

Simulation of Thunderstorms over Rajshahi, Sayedpur and Rangpur, Bangladesh using WRF-ARW Model

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Abstract

An attempt has been made to simulate thunderstorm events over Rajshahi, Sayedpur and Rangpur, Bangladesh occurred from at 0920 UTC to 0950 UTC, 1930 UTC to 2000 UTC and 1900 UTC to 1930 UTC respectively on March 2019 using WRF-ARW model. The model was run in a single domain of 10 km horizontal resolution using GFS datasets for 48 hours from 0000 UTC of 30 March 2019 to 0000 UTC of 01 April 2019 as initial and lateral boundary conditions. Kain-Fritsch cumulus physics scheme, Kessler microphysics scheme, Yonsei University planetary boundary layer scheme, Dudhia Short wave and Rapid Radiative Transfer Model Long wave radiation scheme have been used in present study. Various thermodynamic parameters were examined for deep analyses of the events. For validation of the model performance, simulated values of different parameters have been compared with observed value of BMD. Based on the model outcome, it can be understood that, model simulated result is good enough to predict thunderstorms over Bangladesh.

1. Introduction

Most of the mesoscale weather events occurring over Bangladesh are called Thunderstorms (TSs), locally known as Kal-baishakhis, that occur, especially during the pre-monsoon season (March to May). TSs are local storms produced by a cumulonimbus clouds always accompanied by lightning and thunder, and are usually found with strong gusts of wind, heavy rain, and sometime hail or in contrast, no precipitation at all and inflict huge damage to the life and property and cause severe socio-economic impact in the affected regions. These systems develop mainly due to merging of mid-tropospheric cold dry northwesterly winds and low level southerly warm moist winds from the BoB. TS, resulting from vigorous convective activity, is one of the most magnificent weather phenomena in the earth's atmosphere. From the middle of the 20th century an enormous studies of TSs have been made by a number of scientists due to know the formation and thermodynamic features as well as forecasting the TS events. Although many questions regarding the formation of TS and generation of lightning still remains unresolved. In 1938 Namias have made an attempt to forecast TS events with the aid of isentropic charts [1]. Braham et al. and Moses et al. in 1948 explained the complete picture about TS structure and circulation which was the first comprehensive investigation of ordinary, deep, moist convection [2-3]. Rynolds et al. in 1957, made an effort to determine the basic physical process which gives rise to TS electrification through a laboratory demonstration of these processes [4]. Koteswaram et al. in 1958 studied the synoptic factors responsible for TS formation over Gangetic West Bengal [5]. They stated that the BoB could provide warm humid air masses from the south, the Himalayan range could spill cold dry air masses from the north, and warm, dry air masses could arrive from central India. It is likely that these different air masses form a dry line, much like that occurs in the southern Plains of the United States. Lemonand and Doswel in 1979 investigated the severe TS (super-cell storms) as related to tornado genesis and concluded that there is a consistent pattern of tornado genesis [6]. In 1985, Rotunno et al., examined the rotation and propagation of the supercell-like convection produced by three-dimensional cloud model and found that the thunder storm propagates rightward primarily because of the favorable dynamic vertical pressure gradient that, owing to storm rotation, is always present on the right flank of the updraft [7]. Chowdhury and Karmakar in 1986 investigated the climatology of Nor'westers over Bangladesh with case studies and reported that Nor'westers occurred most frequently in the north central region of Bangladesh during the pre-monsoon season, peaking in April [8]. In 1990, Lilly et al., made an attempt to develop numerical prediction for convective storms and storm environments and describes scientific challenges along with some early progress of NWP [9]. Rasmussen et al., 1998 establishes baseline climatology of parameters commonly used in super-cell TS forecasting and research [10]. Similar study was done about TS over Bangladesh by Karmakar et al. in 2006 [11]. They showed the statistics of convective parameters associated with Nor'westers during the pre-monsoon season in Bangladesh using radiosonde data of Dhaka. They also provided critical values indicating the likelihood of occurrence of Nor'westers for each parameter. However, the critical values provided in their study are subjectively determined. In 2001, Ohsawa et al. investigated the diurnal variations of convective activity and rainfall in tropical Asia, using hourly equivalent black body temperature data from the Japanese Geostationary Meteorological Satellite (GMS-5) and hourly rainfall data from Bangladesh, Thailand, Vietnam and Malaysia [12]. It was suggested that there is a strong possibility that the late night-early morning maxima of convective

