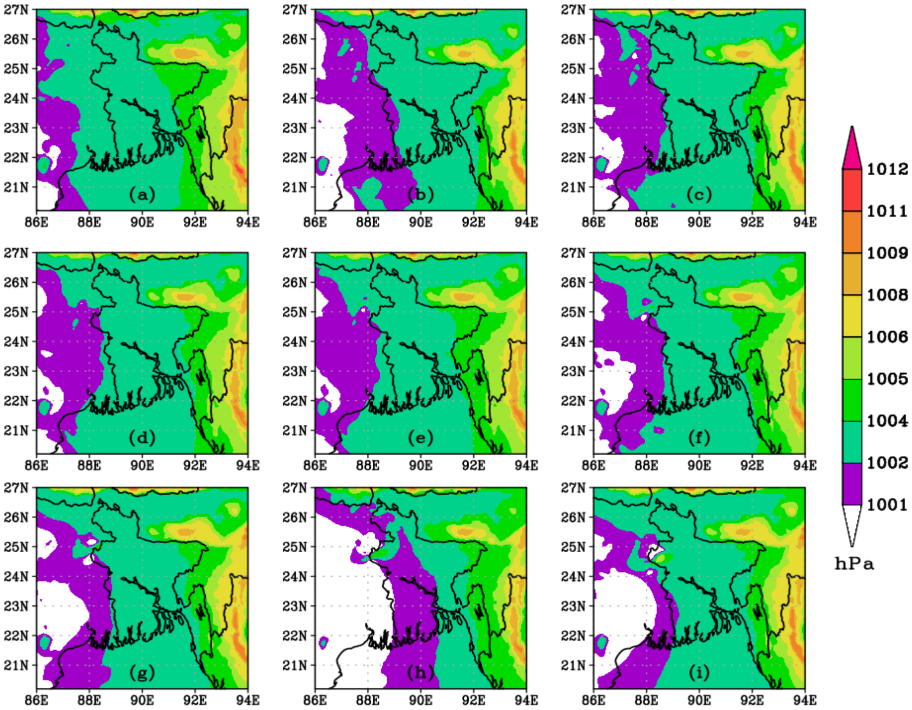

Fig. 1: ARW model simulated MSLP using GFS data at (a) 1700 UTC (b) 1730 UTC (c) 1800 UTC (d) 1830 UTC (e) 1900 UTC (f) 1930 UTC (g) 2000 UTC (h) 2030 UTC and (i) 2100 UTC on 15 May 2017 based on 0000 UTC 14 May 2017 initial conditions.

3.2 Wind Pattern at different pressure level

Wind direction and wind speed play a vital role in the development of thunderstorms. Conjugation of wind from two different directions forces the air to rise which is the basic ingredient for the formation of thunderstorms. During thunderstorms, a strong wind blows over the event area which sometimes becomes vigorous and devastating. In this section, the ability of the WRF-ARW model to simulate the wind speed and direction is described over Bangladesh at different pressure level.

3.2.1 Wind Pattern at 850 hPa Level

The spatial distribution of wind pattern at 850 hPa level valid from 1700 UTC to 2100 UTC on 15 May 2017 is presented in Fig. 3. The southerly wind is blowing through Bangladesh. The convergence zone is seen in the northwest part of the country with high speed more than 16 m/s and both divergence and convergence zones are also been seen in the Bay of Bengal. The wind speed is 6-10 m/s over Barisal and 4-10 m/s over Khulna for that period. Moreover, Rajshahi always maintains southerly wind with speed >10 m/s. So, it can be said that the model has simulated the wind speed at 850 hPa level very well based on 0000 UTC 14 May 2017 initial conditions (shown in Fig. 3).

3.2.2 Wind Patten at 500 hPa Level

From the analysis of model-simulated wind speed and direction at 500 hPa level, it is found that a westerly wind is blowing towards Bangladesh from 1700 UTC to 2100 UTC on 15 May 2017. This wind is cool and dry. When the 850 hPa level's wind which carries moisture, conjugates with this dry air, it is also the pre-condition for the formation of thunderstorms. So, we can say, the model simulates the wind speed at 500 hPa level very well based on 0000 UTC 14 May 2017 initial conditions (shown in Fig. 4).

3.2.3 Wind Pattern at 200 hPa Level

From the analysis of model-simulated wind speed and direction at 200 hPa level, it is found that a northwesterly wind is blowing from 1700 UTC to 2100 UTC on 15 May 2017 (Fig. 5) where wind speed is comparatively high as compared with levels 850 hPa and 500 hPa. This high wind speed breaks the top of the cloud. It is also an essential pre-condition of approaching of thunderstorm s and the model simulates the wind speed very well based on 0000 UTC 14 May 2017 initial conditions.

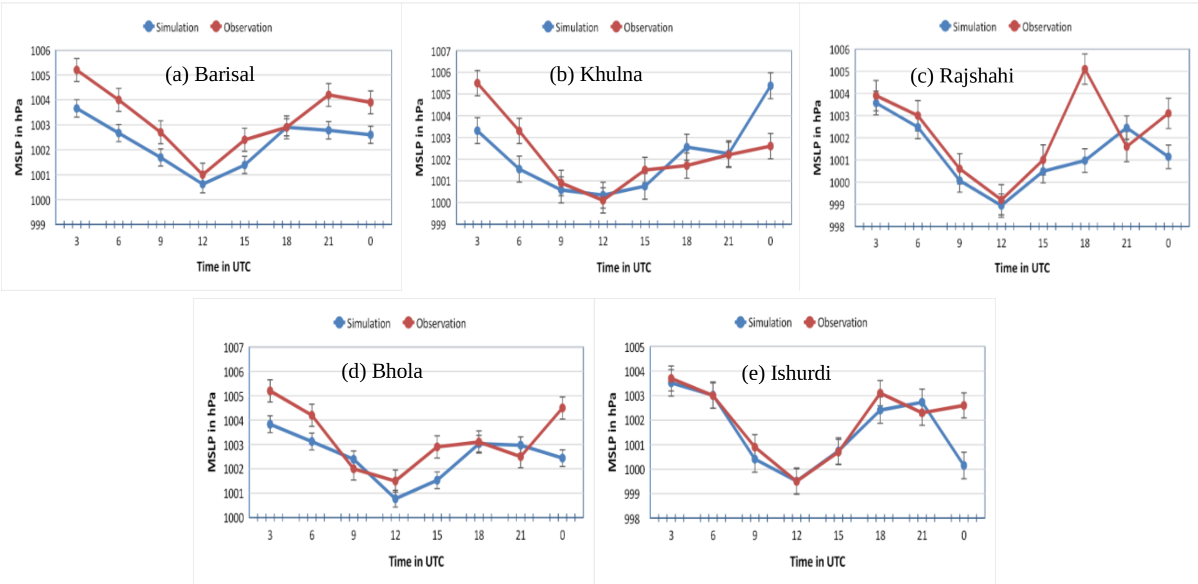

Fig. 2: Comparison of MSLP between model-simulation and observation over **(a)** Barisal **(b)** Khulna **(c)** Rajshahi **(d)** Bhola and **(e)** Ishurdi on 15 May 2017.

