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Simulation of Thunderstorm Event and its Thermodynamic Characteristics Over Bogura, Dhaka, Rajshahi, Tangail and Ishurdi Using WRF Model

Research Article

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Abstract: An attempt has been made to simulate the thunderstorm events of 1 May 2017 and its thermodynamic features using the WRF-ARW model in a single domain of 9 km horizontal resolution. It is found that the model simulated result was good enough to predict thunderstorm events over Bangladesh particularly, Bogura, Dhaka, Rajshahi, Tangail and Ishurdi for the above mentioned date. The Root Mean Square Error (RMSE) of MSLP from 0600 UTC to 1200 UTC over Bogura, Dhaka, Rajshahi, Tangail and Ishurdi are 3.22, 3.45, 3.44, 3.07 and 3.72 hPa respectively. And RMSE of RH from 0900 UTC to 1500 UTC over the above mentioned areas are 13.36, 12.84, 18.76, 19.02 and 12.31% respectively. The result of the current research will help to detect thunderstorms event precisely for forecasting the weather timely to minimize the destruction of the environment as well as human beings.

Keywords: *Thunderstorm ● WRF-ARW Model ● MSLP and CAPE*

1. Introduction

Most of the weather events occurring over Bangladesh and its neighborhood are mesoscale phenomena. These mesoscale events are called thunderstorms, locally known as Nor'westers or Kal-baishakhis, are among the most common natural meteorological phenomena in Bangladesh that occur, especially during the pre-monsoon season (March to May). These systems are embedded within squall lines and accompanied by lightning, thunder, hailstorms and heavy rains. These systems 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 systems is only of few hours, prediction of these systems is a challenging task using any conventional forecasting technique. Research on thunderstorm phenomena during pre-monsoon season is few in Bangladesh.

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. A simulation study was carried out by Vaidya (Vaidya, S. S.,2007) for a pre-monsoon thunderstorm over east coast of India. Mukhopadhyay et al. (2003) worked on objective forecast

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of thundery/non-thundery days using conventional indices over three north-eastern India stations. Rajeevan et al. (2010) simulated the features associated with a severe thunderstorm event over Gadanki (over southeast India) using WRF model and examined its sensitivity to four different microphysical (MP) schemes validated with many observations (Rajeevan and Kesarkar, 2010). This study suggests large sensitivity of the microphysical schemes in the simulations of the thunderstorm. Ahasan *et al.* (2014) carried out a simulation of the TS event over Srimangal, Bangladesh occurred at 1200 UTC on 21 May 2011 using WRF-ARW model. The impact of data assimilation in simulation of the thunderstorm (squall line) event of 11 May 2011 over Bangladesh using WRF model was studied by Ahasan et al. (2015).

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 3.8, released in April 2016, has been used as the principal modeling tool. WRF model was set up by Bangladesh Meteorological Department (BMD) and all the technical supports were also provided by BMD. The model was configured on 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 (23.5^0 N, 90^0 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 30 April 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 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

The behavior of meteorological parameters during a thunderstorm events on 1 May 2017 over Bangladesh are discussed below.

Mean Sea Level Pressure (MSLP)

From the model-simulated MSLP analysis indicates that a trough of a westerly low is extended up to Bangladesh and its adjoining area (Figure 1) where the value of MSLP is about 1002 hPa to 1008 hPa from 1100 UTC to 1500 UTC on 1 May 2017. This trough of westerly low conjugates with easterly waves, then thunderstorm usually forms. The lowest pressure of magnitude of below 1007 hPa is found in theWest Bengal and adjoining area. So, the model simulates the westerly trough very well which is the supportive condition for the formation of thunderstorms based on 0000 UTC30 April 2017 initial conditions.

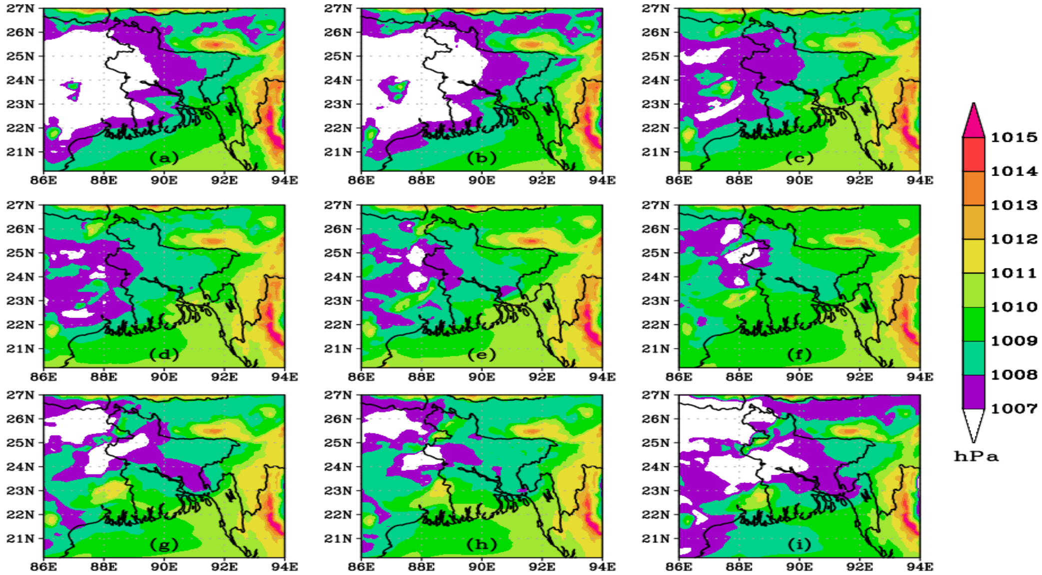
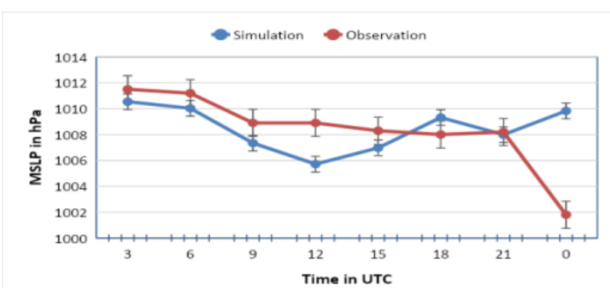
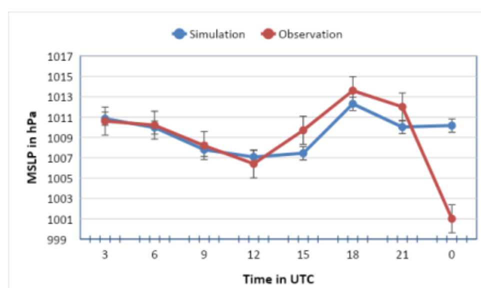


Figure 1. ARW model simulated MSLP data at (a) 1100 UTC (b) 1130 UTC (c) 1200 UTC (d) 1230 UTC (e) 1300 UTC (f) 1330 UTC (g) 1400 UTC (h) 1430 UTC and (i) 1500 UTC on 1May 2017 based on 0000 UTC 30 April 2017 initial conditions.