activity and rainfall have a great effect on energy and water cycles in tropical Asia. Space and time variations of TSs, physical characteristics of the atmosphere for their formation and frequency distribution of the days of TS over Indo-Bangla region were studied by Karmakar in 2000 and 2001 [13]. Peterson et al., 2002 showed that TS over these regions are most common in the afternoon and overnight [14]. Brooks et al., 2003 depicted that the atmospheric conditions displaying high Convective Available Potential Energy (CAPE) and strong vertical wind shear are favorable for convective storms [15]. Yamane and Hayashi, 2006 showed the seasonal variation of CAPE and the vertical wind shear between the surface and the midlevel of the troposphere in Bangladesh [16]. They showed that both CAPE and vertical wind shear are high during the pre-monsoon season with a peak in April. Although studies have been conducted for pre-monsoon TSs over the Indo-Bangla region, a serious attempt to predict the development is a recent activity by Chaudhuri et al., 2008; Mukhopadhyay et al., 2009; Latha et al., 2011; Tyagi et al., 2011 [17-20]. Chaudhuri, 2008 has studied low level clouds associated with the genesis of severe TS using soft computing technique [17]. Yamane et al., 2016 investigated the climatology of severe local convective storms in Bangladesh using the storm events over a long period from 1990 to 2005 [21]. Latha et al., 2011 have presented pre-monsoon TS development in terms of turbulence and wind fields using Doppler Sonic Detection and Ranging (SODAR) observations [19]. Karmakar et al., 2011 analyzed different modified stability indices with relation to the occurrence of Nor'wester over Bangladesh [22]. Das et al. conducted a coordinated field experiment on severe TS observations and regional modeling over the South Asian Region in 2014 [23]. Mezuman et al., 2014 studied the spatial and temporal distribution of global TS cells and shown that it is possible to use global lightning detection networks, with relatively low detection efficiencies, to determine the location, time and variability of global TS cells [24]. They also developed a methodology of using lightning data in a clustering scheme to determine the number of global TSs as a function of time and space.

Since the last decade, the use of Numerical Weather Prediction (NWP) system to complement the interpretation of conventional observations added great value to TS forecasting. A simulation study was carried out by Vaidya et al., 2007 for pre-monsoon TS over east coast of India [25]. Chatterjee et al., 2008 has been used mesoscale model MM5 with some modifications in the cloud microphysics scheme to simulate two hailstorm events over the Gangetic Plain of West Bengal [26]. The authors recommended that the model MM5 has the ability to simulate hailstorm if the cloud microphysics scheme of Schultz is modified appropriately. In 2008 Litta et al. performed a simulation of a severe TS event using WRF model [27]. Characteristics of severe TS over Bangladesh studied by Basnayake et al., 2009 using Advanced Research WRF (WRF-ARW) model [28]. Rajeevan et al. in 2016 simulated the features associated with a severe TS event over Gadanki of southeast India using WRF model and examined its sensitivity to four different microphysics schemes validated with many observations [29]. This study showed large sensitivity of the microphysics schemes in the simulations of the TS. Das et al., 2015 studied the sensitivity with physical parameterization schemes of WRF-ARW model in the simulation of mesoscale convective systems associated with squall events [23]. Litta et al., 2012 made a comparison of TS simulations between WRF-NMM and WRF-ARW models over East Indian region [30]. It was shown that NMM has performed better than ARW in capturing the sharp rise in humidity and drop in temperature. This suggests that NMM model has the potential to provide unique and valuable information for severe TS forecasters over East Indian region. Ahasan et al in 2014 carried out a simulation of the TS event over Srimangal, Bangladesh on 21 May 2011 using WRF-ARW model [31]. They found that the model overestimated the 24-hour rainfall over the country by 46.72% compared to the rainfall amounts recorded by Bangladesh Meteorological Department (BMD). So, an attempt has been made to simulate TS events over Rajshahi, Rangpur and Sayedpur, Bangladesh on 31 march 2019 using WRF-ARW model. Various weather parameters were examined for deep analyses of the event. For validation of the model performance, simulated values of different parameters have been compared with observed value of BMD. Based on the outcome it can be understood that, model simulated result is good enough to predict TSs over Bangladesh.

2. Experimental Setup, Data Used and Methodology

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 2019 and lateral boundary condition is taken for 48 hours.

The Global Forecast System (GFS) dataset run by the National Centre for Environmental Prediction (NCEP) with the 1°×1° horizontal and 6 hour temporal resolution were used as the initial and

lateral boundary condition in this study. The WRF-ARW model has the availability of a good number of schemes for the examination of different physics such as microphysics, planetary boundary layer (PBL) physics, surface layer physics, radiation physics and cumulus parameterization. The physics and dynamics employed in the model in this study are summarized in Table 1. Three-hourly observed data of MSLP, Temperature, RH and rainfall have been collected from Bangladesh Meteorological Department (BMD) for the validation of model performance.