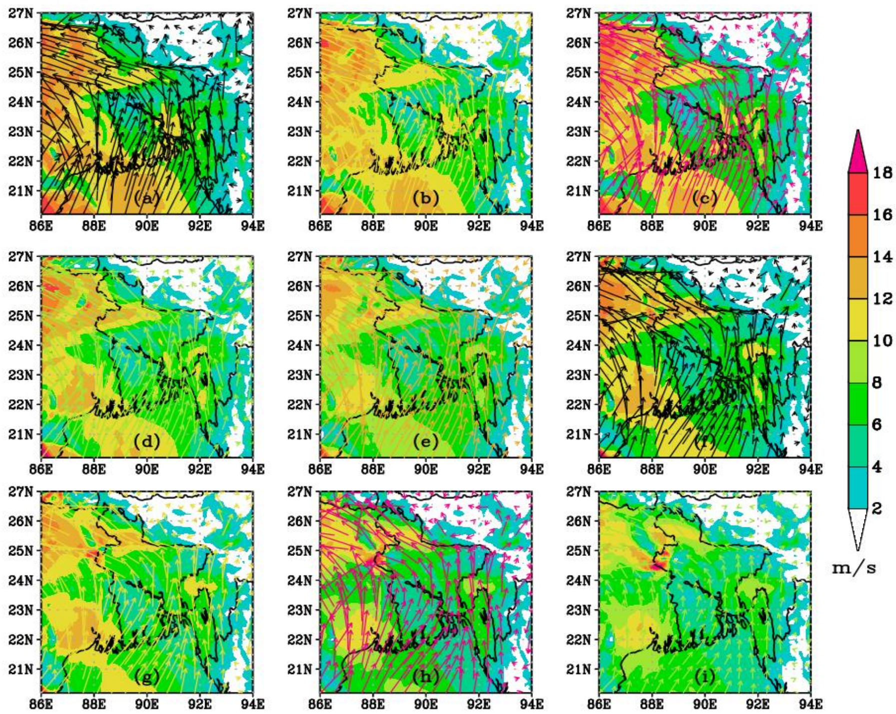

Fig. 3: ARW model simulated wind speed and direction at 850 hPa level using GFS data at (a) 1700 UTC (b) 1730 UTC (c) 1800 UTC (d) 1830 UTC (e) 1900 UTC (f) 1930 UTC (g) 2000 UTC (h) 2030 UTC and (i) 2100 UTC on 15 May 2017 based on 0000 UTC 14 May 2017 initial conditions.

3.3 Temperature at 2-m Height

From the analysis of model-simulated temperature at 2-meter height, it is found that the western part of Bangladesh and adjoining Indian regions, as well as the Bay of Bengal, have a higher magnitude of temperature which is more than 30°C from 1700 UTC to 2100 UTC on 15 May 2017 (see Fig. 6) as compared to the Eastern part of Bangladesh and adjoining areas. Subsequently, the temperature drops to 24°C-28°C which is very much

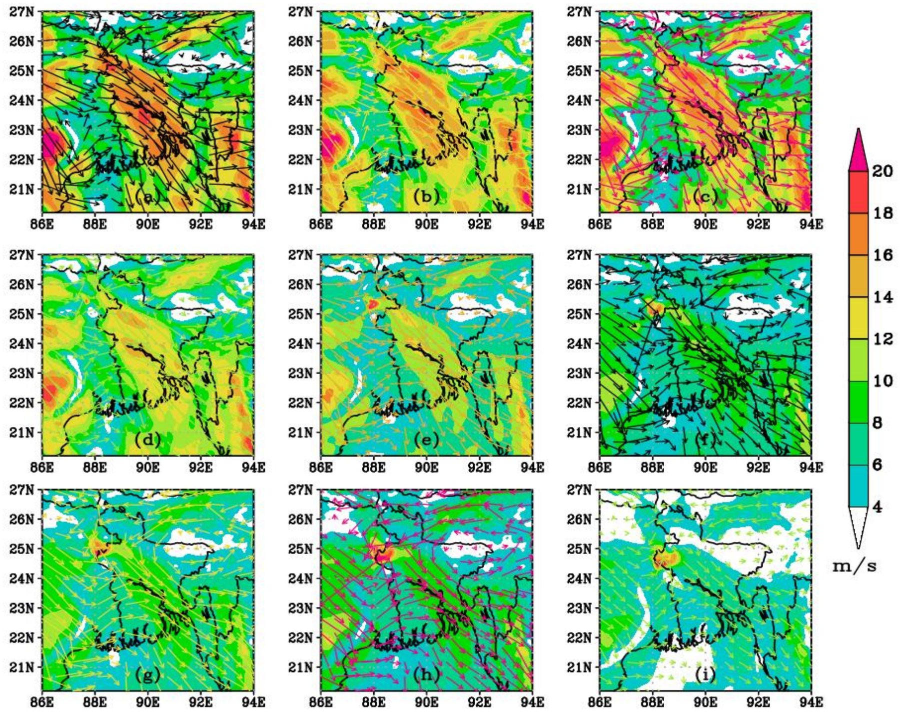

Fig. 4: ARW model simulated wind speed and direction at 500 hPa level using GFS data at (a) 1700 UTC (b) 1730 UTC (c) 1800 UTC (d) 1830 UTC (e) 1900 UTC (f) 1930 UTC (g) 2000 UTC (h) 2030 UTC and (i) 2100 UTC on 15 May 2017 based on 0000 UTC 14 May 2017 initial condition