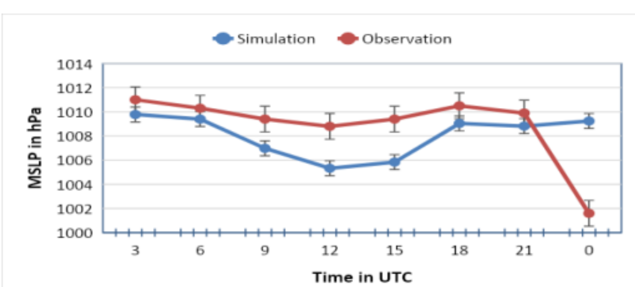
For the validation of model-simulated MSLP, a comparison is made with three hourly observed MSLP recorded by BMD over Bogura, Dhaka, Rajshahi, Tangail and Ishurdi on 1 May 2017. This comparison is shown in Figures 3(a-e). From the simulation result, a sharp fall of MSLP from 1010.03 hPa to 1005.71 hPa, 1009.97 hPa to 1007.08 hPa, and 1009.40 hPa to 1005.33 hPa are found over Bogura, Dhaka and Rajshahi, respectively on 1 May 2017 during 0600 UTC to 1200 UTC. The Fig. 1 shows a fall of MSLP from 1011.20 hPa to 1008.90 hPa, 1010.20 hPa to 1006.40 hPa and 1010.30 hPa to 1008.8 hPa over Bogura, Dhaka, and Rajshahi, respectively during the same period. Moreover, the fluctuation of MSLP over Tangail is perfectly matched until 1200 UTC and from 1800 UTC to 2100 UTC. Almost similar variation has been seen for Ishurdi between 0300 UTC and 1200 UTC. In all regions, the gap between model data and observed data had been seen at 0000 UTC. So, it can be said that the model captures the sharp fall of MSLP very well that confirm the validity of our model.



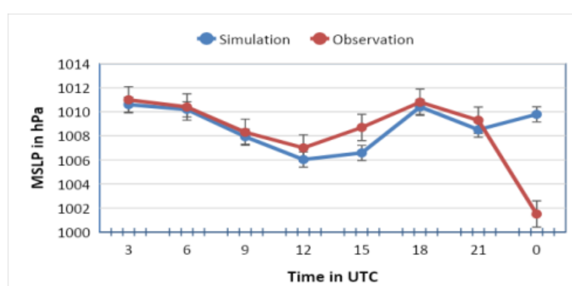
(a) Bogura



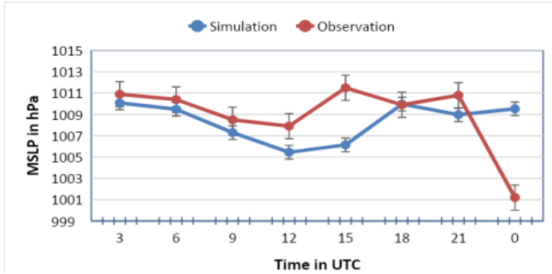
(b) Dhaka



(c) Rajshahi



(d) Tangail



(e) Ishurdi

Figure 2. Comparison of MSLP between model-simulation and observation over **(a)** Bogura **(b)** Dhaka **(c)** Rajshahi **(d)** Tangail **(e)** Ishurdi on 1 May and 2 May 2017 Respectively

Wind Pattern

Wind Pattern at different pressure level

The model has simulated the wind speed at 850 hPa level very well based on 0000 UTC 30 April 2017 initial conditions (Figure 3).

At 500 hPa level a westerly wind is blowing towards Bangladesh from 1100 UTC to 1500 UTC on 1 May 2017. This wind is cool and dry. When the 850 hPa level's wind 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 30 April 2017 initial conditions (Figure 4).

For the case of 200 hPa level, wind is blowing from 1100 UTC to 1500 UTC on 1 May 2017 (Figure 5) where wind speed is very high 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 thunderstorms and the model simulates the wind speed very well based on 0000 UTC 30 April 2017 initial conditions.

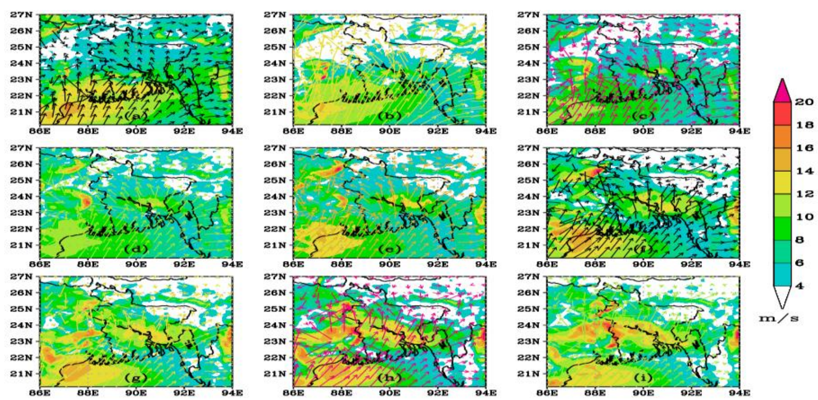


Figure 3. ARW model simulated wind speed and direction at 850 hPa level based on data from1100 UTC to 1500 UTC on 1May 2017