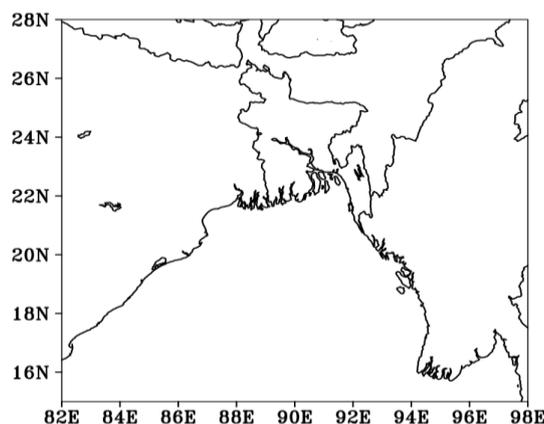


Figure 1: WRF model domain configuration

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 -	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

The WRF-ARW Model has been used for the study of the selected thunderstorm events occurred over Rajshahi, Sayedpur and Rangpur, Bangladesh on 31 March 2019. Model was run using six hourly NCEP-GFS datasets from 0000 UTC of 30 March 2019 to 0000 UTC of 01 April 2019 as initial and lateral boundary condition. Hourly outputs of the model were analyzed for investigating the causes and mechanisms for the formation of the thunderstorm 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.

3. Results 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 for the formation and development of thunderstorms. Three thunderstorm events have been taken for observing the comparison result, which was occurred on 31 March 2019 over Rajshahi, Sayedpur and Rangpur at 0920 UTC to 0950 UTC, 1930 UTC to 2000 UTC and 1900 UTC to 1930 UTC respectively. In this section, behavior of these parameters during a thunderstorm event on 31 March 2019 over Bangladesh is discussed.

3.1 MSLP Analysis

Development of low pressure area is one of most important ingredient of the formation of thunderstorm. So analysis of MSLP is very important for the simulation of thunderstorm events. From the model simulated MSLP analysis, it is found that a trough of westerly low extends up to Bangladesh and it's adjoining area shown in figure

2 (a-i) where the values of MSLP is about 1002 to 1011 hPa from 0700 UTC to 2100 UTC. This trough of westerly low conjugates with easterly waves, then thunderstorms usually form. So, the model simulated the westerly trough very well which is the supportive condition for the formation of thunderstorms based on 0000 UTC 30 March, 2019 initial conditions.

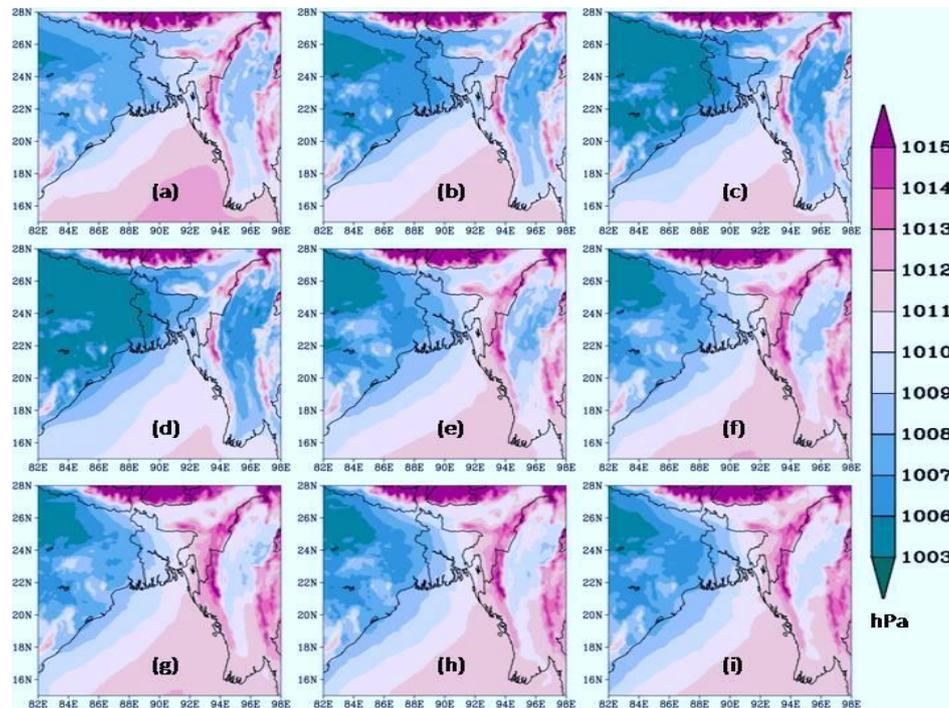


Figure 2 (a-i): ARW model simulated MSLP using Cu_1 and GFS data at (a) 0700 UTC (b) 0800 UTC (c) 0900 UTC (d) 1000 UTC (e) 1700 UTC (f) 1800 UTC (g) 1900 UTC (h) 2000 UTC (i) 2100 UTC on 31 March 2019 based on 0000 UTC 30, March, 2019 initial conditions.