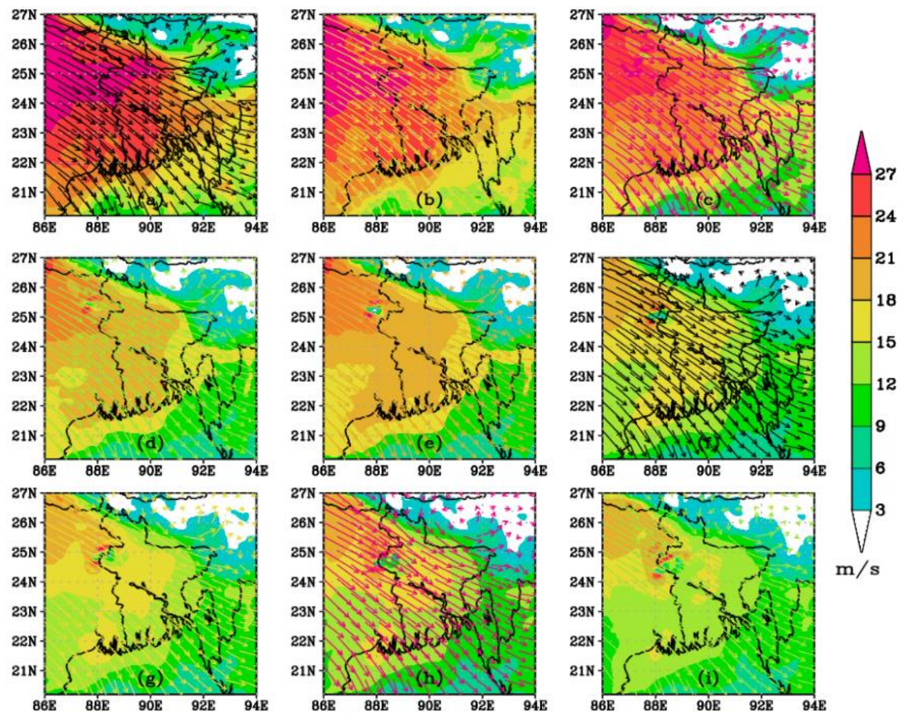

Fig. 5: ARW model simulated wind speed and direction at 200 hPa level using GFS data at (a) 1700 UTC (b) 1730 UTC (c) 1800 UTC (d) 1830 UTC (e) 1900 UTC (f) 1930 UTC (g) 2000 UTC (h) 2030 UTC and (i) 2100 UTC on 15 May 2017 based on 0000 UTC 14 May 2017 initial conditions.

supportive for occurring of convective precipitation and have been seen in the south part of Bangladesh. So, the model simulates the temperature very well based on the 0000 UTC 15 May 2017 initial conditions. To validate the model-simulated 2-meter height temperature, three hourly temperature hourly temperature recorded by BMD. This comparison over Barisal, Khulna, Rajshahi, Bhola, and Ishurdi is shown in Fig. 7(a-e). The observed temperature indicates that a sudden fall e of 15 May 2017 simulated by the WRF-ARW model using GFS data combination is compared with three between 31.10°C and 23°C, 36.60°C and 28.80°C, and 33°C and 21.90°C is found over Barisal, Khulna, and Rajshahi, respectively on 15 May 2017 during 0900 UTC to 2100 UTC. It is also found that simulated result shows a drop of temperature from 34.55°C to 27.13°C, 34.53°C to 28.23°C, and 36.29°C to 30.04°C over Barisal, Khulna, and Rajshahi, respectively during this time. Besides, Bhola experienced the least variation of temperature throughout the time but Ishurdi shows the variation at least 5°C throughout the

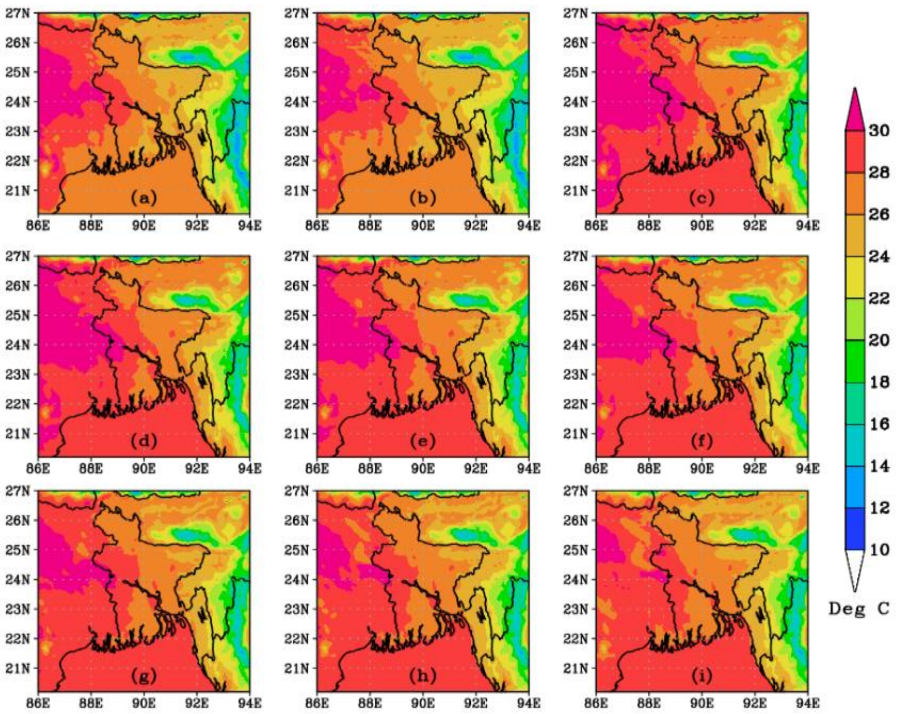

Fig. 6: ARW model simulated temperature at 2-m height using GFS data at (a) 1700 UTC (b) 1730 UTC (c) 1800 UTC (d) 1830 UTC (e) 1900 UTC (f) 1930 UTC (g) 2000 UTC (h) 2030 UTC and (i) 2100 UTC on 15 May 2017 based on 0000 UTC 14 May 2017 initial conditions.

time except for 0600 UTC. So, it can be said that the model shows a decrease in temperature, but the model captures the sharp fall of temperature very well over these five regions.

3.4 Relative Humidity (RH) at 2-m Height

RH is an important factor for the detection of cloud and rainfall. From the analysis of model-simulated relative humidity at 2-meter height, it is noticed that between 1700 UTC to 2100 UTC over Barisal, Khulna, Bhola, and their adjoining areas is more than 90% which is likely to occur thunderstorms in that areas. Moreover, RH varies from around 60% to 80% from 1800 UTC to 2100 UTC as shown in Fig. 8. Usually, thunderstorm forms at the