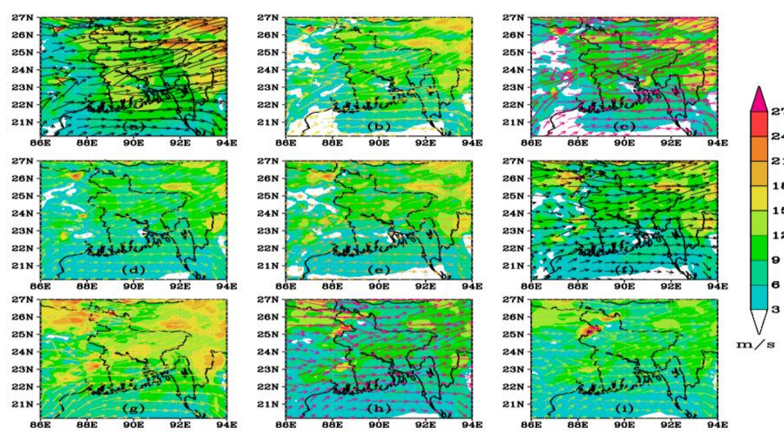


Figure 4. ARW model simulated wind speed and direction for 500 hPa level at (a) 1100 UTC (b) 1130 UTC (c) 1200 UTC (d) 1230 UTC (e) 1300 UTC (f) 1330 UTC (g) 1400 UTC (h) 1430 UTC and (i) 1500 UTC on 1 May 2017 based on 0000 UTC 30 April 2017 initial conditions.

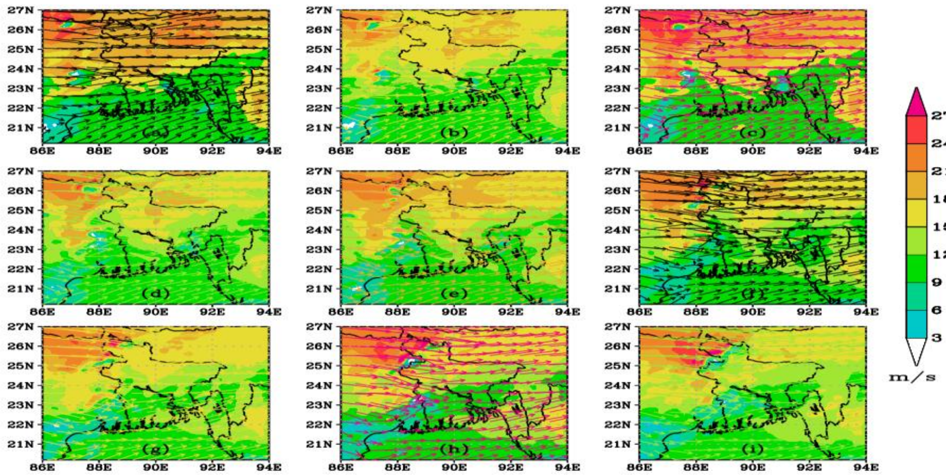


Figure 5. ARW model simulated wind speed and direction for 200 hPa level based on data at (a) 1100 UTC (b) 1130 UTC (c) 1200 UTC (d) 1230 UTC (e) 1300 UTC (f) 1330 UTC (g) 1400 UTC (h) 1430 UTC and (i) 1500 UTC on 1May 2017 based on 0000 UTC 30 April 2017 initial conditions.

Temperature at 2-meter 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 have a higher magnitude of temperature which is more than 33°C from 1100 UTC to 1230 UTC on 1 May 2017 (Figures 6(a-d)). Subsequently, the temperature drops to 24°C-30°C which is very much supportive for occurring of convective precipitation and the model simulates the temperature very well based on the 0000 UTC 30 April2017 initial conditions.

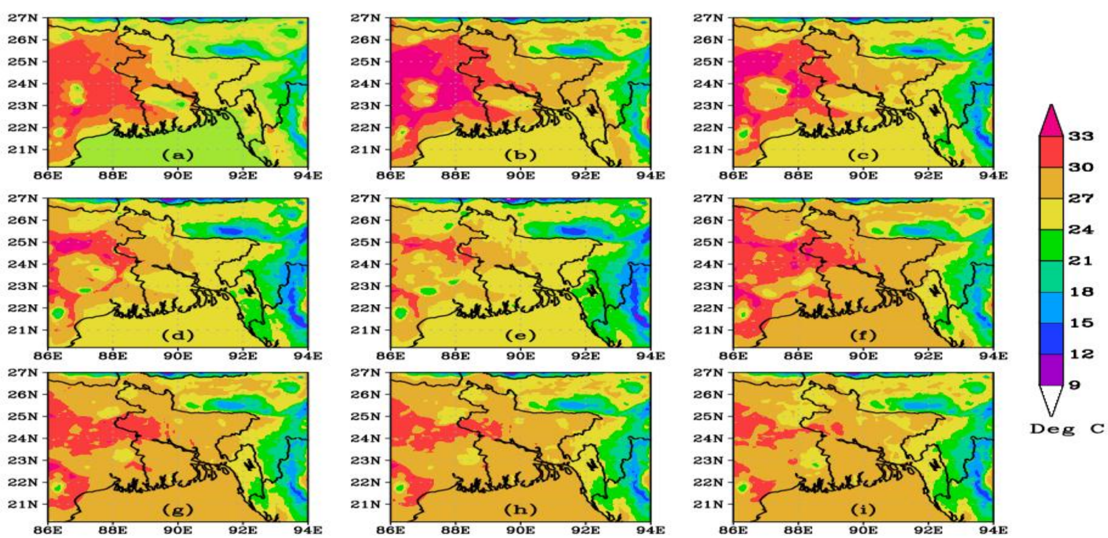
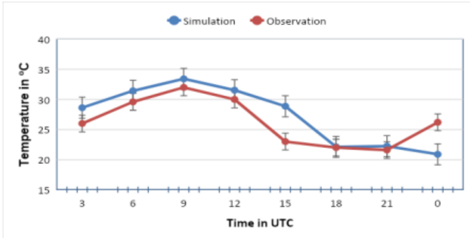
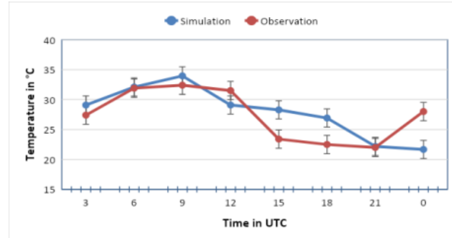


Figure 6. ARW model simulated temperature at 2-m height using data at (a) 1100 UTC (b) 1130 UTC (c) 1200 UTC (d) 1230 UTC (e) 1300 UTC (f) 1330 UTC (g) 1400 UTC (h) 1430 UTC and (i) 1500 UTC on 1May 2017 based on 0000 UTC 30 April 2017 initial conditions.