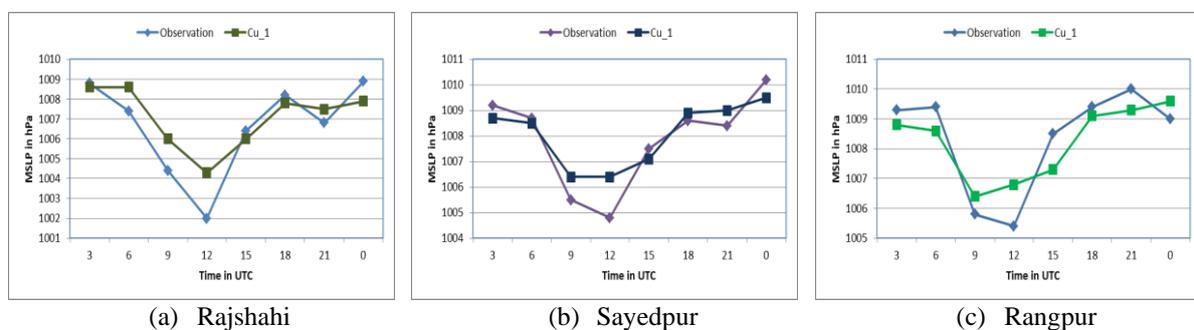


Figure 3 (a-c): Comparison of MSLP between model simulation and observation (a) Over Rajshahi (b) Over Sayedpur (c) Over Rangpur on 31 March 2019.

For the validation of model simulated MSLP, a comparison is made with three hourly observed MSLP recorded by BMD over Rajshahi, Sayedpur and Rangpur on 31 March 2019. This comparison is shown in the figure 3(a), 3(b) and 3(c). From the observed data, a sharp fall of MSLP from 1007.4 hPa to 1002 hPa, 1008.7 hPa to 1004.8 hPa and 1009.4 hPa to 1005.4 hPa is found over Rajshahi, Sayedpur and Rangpur respectively on 31 March 2019 during 0600 UTC to 1200 UTC. From the figure 3, it is found that, Cu_1 capture the sharp fall of MSLP very well over Rajshahi, Sayedpur and Rangpur.

3.2 Wind Pattern Analysis

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

3.2.1 Wind at 850 Level

From the analysis of model simulated wind speed and direction at 850 level, it is found that, a well organized convergence zone is found in foot hill of himalaya and adjoining north bihar. The model simulated the westerly trough of wind very well where the magnitude of wind speed is lower in the center of the convergence zone where as the higher value of wind speed is found at the surrounding adjacent of the convergence zone.

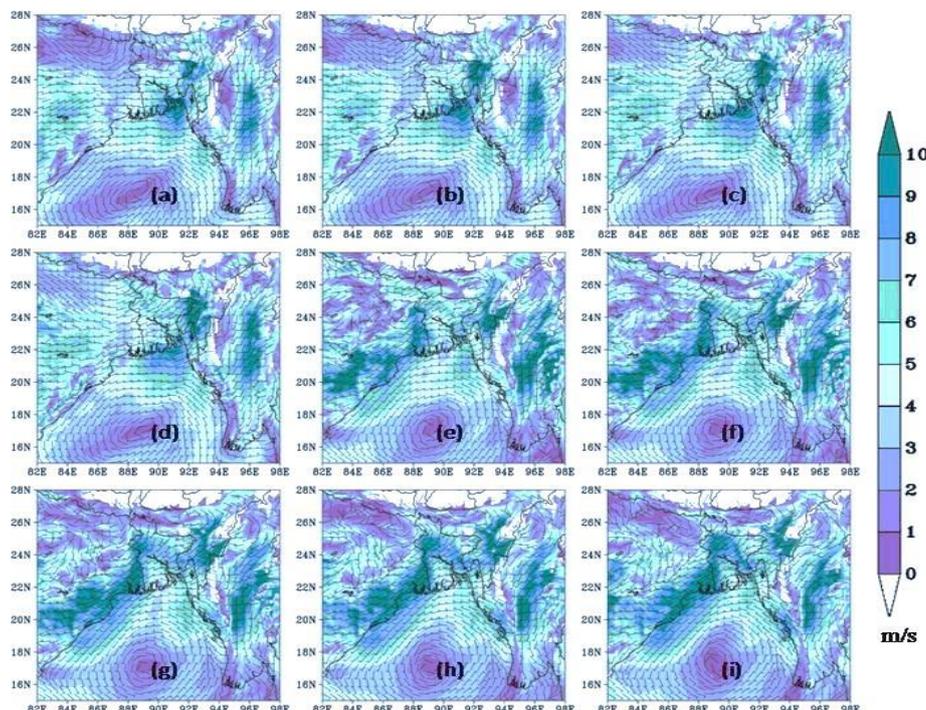


Figure 4 (a-i): ARW model simulated wind speed and direction at 850 level using Cu_1 and GFS data at (a) 0700 UTC (b) 0800 UTC (c) 0900 UTC (d) 1000 UTC (e) 1700 UTC (f) 1800 UTC (g) 1900 UTC (h) 2000 UTC (i) 2100 UTC on 31 March 2019 based on 0000 UTC 30, March, 2019 initial conditions.