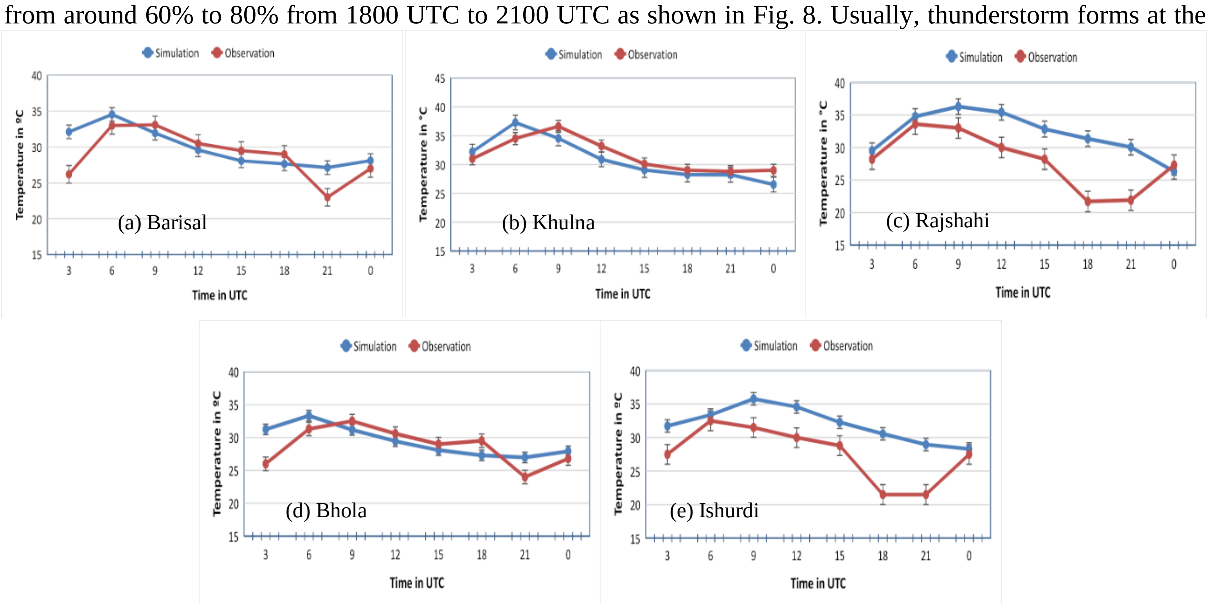

Fig. 7: Comparison of two-meter height temperature between model simulation and observation over (a) Barisal (b) Khulna (c) Rajshahi (d) Bhola and (e) Ishurdi on 15 May 2017.

higher value of RH (i.e., >60 %). So, we can say, the model has simulated the relative humidity very well based on the 0000 UTC 14 May 2017 initial conditions.

For the validation of model-simulated 2-meter height RH, three hourly RH of 15 May 2017 simulated by WRF-ARW model using GFS dataset combination is compared with three hourly RH recorded by BMD. From the observed data, a sharp rise of RH from 54% to 98% (by 44%) during 0600 UTC to 2100 UTC is found over Barisal. Observed data also show a rise of RH from 63% to 94% (by 31%) and 61% to 99% (by 38) for the same period over Khulna and Rajshahi, respectively. From the model simulation result, the increase of RH over Barisal is around 60% to 98% which is shown in Fig. 9(a). The rise of RH over Khulna is 54.40% to 94% which is shown in Fig. 9(b) and the rise of RH over Rajshahi is 56.41% to 79.27% which is shown in Fig. 9(c). More than 60% of RH value has been seen after 1500 UTC both in Bhola and Ishurdi depicted in Fig. 9(d-e). From the above analysis, it is found that the model captures the rise of RH very well. In conclusion, we can say that thunderstorms occurred after 0900 UTC because of RH value is always more than 60% in that time which is pre-condition to occur thunderstorms.

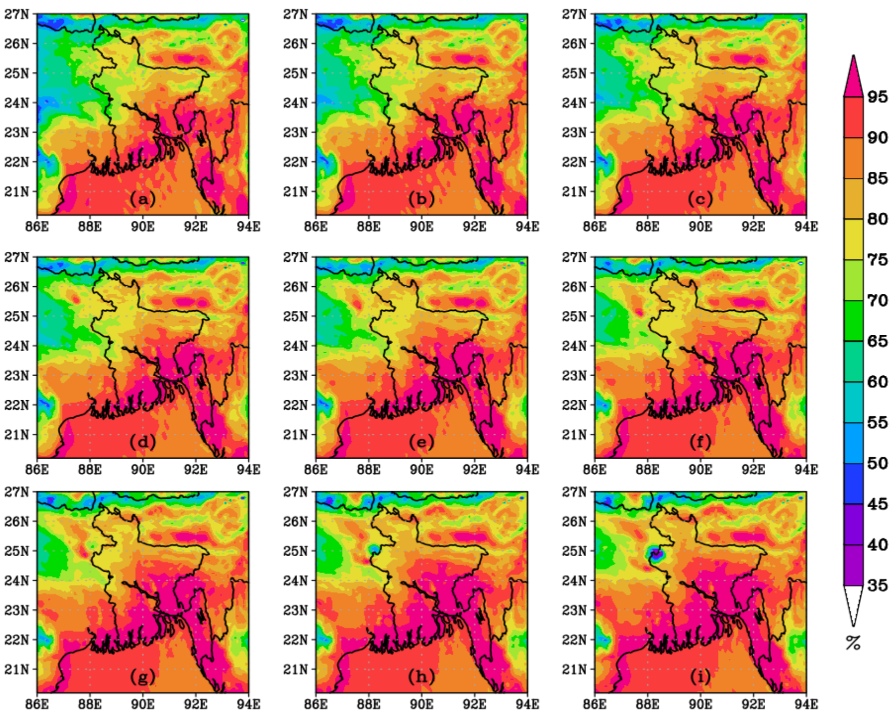

Fig. 8: ARW model simulated relative humidity at 2-m height using GFS data at (a) 1700 UTC (b) 1730 UTC (c) 1800 UTC (d) 1830 UTC (e) 1900 UTC (f) 1930 UTC (g) 2000 UTC (h) 2030 UTC and (i) 2100 UTC on 15 May 2017 based on 0000 UTC 14 May 2017 initial conditions.