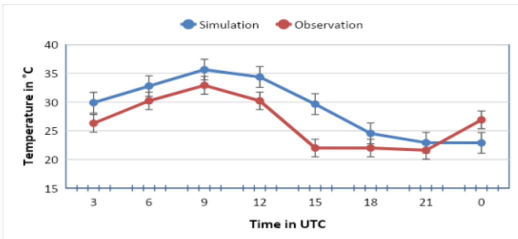
Three hourly temperature of 1 May 2017 simulated by the WRF-ARW model using GFS data combination is compared with that temperature recorded by BMD. This comparison over Bogura, Dhaka, Rajshahi, Tangail and Ishurdi is shown in Figures 7(a-e). From the observed temperature, a sudden fall from 32°C to 23°C, 32.40°C to 23.40°C, and 32.90°C to 22°C is found over Bogura, Dhaka, and Rajshahi, respectively on 1 May 2017 during 0900 UTC to 1500 UTC. Figures 7(a-c) show that a drop of temperature from 33.42°C to 28.87°C, 33.96°C to 28.28°C, and 35.63°C to 29.63°C over Bogura, Dhaka, and Rajshahi, respectively during this time. Besides, Tangail experienced the least variation of temperature between 0300 UTC and 1200 UTC. In all three regions, the gap between model data and observed data had been seen at 1500 UTC. So it can be said that the model shows a decrease of temperature, similarly, the model captures the sharp fall of temperature very well over Bogura and Rajshahi.



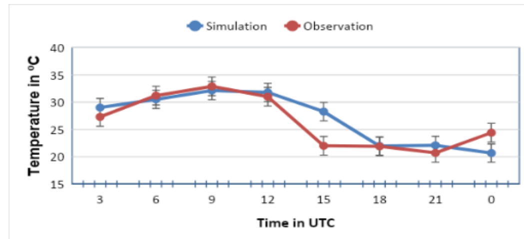
(a) Bogura



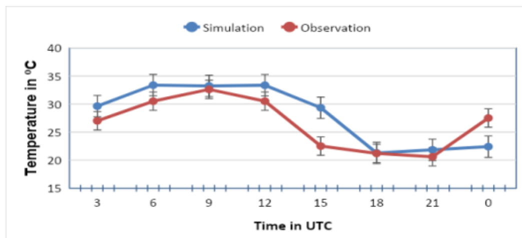
(b) Dhaka



(c) Rajshahi



(d) Tangail



(e) Ishurdi

Figure 7. Comparison of 2-meter height temperature between model-simulation and observation over (a) Bogura (b) Dhaka (c) Rajshahi (d) Tangail (e) Ishurdi on 1 May and 02 May 2017 respectively.

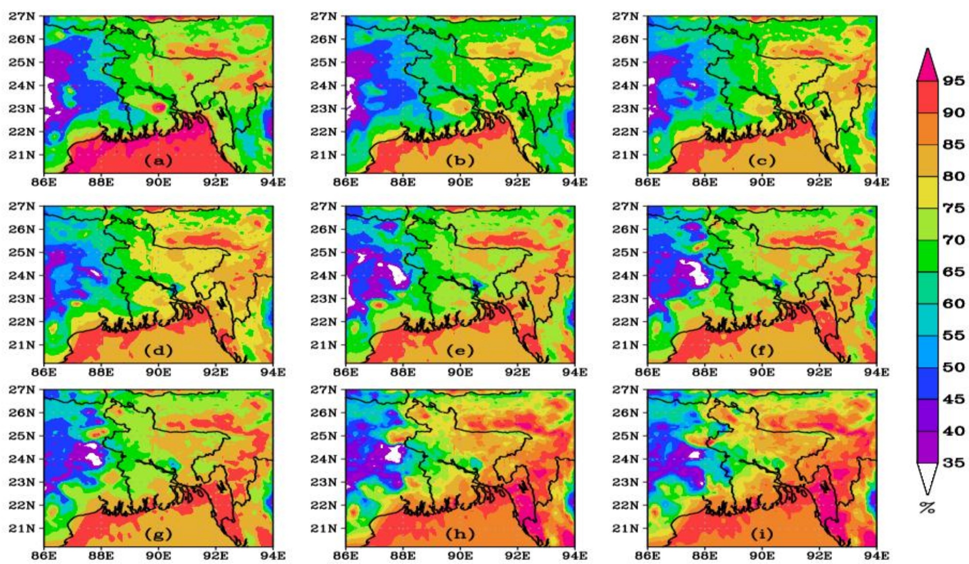
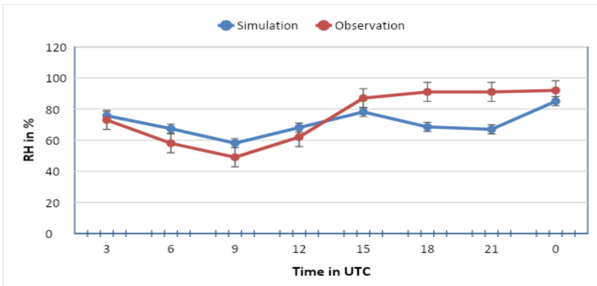


Figure 8. ARW model simulated relative humidity at 2-m height using data at (a) 1100 UTC (b) 1130 UTC (c) 1200 UTC (d) 1230 UTC (e) 1300 UTC (f) 1330 UTC (g) 1400 UTC (h) 1430 UTC and (i) 1500 UTC on 1May 2017 based on 0000 UTC 30 April 2017 initial conditions.

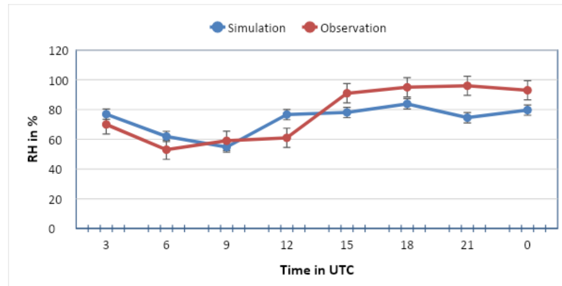
Relative Humidity at 2-m Height

The increase of relative humidity is the pre-condition of the formation of thunderstorms. So, we can say, the model has simulated the relative humidity very well based on the 0000 UTC 30 April 2017 initial conditions (Figure 8).