On the other hand, a high pressure area or a divergence zone is found on the BoB. So, from the divergence zone wind travels to the convergence zone, from the BoB towards bangladesh. These winds carry high amount of moisture over bangladesh which is the initial condition for the thunderstorm formation and gathering lower level heat energy flux. So, we can say, the model simulate the wind speed at 850 level very well based on 0000 UTC 30 March, 2019 initial conditions. This is shown in figure 4 (a-i).

3.2.2 Wind at 500 Level

From the analysis of model simulated wind speed and direction at 500 level, it is found that, a westerly wind is blowing towards bangladesh from 0700 UTC to 2100 UTC. This wind is cool and dry. When the 850 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 simulate the wind speed at 500 level very well based on 0000 UTC 30 March, 2019 initial conditions. This is shown in figure 5 (a-i)

3.2.3 Wind at 200 Level

From the analysis of model simulated wind speed and direction at 200 level, it is found that, a westerly wind is blowing from 0700 UTC to 2100 UTC shown in fig 6 (a-i) where wind speed is very high. This high wind speed breaks the top of the cloud. It is also an essential pre-condition of approaching of thunderstorms and the model simulate the wind speed very well based on 0000 UTC 30 March, 2019 initial conditions.

3.3. Analysis of Temperature at 2m Height

From the analysis of model simulated temperature at 2 meter height, it is found that, the western part of Bangladesh and adjoining Indian region has higher magnitude of temperature which is more than 34°C from 0700 UTC to 1000 UTC. Afterwards, the temperature drops to 22°C to 26°C which is very much supportive for occurring of convective precipitation and the model simulate the temperature very well based on the 0000 UTC 30 March, 2019 initial conditions. This is shown in figure 7 (a-i).

For the validation of model simulated 2 meter height temperature, three hourly temperature of 31 March 2019 simulated by WRF-ARW model using Cu_1 and GFS data combination is compared with three hourly temperature

recorded by BMD. This comparison over Rajshahi, Sayedpur and Rangpur is shown in figure 8 (a), 8 (b) and 8 (c).

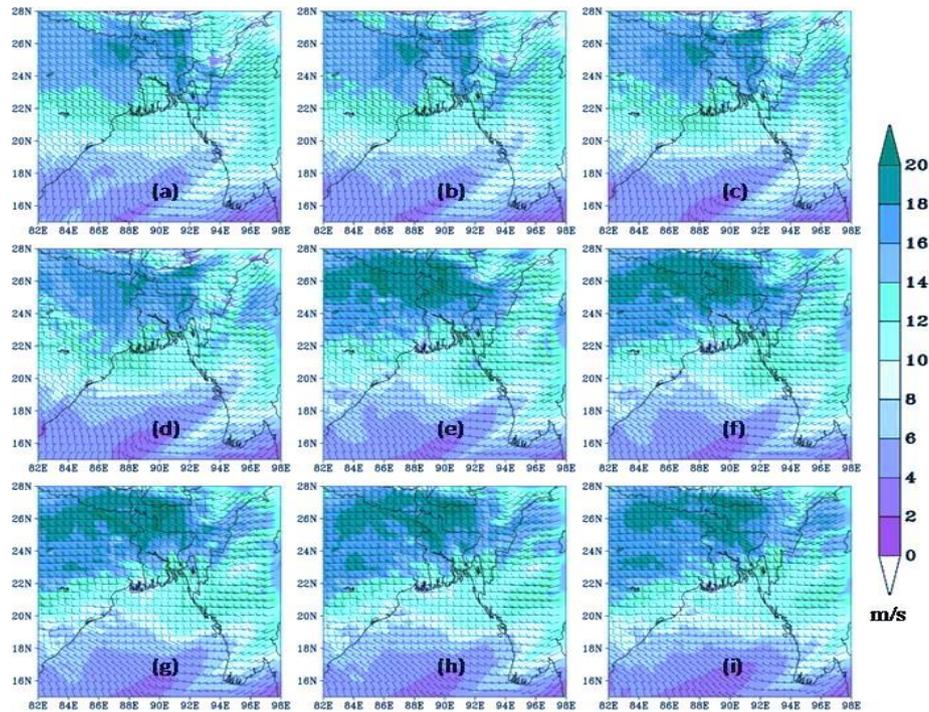


Figure 5 (a-i): ARW model simulated wind speed and direction at 500 level using Cu_1 and GFS data at (a) 0700 UTC (b) 0800 UTC (c) 0900 UTC (d) 1000 UTC (e) 1700 UTC (f) 1800 UTC (g) 1900 UTC (h) 2000 UTC (i) 2100 UTC on 31 March 2019 based on 0000 UTC 30, March, 2019 initial conditions.