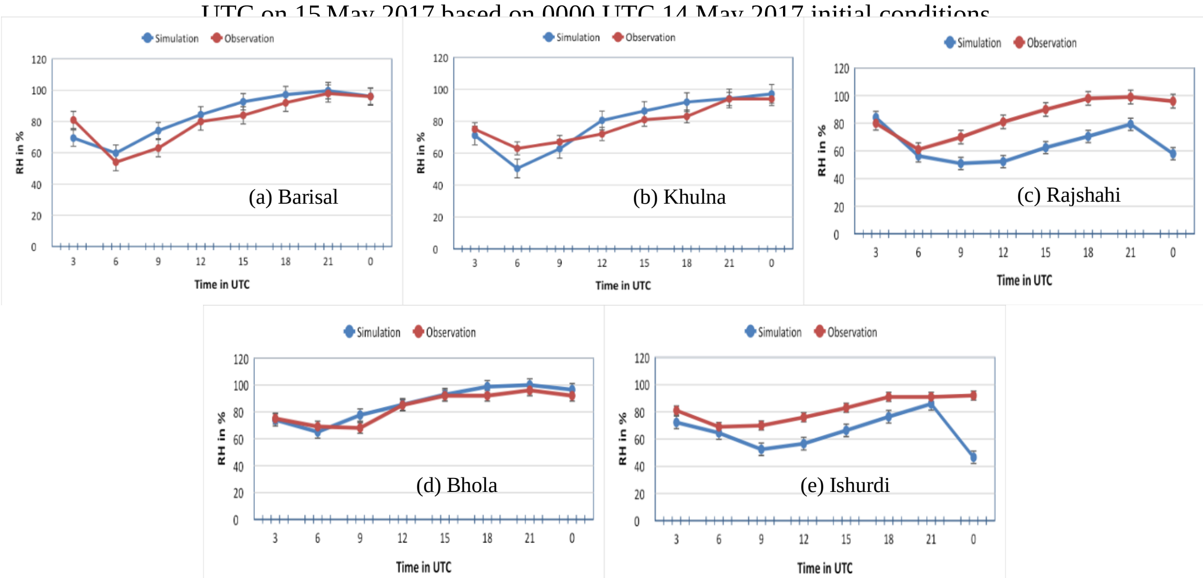

Fig. 9: Comparison of two-meter height relative humidity between model simulation and observation over (a) Barisal(b) Khulna (c) Rajshahi (d) Bhola and (e) Ishurdi on 15 May 2017.

3.5 Vorticity at different pressure 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 vertical component of the curl of the wind. In this section, the ability of the WRF-ARW model to simulate the vorticity over Bangladesh at different pressure level.

3.5.1 Vorticity at 850 hPa Level

From the analysis of model-simulated vorticity, it is found that the value of vorticity is (-20 to 20)$\times 10^{-5}\, s^{-1}$ in most of the region of Bangladesh from 1700 UTC to 2100 UTC on 15 May 2017. There are some areas in Bangladesh where the value of vorticity is (20-40)$\times 10^{-5}\, s^{-1}$ for the same period. Negative vorticity is also seen in some regions of Bangladesh at 1930 UTC. So, it is seen that the value of vorticity is positive throughout the country which is the pre-condition of formation of thunderstorms and the model simulates vorticity very well based on the 0000 UTC 15 May 2017 initial conditions (shown in Fig. 10).

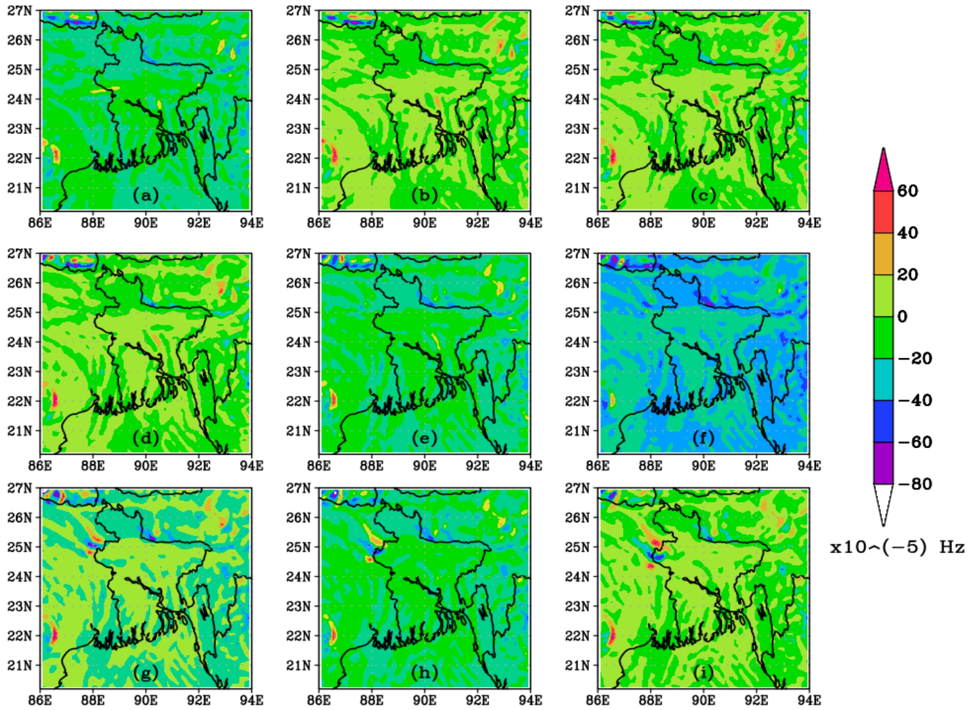

Fig. 10: ARW model simulated vorticity at 850 hPa level using GFS data at (a) 1700 UTC (b) 1730 UTC (c) 1800 UTC (d) 1830 UTC (e) 1900 UTC (f) 1930 UTC (g) 2000 UTC (h) 2030 UTC and (i) 2100 UTC on 15 May 2017 based on 0000 UTC 14 May 2017 initial conditions.

3.5.2 Vorticity at 500 Level

From the analysis of model-simulated vorticity, it is found that the value of vorticity is lower at 500 hPa level than vorticity at 850 hPa level from 1700 UTC to 2100 UTC on 15 May 2017. The northern part of the Bangladesh vorticity comprises from -60$\times 10^{-5}\, s^{-1}$ to 30$\times 10^{-5}\, s^{-1}$. A positive value indicates to occur thunderstorms. It is seen that positive vorticity with 60$\times 10^{-5}\, s^{-1}$ is approaching towards northwesterly thought-out the time (Fig. 11).

3.5.3 Vorticity at 200 hPa Level

The vorticity of most of the regions in Bangladesh is a negative value (0 to -50$\times 10^{-5}\, s^{-1}$) at 200 hPa level from 1700 UTC to 2100 UTC on 15 May 2017 although in the Barisal this value is 50×10^(-5) s^(-1) at 1900 UTC [see Fig. 12(e)] which is favourable to occur thunderstorms in this region in that time based on the 0000 UTC 14 May 2017 initial conditions.