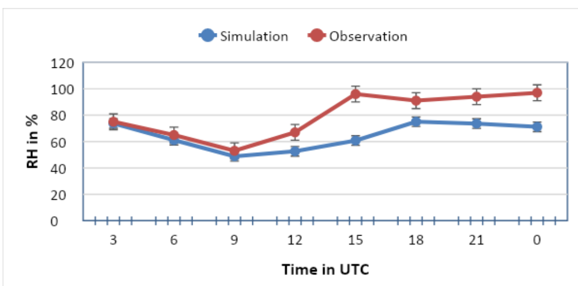
For the validation of model-simulated 2-meter height RH, three hourly RH of 1 May 2017 simulated by WRF-ARW model using GFS dataset combination is compared with three hourly RH recorded by BMD. From the observed data, a sharp rise of RH from 49% to 87% during 0900 UTC to 1500 UTC is found over Bogura. Observed data also show a rise of RH from 59% to 91% and 53% to 96% during 0900 UTC to 1500 UTC over Dhaka and Rajshahi, respectively. From the model simulation result, the increase of RH over Bogura is 58.09% to 79.09% which is shown in Figure 8(a). The rise of RH over Dhaka is 54.79% to 83.86% which is shown in Figure 8(b) and the rise of RH over Rajshahi is 48.87% to 60.78% which is shown in Figure 8(c). More than 60% of RH value has been seen after 12 UTC both in Tangail and Ishurdi depicted in Figures 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 1200 UTC because of RH value is more than 60% in that time.



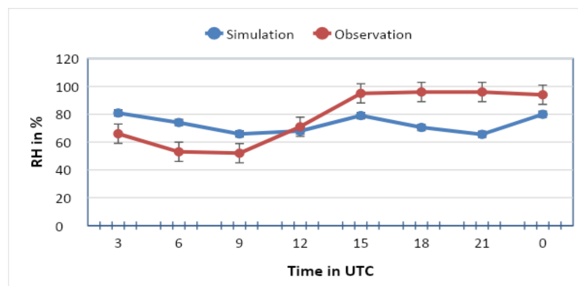
(a) Bogura



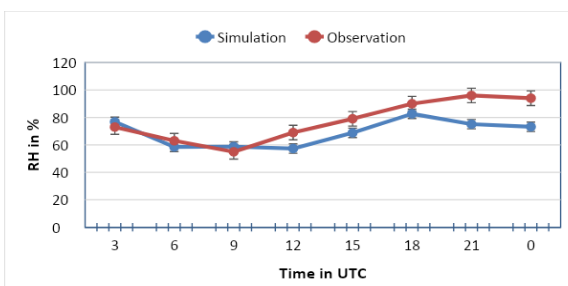
(b) Dhaka



(c) Rajshahi



(d) Tangail



(e) Ishurdi

Figure 9. Comparison of 2-meter height RH between model-simulation and observation data over (a) Bogura (b) Dhaka (c) Rajshahi (d) Tangail (e) Ishurdi on on 1 May and 02 May 2017 respectively.

Vorticity

From the analysis, it is found that the value of vorticity is (0-30) x$10^{-5}s^{-1}$ in most of the region of Bangladesh from 1100 UTC to 1500 UTC on 1 May 2017. There are some areas in Bangladesh where the value of vorticity is (30-60)x$10^{-5}s^{-1}$ for the same period. Negative vorticity is also seen in some regions of Bangladesh. 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 30 April 2017 initial conditions (Figure 10). Vorticity is lower at 500 hPa level than that at 850 hPa level from 1100 UTC to 1500 UTC on 1 May 2017. The northern part of the Bangladesh vorticity comprises from -100x$10^{-5}s^{-1}$ to 50x$10^{-5}s^{-1}$. A positive value indicates occurring of thunderstorms. It is seen that vorticity is positive with 50x$10^{-5}s^{-1}$ in Bogura throughout the time (Figure 11).

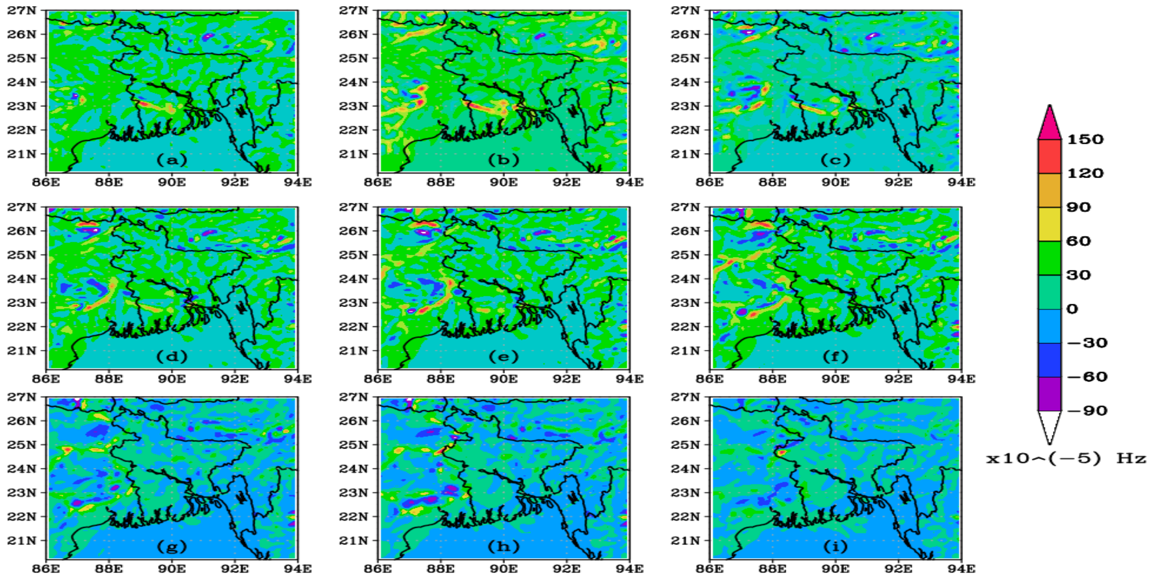


Figure 10. ARW model simulated vorticity at 850 hPa level using data at (a) 1100 UTC (b) 1130 UTC (c) 1200 UTC (d) 1230 UTC (e) 1300 UTC (f) 1330 UTC (g) 1400 UTC (h) 1430 UTC and (i) 1500 UTC on 1May 2017 based on 0000 UTC 30 April 2017 initial conditions.