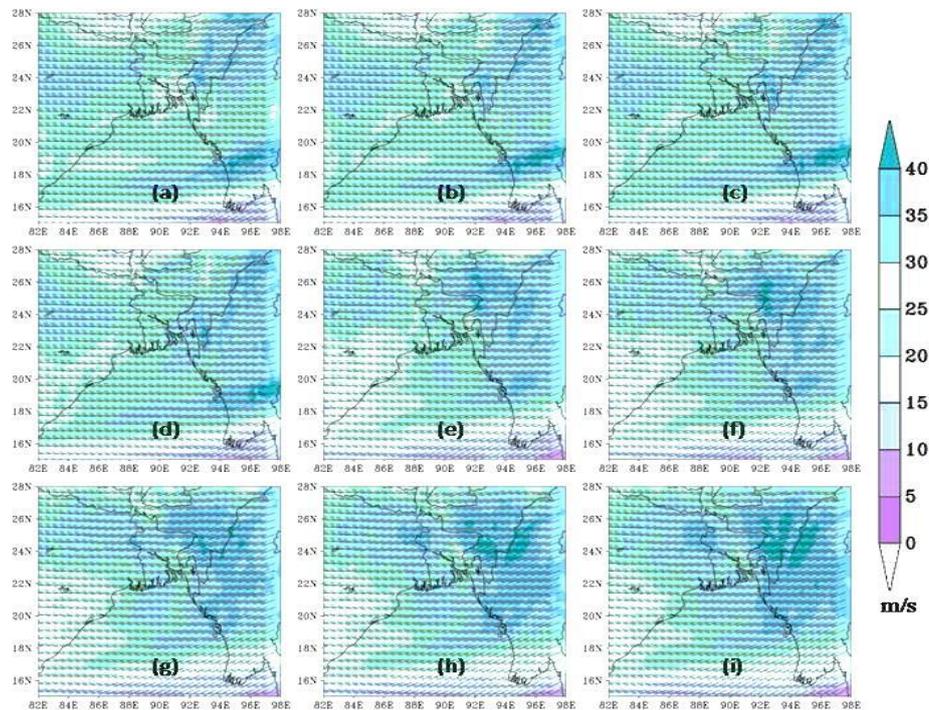


Figure 6 (a-i): ARW model simulated wind speed and direction at 200 level using Cu_1 and GFS data at (a) 0700 UTC (b) 0800 UTC (c) 0900 UTC (d) 1000 UTC (e) 1700 UTC (f) 1800 UTC (g) 1900 UTC (h) 2000 UTC (i) 2100 UTC on 31 March 2019 based on 0000 UTC 30, March, 2019 initial conditions.

From the observed temperature, a sudden fall from 35.5°C to 24°C, 27.5°C to 21°C and 26.3°C to 21.2°C is found over Rajshahi, Sayedpur and Rangpur respectively on 31 March 2019 during 0900 UTC to 1500 UTC. From the figure 8, it is found that, Cu_1 show a fall of temperature but Cu_1 capture the sharp fall of temperature very well over Sayedpur and Rangpur.