3.6 Convective Available Potential Energy

From the analysis of model-simulated modified convective available potential energy (CAPE), it is found that the value of CAPE at most unstable layer from 1700 UTC to 2100 UTC on 15 May 2017, is greater than 2500 J/Kg

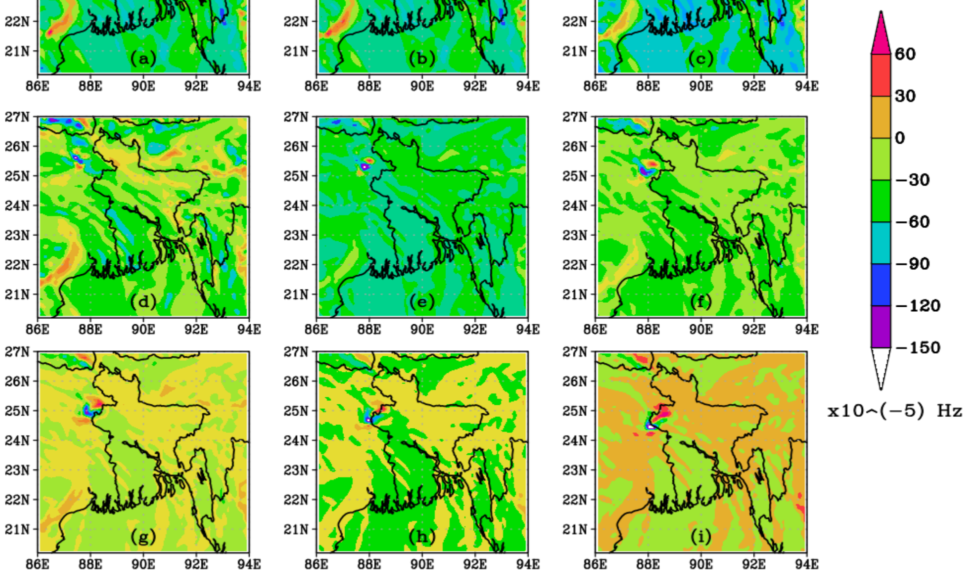

Fig. 11: ARW model simulated vorticity at 500 hPa level using GFS data at (a) 1700 UTC (b) 1730 UTC (c) 1800 UTC (d) 1830 UTC (e) 1900 UTC (f) 1930 UTC (g) 2000 UTC (h) 2030 UTC and (i) 2100 UTC on 15 May 2017 based on 0000 UTC 14 May 2017 initial conditions.

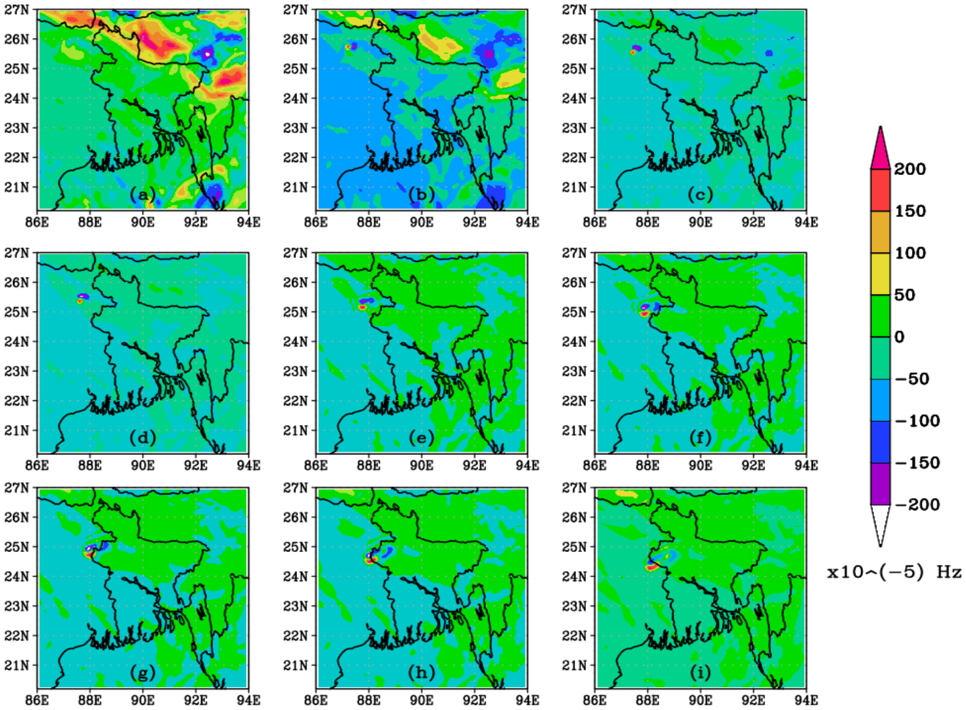

Fig. 12: ARW model simulated vorticity at 200 hPa level using GFS data at (a) 1700 UTC (b) 1730 UTC (c) 1800 UTC (d) 1830 UTC (e) 1900 UTC (f) 1930 UTC (g) 2000 UTC (h) 2030 UTC and (i) 2100 UTC on 15 May 2017 based on 0000 UTC 14 May 2017 initial conditions.

in the southwestern and northwestern parts of Bangladesh. CAPE value greater than 1500 J/Kg is required for the formation of a thunderstorm. From the model-simulated result, it is seen that in most of Bangladesh CAPE value varies from 2000 J/Kg to 4500 J/Kg. From 1700 UTC to 2000 UTC, the value of CAPE is more than 3000 J/Kg in Rajshahi. The value started to decrease for the rest of the time. So, the value of CAPE is greater than 1500 J/Kg throughout the country which is the precondition of formation of thunderstorms and the model simulates CAPE very well based on the 0000 UTC 14 May 2017 initial conditions. This is depicted in Fig. 13.

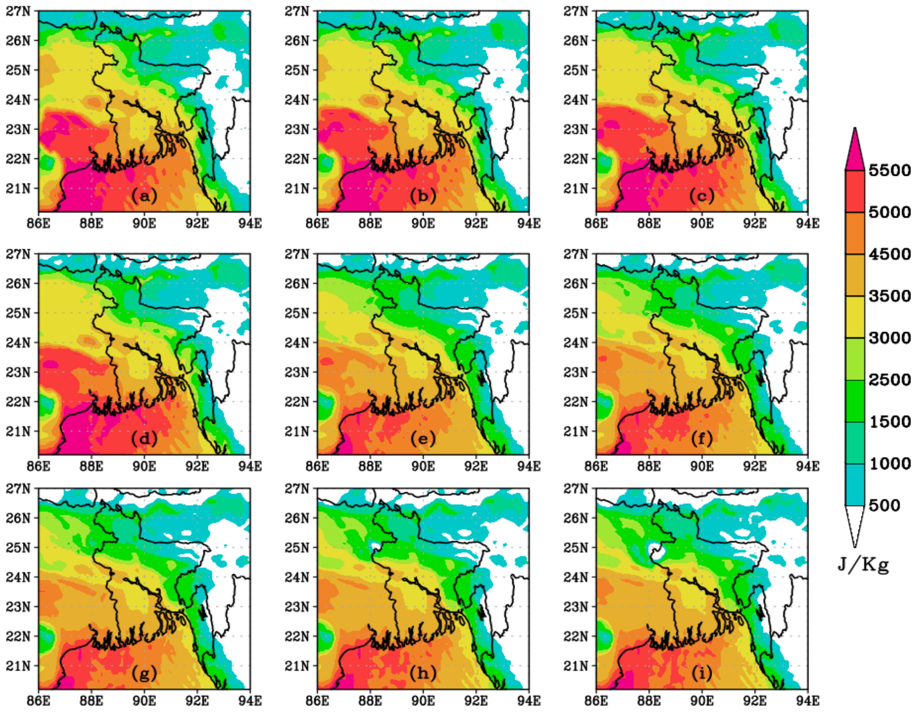

Fig. 13: ARW model simulated CAPE using GFS data at (a) 1700 UTC (b) 1730 UTC (c) 1800 UTC (d) 1830 UTC (e) 1900 UTC (f) 1930 UTC (g) 2000 UTC (h) 2030 UTC and (i) 2100 UTC on 15 May 2017 based on 0000 UTC 14 May 2017 initial conditions.