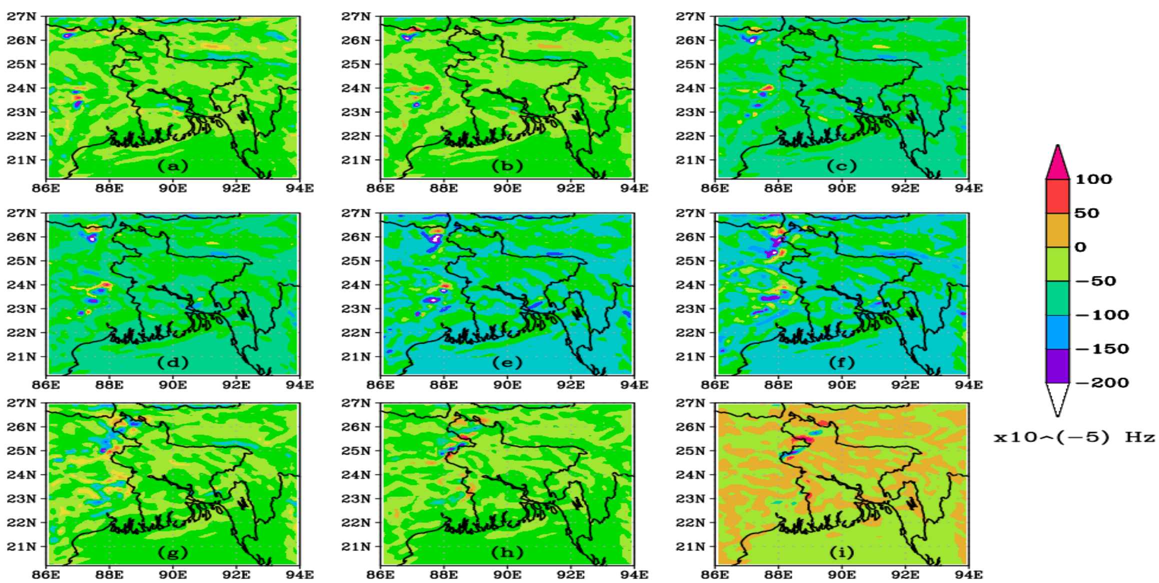


Figure 11. ARW model simulated vorticity at 500 hPa level using data at (a) 1100 UTC (b) 1130 UTC (c) 1200 UTC (d) 1230 UTC (e) 1300 UTC (f) 1330 UTC (g) 1400 UTC (h) 1430 UTC and (i) 1500 UTC on 1May 2017 based on 0000 UTC 30 April 2017 initial conditions.

Vertical Wind Shear

The value of vertical wind shear is almost positive all over Bangladesh from 1100 UTC to 1500 UTC on 1 May 2017. We know that the value of vertical wind shear greater than 10 ms^{-1}, is very supportive of the formation of a thunderstorm. It can be seen that Bogura, Dhaka, and Rajshahi and its adjoining area has a higher value of vertical wind shear which varies from 10 ms^{-1} to 40 ms^{-1} from 1100 UTC to 1500 UTC. So, the value of vertical wind shear is positive throughout the country and very high in some parts of the country which is the pre-condition of formation of thunderstorms and the model simulates vertical wind shear very well based on the 0000 UTC 30 April 2017 initial conditions (Figure 12).

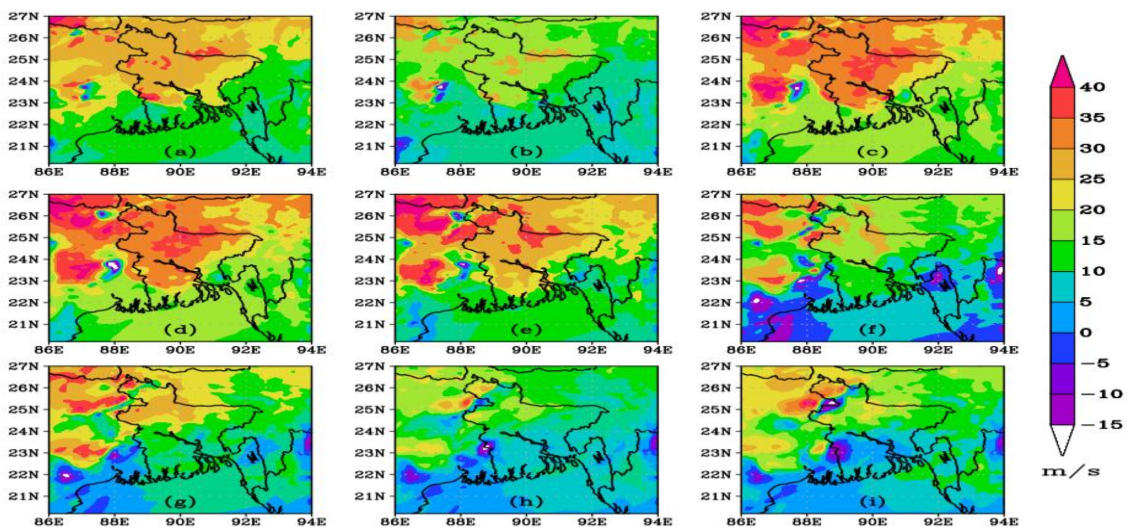


Figure 12. ARW model simulated vertical wind shear based on data at (a) 1100 UTC (b) 1130 UTC (c) 1200 UTC (d) 1230 UTC (e) 1300 UTC (f) 1330 UTC (g) 1400 UTC (h) 1430 UTC and (i) 1500 UTC on 1May 2017 based on 0000 UTC 30 April 2017 initial conditions.