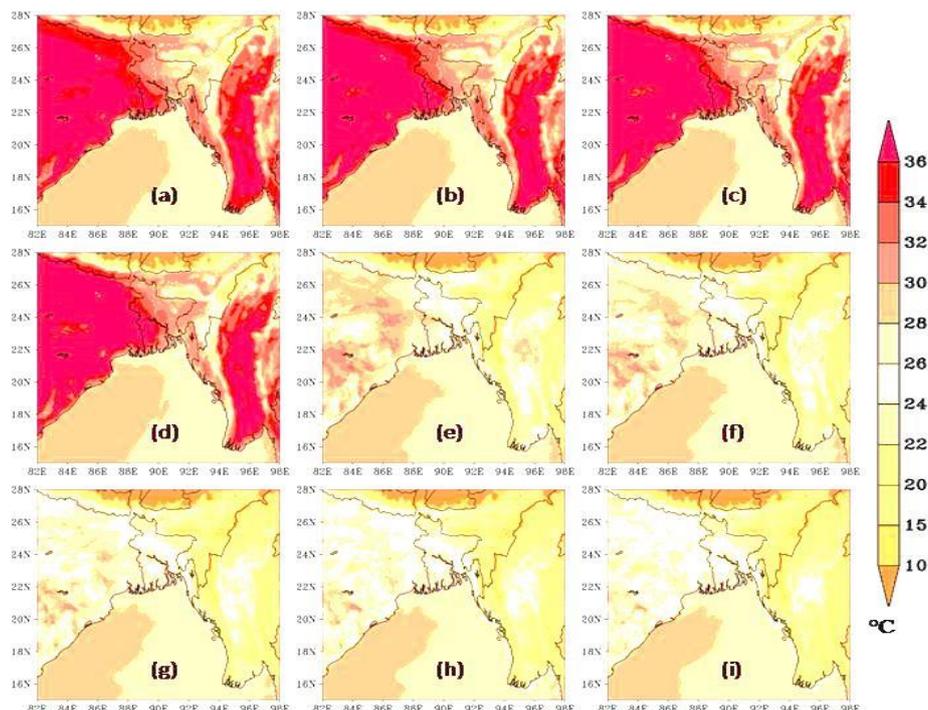


Figure 7 (a-i): ARW model simulated temperature at 2m height using Cu_1 and GFS data at (a) 0700 UTC (b) 0800 UTC (c) 0900 UTC (d) 1000 UTC (e) 1700 UTC (f) 1800 UTC (g) 1900 UTC (h) 2000 UTC (i) 2100 UTC on 31 March 2019 based on 0000 UTC 30, March, 2019 initial conditions.

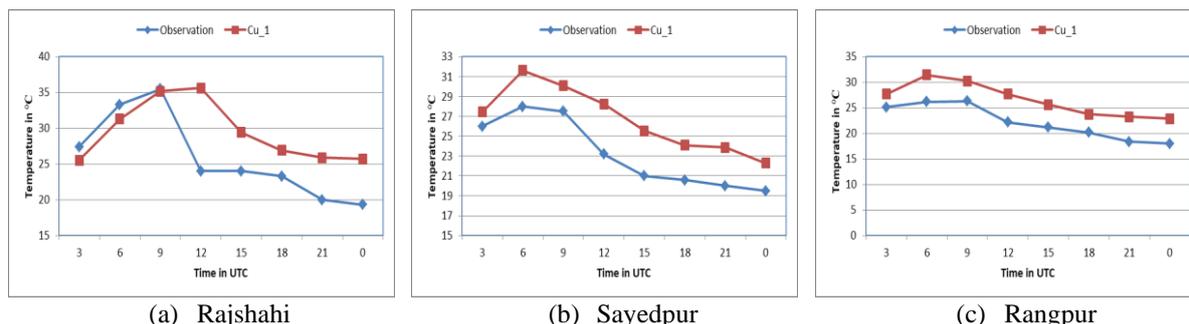


Figure 8 (a-c): Comparison of two meter height temperature between model simulation and observation (a) Over Rajshahi (b) Over Sayedpur (c) Over Rangpur on 31 March 2019.

3.4. Analysis of Relative Humidity at 2m Height

From the analysis of model simulated relative humidity at 2 meter height, it is found that, the dry line penetrates towards Bangladesh from 0700 UTC to 1000 UTC. The relative humidity is less than 40% in the left side of the marker dark black line or dry line and relative humidity is more than 40% in the right side of the dry line from 0700 UTC to 1000 UTC. Afterwards, the relative humidity is started to increase. Usually, thunderstorm forms at the right vicinity of dry line. The increase of relative humidity at the right side of the dry line is the pre-condition of formation of thunderstorms. So, we can say, the model simulated the relative humidity very well based on the 0000 UTC 30 March, 2019 initial conditions. This is shown in figure 9 (a-i).

For the validation of model simulated relative humidity, a comparison is made with three hourly observed relative humidity. From the observed data, a sharp rise of RH from 72% to 98% during 1500 UTC to 2100 UTC is found over Rajshahi. Model also found a rise of RH from 57% to 80% and 62% to 84% during 0900 UTC to 1800 UTC over Sayedpur and Rangpur respectively. From the model simulation result, the rise of RH over Rajshahi is 60% to 83.2% which is shown in figure 10 (a). The rise of RH over Sayedpur is 56.5% to 82.3% which is shown in figure 10 (b) and the rise of RH over Rangpur is 55% to 81.4% which is shown in figure 10 (c). From the above analysis, it is found that, Cu_1 capture the rise of RH very well.

3.5 Analysis of Vorticity

From the analysis of model simulated vorticity, it is found that, the value of vorticity is $(0-20) \times 10^{-5} \text{ s}^{-1}$ in most of the region of Bangladesh from 0700 UTC to 2100 UTC. There are some areas in Bangladesh where the value of vorticity is $(30-40) \times 10^{-5} \text{ s}^{-1}$ from 0700 UTC to 1000 UTC. So, we can see the value of vorticity is positive throughout the country which is the pre-condition of formation of thunderstorms and the model simulate vorticity very well based on the 0000 UTC 30 March,2019 initial conditions. This is shown in figure 11 (a-i).