3.7 Rainfall

When downdraft starts to dominate over updraft, thunderstorm gradually dies through heavy rain. So, rainfall plays an important role in a thunderstorm. Model-simulated 24 hours accumulated rainfall with 3 hours' interval between 0300 UTC and 0000 UTC on 15 May 2017 based on 14 May 2017 initial condition has been shown in Fig. 14. It is found that the model has generated the highest amount of rainfall in Bhola (29.04 mm) following Barisal an amount of 28.84 mm and the lowest in Ishurdi (11.73 mm). Simulated rainfall is recorded more than 23 mm in Khulna.

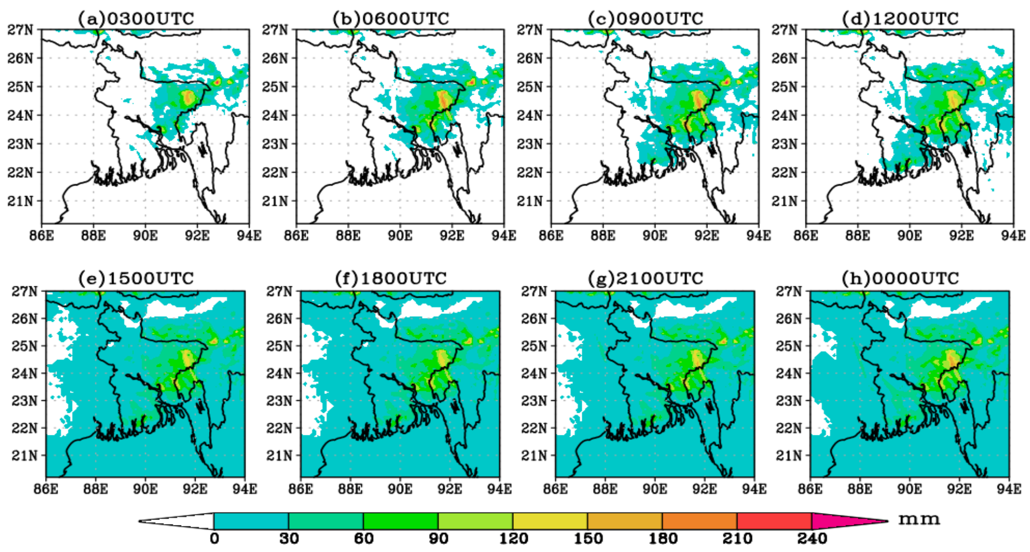

Fig. 14: ARW model accumulated simulated rainfall using GFS data from 0300 UTC to 0000 UTC with 3 hours' interval on 15 May 2017 based on 0000 UTC 14 May 2017 initial conditions.

The lowest amount of rainfall is simulated over Ishurdi and adjoining area on 15 May 2017 which is 11.73 mm and the highly localized rainfall has occurred over Barisal and Bhola due to the formation of deep convective clouds.

For the validation of model-simulated rainfall, a comparison is made between the model-simulated three hourly 24 hours of rainfall using GFS dataset combination and the BMD's observed rainfall data. The comparison is shown in Fig. 15. From the above Fig. 15(f), it is found that model simulated rainfall is much higher than the observed rainfall in Khulna. However, Barisal and Bhola show the small difference although Rajshahi reads moderate between model-simulated rainfall and observed rainfall which is acceptable according to standard error. So, in this case, the model is capable to capture the rainfall of the thunderstorms though it has biases.

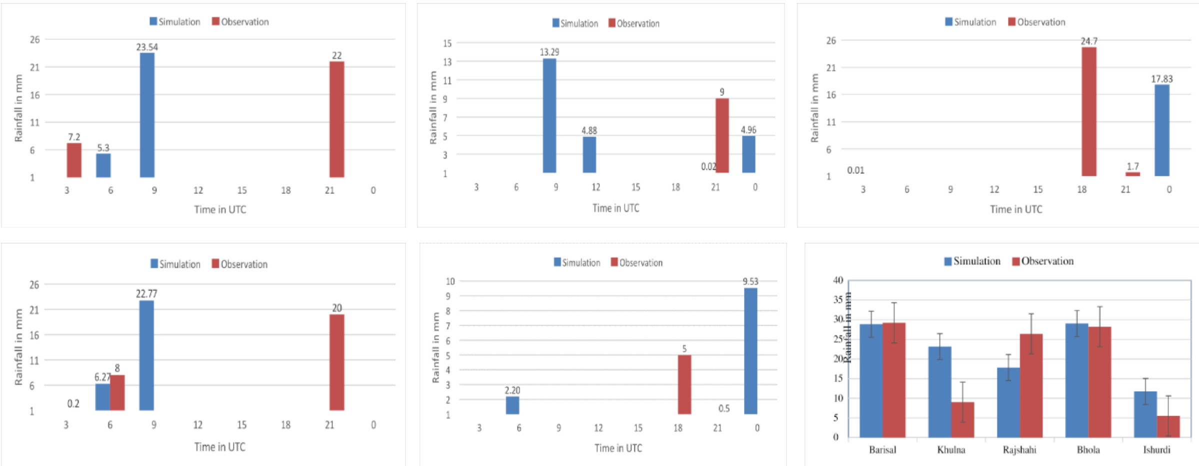

Fig. 15: Comparison of 3-hourly rainfall between model-simulation and observation over (a) Barisal (b) Khulna (c) Rajshahi (d) Bhola (e) Ishurdi and (f) Comparison of 24 hours model-simulated rainfall and observed rainfall on 15 May 2017.