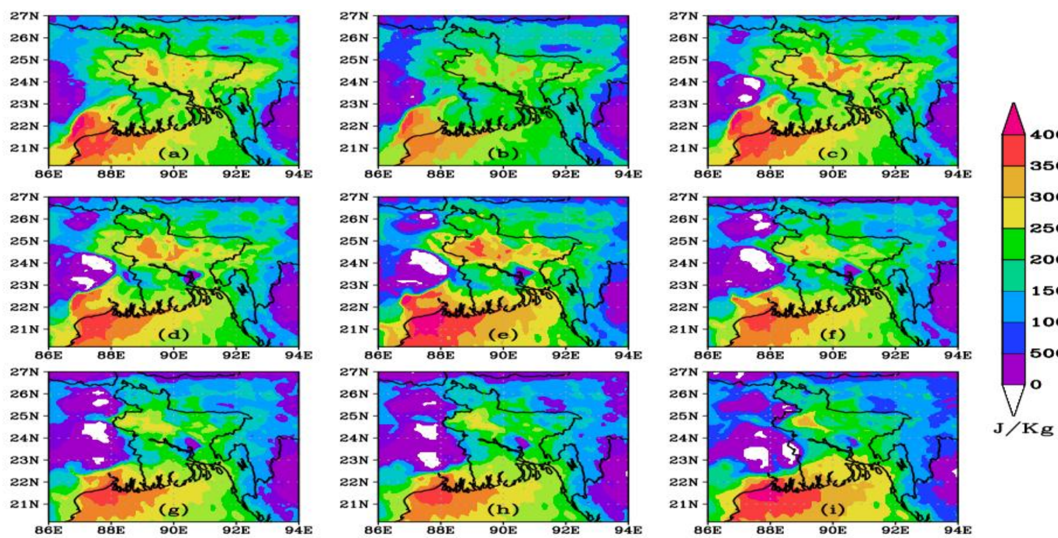


Figure 13: ARW model simulated CAPE based on data at (a) 1100 UTC (b) 1130 UTC (c) 1200 UTC (d) 1230 UTC (e) 1300 UTC (f) 1330 UTC (g) 1400 UTC (h) 1430 UTC and (i) 1500 UTC on 1May 2017 based on 0000 UTC 30 April 2017 initial conditions.

Convective Available Potential Energy (CAPE)

The value of CAPE at most unstable layer from 1100 UTC to 1500 UTC on 1 May 2017, is greater than 2500 J/Kg. CAPE value greater than 1500 J/Kg is required for the formation of a supercell thunderstorm. The present result shows the CAPE value varies from 2000 J/Kg to 4000 J/Kg from 1100 UTC to 1300 UTC. The value started to decrease for the rest of the time. The simulated value of CAPE over Bogura at 1300 UTC is 4000 J/Kg. The value of CAPE is greater than 1500 J/Kg throughout the country which is the pre-condition of formation of thunderstorm and the model simulates CAPE very well based on the 0000 UTC 30 April 2017 initial conditions. This is depicted in Figure 13.

Rainfall

Model-simulated 24-hours accumulated rainfall with 3hours' interval between 0300 UTC and 0000 UTC on 1 May 2017 based on 30 April 2017 initial condition has been depicted in Figure 15. It is found that the model has generated the highest amount of rainfall over Bogura and adjoining areas (around 21.32 mm) as shown in Figure 14 (a-f). Simulated rainfall is recorded around 16 mm in Dhaka and approximately 4 mm in Rajshahi. Moreover, Tangail experienced the second-highest rainfall of 20.18 mm while Ishurdi has recorded only 10.43 mm daily rainfall.

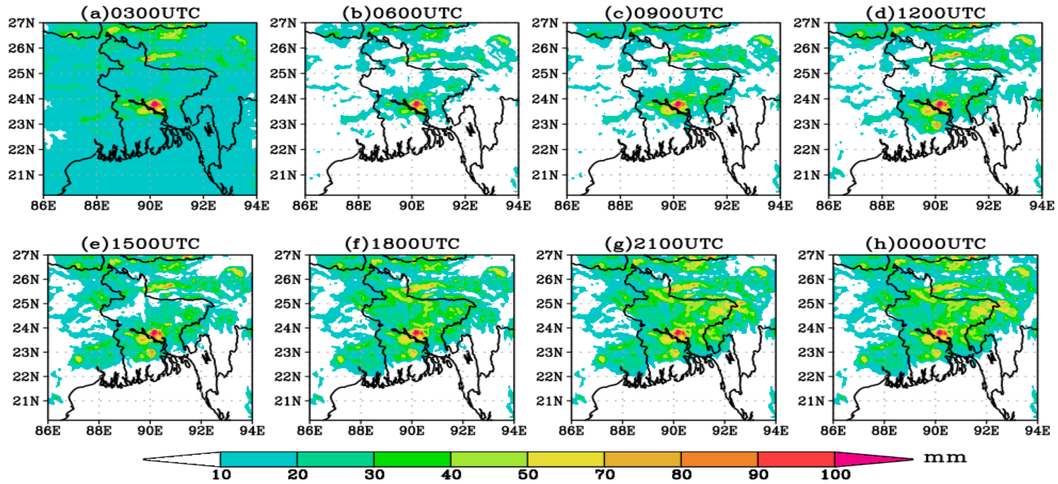
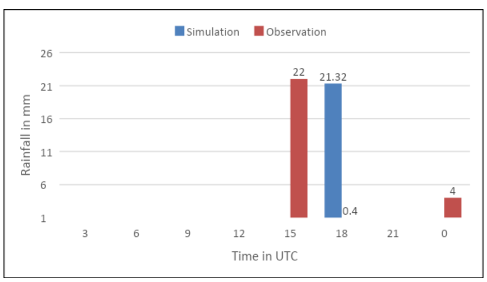
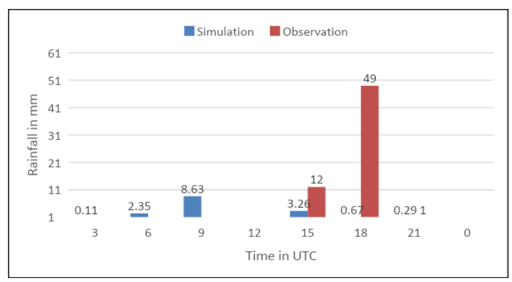


Figure 14. ARW model accumulated simulated rainfall based on data from 0300 UTC to 0000 UTC with 3 hours' interval on 1May 2017 based on 0000 UTC 30 April 2017 initial conditions.

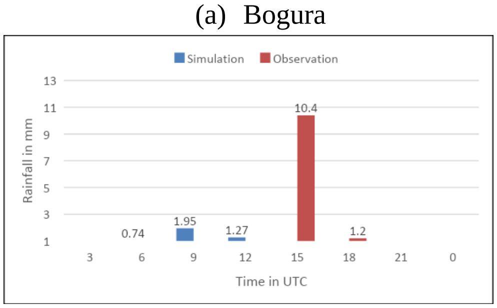
A very low amount of rainfall is simulated over Rajshahi and adjoining area on 1 May 2017 which is about 4 mm. The highly localized rainfall has occurred over Bogura and adjoining area due to the formation of deep convective clouds. For the validation of model-simulated rainfall, comparisons are made between the model-simulated 24 hours of rainfall with 3 hours interval using GFS dataset combination and the BMD's observed rainfall data. The comparisons are shown in Figure 15.