Table 2: Overview of the model-simulated result with observed data over Barisal

Parameters	Model	Observation	RMSE
Fall of MSLP from 0600 UTC to 1500 UTC in hPa	1002.67 to 1001.39	1004.00 to 1002.00	1.12
Fall of Temperature from 1500 UTC to 2100 UTC in °C	28.08 to 27.13	29.50 to 23.00	2.78
Rise of RH from 1500 UTC to 2100 UTC in %	92.63 to 99.73	84.00 to 98.00	7.21
Rise of Rainfall from 1500 UTC to 2100 UTC in mm	0.00 to 0.00	0.00 to 22.00	11.82
24 Hours of Rainfall in mm	28.84	29.20	---

Table 3: Overview of the model-simulated result with observed data over Khulna

Parameters	Model	Observation	RMSE
Fall of MSLP from 0600 UTC to 1500 UTC in hPa	1001.54 to 1000.75	1003.00 to 1002.00	1.46
Fall of Temperature from 1500 UTC to 2100 UTC in °C	29.05 to 28.23	29.5 to 23.00	1.83
Rise of RH from 1500 UTC to 2100 UTC in %	86.48 to 94.23	84 to 98	6.95
Rise of Rainfall from 1500 UTC to 2100 UTC in mm	0 to 0.02	0 to 22	6.18
24 Hours of Rainfall in mm	23.15	9.00	---

Table 4: Overview of the model-simulated result with observed data over Rajshahi

Parameters	Model	Observation	RMSE
Fall of MSLP from 0600 UTC to 1500 UTC in hPa	1002.48 to 1000.49	1003 to 1001	1.68
Fall of Temperature from 1500 UTC to 2100 UTC in °C	32.83 to 30.04	28.20 to 21.9	5.30
Rise of RH from 1500 UTC to 2100 UTC in %	62.43 to 79.27	90 to 99	23.91

Rise of Rainfall from 1500 UTC to 2100 UTC in mm	0 to 0	0 to 1.7	10.79
24 Hours of Rainfall in mm	17.84	26.40	---

Table 5: Overview of the model-simulated result with observed data over Bhola

Parameters	Model	Observation	RMSE
Fall of MSLP from 0600 UTC to 1500 UTC in hPa	1003.12 to 1001.53	1004.2 to 1001.90	1.12
Fall of Temperature from 1500 UTC to 2100 UTC in °C	28.08 to 26.98	29.00 to 24.00	2.51
Rise of RH from 1500 UTC to 2100 UTC in %	92.78 to 99.99	92.00 to 96.00	4.90
Rise of Rainfall from 1500 UTC to 2100 UTC in mm	0.00 to 0.00	0.00 to 20.00	10.73
24 Hours of Rainfall in mm	29.04	28.20	---

Table 6: Overview of the model-simulated result with observed data over Ishurdi

Parameters	Model	Observation	RMSE
Fall of MSLP from 0600 UTC to 1500 UTC in hPa	1003.02 to 1000.74	1003.00 to 1000.70	0.93
Fall of Temperature from 1500 UTC to 2100 UTC in °C	32.28 to 28.96	28.80 to 21.50	5.10
Rise of RH from 1500 UTC to 2100 UTC in %	66.42 to 85.87	83.00 to 91.00	20.45
Rise of Rainfall from 1500 UTC to 2100 UTC in mm	0.00 to 0.00	0 to 0.5	3.89
24 Hours of Rainfall in mm	11.73	5.50	---

The observed value of other parameters is unavailable. So, the validation of other parameters is not done in this paper. The WRF model performed reasonably well. Similar studies should be extended for more cases for further refinement of the model application.

4. Conclusion

Different microphysics, cumulus physics and PBL physics schemes that are responsible for cloud and rainfall generation of WRF model have been used in this study. Model outputs are compared with BMD and TRMM observed and ECMWF model data. On the basis of the present study the following conclusions can be drawn:

- A summary of the model simulated result along with the observed data over Barisal, Khulna, Rajshahi, Bhola, and Ishurdi on 15 May 2017 is shown in Tables 2, 3, 4, 5 and 6, respectively. Here, Root Mean Square Error (RMSE) is measured from 0300 UTC to 0000 UTC (where no. of observations n=8 since 24/3=8). The model data and observed data have fitted during the occurrence of thunderstorms in different regions of Bangladesh. The values of RMSE are acceptable due to error found beyond the events time.
- The sensitivity test of different parameterization schemes of WRF model show that the NSSL 2-moment microphysics (MP-17) scheme with Kain–Fritsch (CP-1) Scheme and Yonsei University (YSU) Scheme (PBL-1) option produces more or less realistic results in both spatial and quantitative comparisons. Therefore, these schemes have been considered as the best for synoptic analysis and prediction of thunderstorm which passes over north-eastern part of Bangladesh.
- The model predicted lowest MSLP of the thunderstorm is about 1003-1005 hPa at 1200 UTC of 23 September, 2012; 1004-1006 hPa at 1200 UTC of 18 April, 2015; 1006-1008 hPa at 1200 UTC of 29 March, 2017; 1000-1003 hPa at 0000 to 1200 UTC of 14 June, 2017 and 1000-1002 hPa at 1200 UTC of 25 June, 2019 for 48-h, and 72-h model run. The average lowest MSLP of the thunderstorm is found 1000-1008 hPa during 2012-2019 which is very close to the observed lowest MSLP.
- It is found that the model predicted vorticity over north-eastern part of Bangladesh at 850 hPa level are positive of magnitude (06-10)×10^{-5} s^{-1} and negative of magnitude (6-10)×10^{-5} s^{-1} for 48-h model run which is indicate to updraft and downdraft occur simultaneously. At 500 hPa level, negative vorticity is dominant of 23 September, 2012; 14 June, 2017 and 25 June, 2019 which indicates to hinders the further

updraft of the system and positive vorticity dominant of 18 April, 2015 and 29 March, 2017 which is the indication of priority of further updrafts the system.

- The RH is found 75-100% over Sylhet and adjoining area which is very close to the observation and 60-100% moisture is extended up to 400-200 hPa level. The high amount of moisture is responsible for buoyant of air and ultimately cloud formation.
- The model simulated CAPE is found 400 – 800 J/Kg at developing stage and 800-1000 J/Kg or more at mature stage over Sylhet and adjoining area which is responsible for moderately unstable condition of the atmosphere.
- The model simulated rainfall amount and associated areas are sensibly well compared with the data observed by Bangladesh Meteorological Department (BMD), Tropical Rainfall Measuring Mission (TRMM) and European Centre for Medium-Range Weather Forecasts (ECMWF).

It may be concluded that the Fifth-Generation PSU/NCAR mesoscale model WRF version 3.9 with the right combination of the fixed domain, horizontal resolution and the suitable parameterization schemes is able to simulate and predict the Orographic Rain over north-eastern part of Bangladesh reasonably well, though there are some spatial and temporal biases in the simulated rainfall pattern.

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