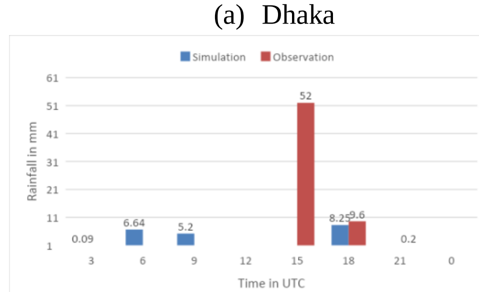
(a) Bogura



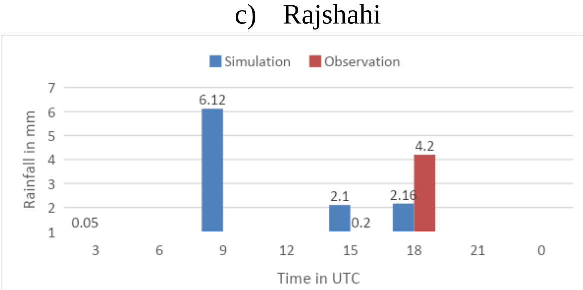
(a) Dhaka



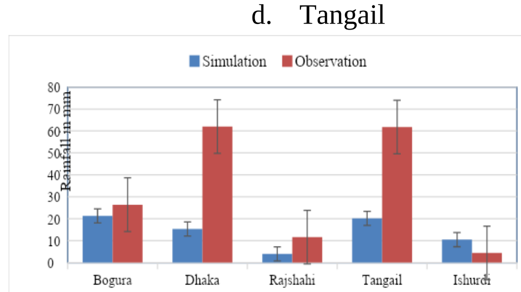
c) Rajshahi



d. Tangail



e. Ishurdi



(f) 24 hours of rainfall

Figure 15. Comparison of 3-hourly rainfall between model-simulation and observation over **(a)** Bogura **(b)** Dhaka **(c)** Rajshahi **(d)** Tangail **(e)** Ishurdi,and **(f)** Comparison of 24 hours model-simulated rainfall and observed rainfall on 1 May and 2 May 2017 respectively.

From the above Figure 15, it is found that model simulated rainfall is lower than the observed rainfall in all regions except Ishurdi. Moreover, Dhaka shows the big differences between model-simulated rainfall and observed rainfall around 47 mm following Tangail approximately 22 mm. So, in this case, model-simulated rainfall underestimates compared to the observed rainfall. But the model is capable to capture the rainfall of the thunderstorms though it has biases.

4. Conclusion

A summary of the model simulated result along with the observed data over Bogura, Dhaka, Rajshahi, Tangail and Ishurdi on 1 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) on that day. 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.

Table 2. Overview of the model-simulated result with observed data over Bogura

Parameters	**Model**	**Observation**	**RMSE**
Fall of MSLP from 0600 UTC to 1200 UTC in hPa	1010.03 to 1005.71	1011.20 to 1008.90	3.22
Fall of Temperature from 0900 UTC to 1500 UTC in °C	33.42to 28.87	32.00 to 23.00	3.12
Rise of RH from 0900 UTC to 1500 UTC in %	58.09 to 78.09	72.00 to 98.00	13.36
increase Rainfall from 1200 UTC to 1500 UTC in mm. It is done to show in which time rainfall occurs.	0.00 to 0.00	0.00 to 22.00	10.83
24 Hours of Rainfall in mm	21.32	26.40	---

Table 3. Overview of the model-simulated result with observed data over Dhaka

Parameters	**Model**	**Observation**	**RMSE**
Fall of MSLP from 0600 UTC to 1200 UTC in hPa	1009.97 to 1007.08	1010.2to 1006.40	3.45
Fall of Temperature from 0900 UTC to 1500 UTC in °C	33.96 to 28.28	32.40 to 23.40	3.44
Rise of RH from 0900 UTC to 1500 UTC in %	54.79 to 78.08	59.00 to 91.00	12.84
Rise of Rainfall from 1200 UTC to 1500 UTC in mm	0.00 to 3.26	0.00 to 12.00	17.65
24 Hours of Rainfall in mm	15.31	62.00	---

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

Parameters	Model	Observation	RMSE
Fall of MSLP from 0600 UTC to 1200 UTC in hPa	1009.40 to 1005.33	1010.30 to 1008.80	3.44
Fall of Temperature from 0900 UTC to 1500 UTC in °C	35.63 to 29.63	32.90 to 22.00	3.98
Rise of RH from 0900 UTC to 1500 UTC in %	48.87 to 60.78to	53.00to 96.00	18.76
Rise of Rainfall from 1200 UTC to 1500 UTC in mm	1.27 to 0.00	0.00 to 10.40	3.80
24 Hours of Rainfall in mm	3.96	11.60	---

Table 5. Overview of the model-simulated result with observed data over Tangail

Parameters	Model	Observation	RMSE
Fall of MSLP from 0600 UTC to 1200 UTC in hPa	1010.20 to 1006.03	1010.40 to 1007	3.07
Fall of Temperature from 0900 UTC to 1500 UTC in °C	32.13 to 28.27	32.90 to 22.00	2.73
Rise of RH from 0900 UTC to 1500 UTC in %	65.86 to 79.06	52.00 to 95.00	19.02
Rise of Rainfall from 1200 UTC to 1500 UTC in mm	0.00 to 0.00	0.00 to 52.00	18.63
24 Hours of Rainfall in mm	20.18	61.80	---

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

Parameters	Model	Observation	RMSE
Fall of MSLP from 0600 UTC to 1200 UTC in hPa	1009.48 to 1005.45	1010.40 to 1007.90	3.72
Fall of Temperature from 0900 UTC to 1500 UTC in °C	33.23 to 29.33	32.60 22.50	3.49
Rise of RH from 0900 UTC to 1500 UTC in %	58.78 to 68.79	55.00 to 79.00	12.31
Rise of Rainfall from 1200 UTC to 1500 UTC in mm	0.00 to 2.10	0.00 to 0.20	3.37
24 Hours of Rainfall in mm	10.43	4.40	---

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. The similar studies should be extended for more cases for further refinement of the model application.

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