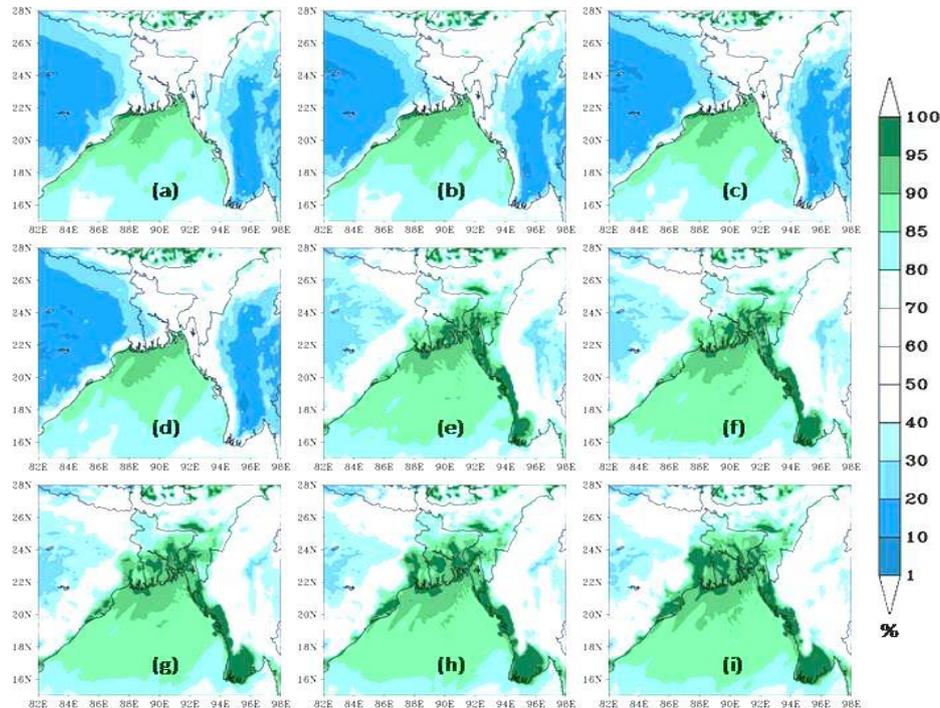


Figure 9 (a-i): ARW model simulated relative humidity at 2m height using Cu_1 and GFS data at (a) 0700 UTC (b) 0800 UTC (c) 0900 UTC (d) 1000 UTC (e) 1700 UTC (f) 1800 UTC (g) 1900 UTC (h) 2000 UTC (i) 2100 UTC on 31 March 2019 based on 0000 UTC 30, March,2019 initial conditions.

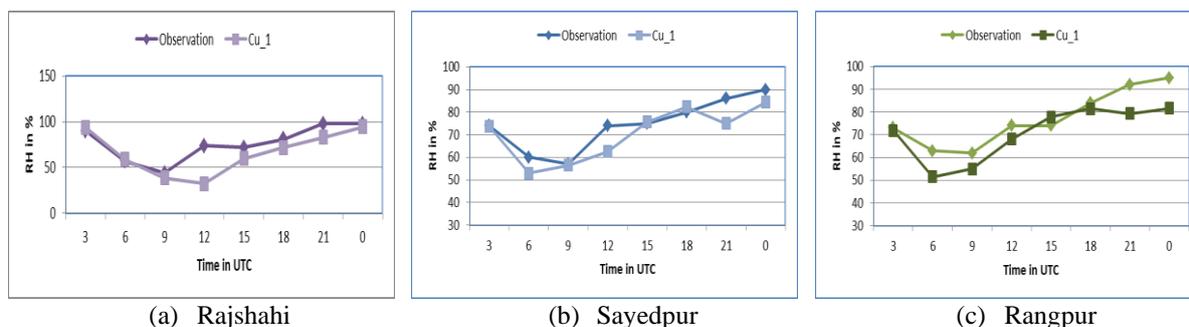


Figure 10 (a-c): Comparison of two meter height relative humidity between model simulation and observation (a) Over Rajshahi (b) Over Sayedpur (c) Over Rangpur on 31 March 2019.

3.6 Analysis of Vertical Wind shear

From the analysis of model simulated vertical windshear, it is found that, the value of vertical windshear is positive all over Bangladesh from 0700 UTC to 2100 UTC. We know that, the value of vertical windshear greater than 10 m/s, is very supportive for the formation of thunderstorm. We can see from the model simulated output that, Rangpur, Mymensingh, Sylhet and it's adjoining area has a higher value of vertical windshear which varies from 10 m/s to 20 m/s from 0700 UTC to 2100 UTC. So, we can see the value of vertical windshear is positive throughout the country and very high in some part of the country which is the pre-condition of formation of thunderstorms and the model simulate vertical windshear very well based on the 0000 UTC 30 March,2019 initial conditions. This is shown in figure 12 (a-i).

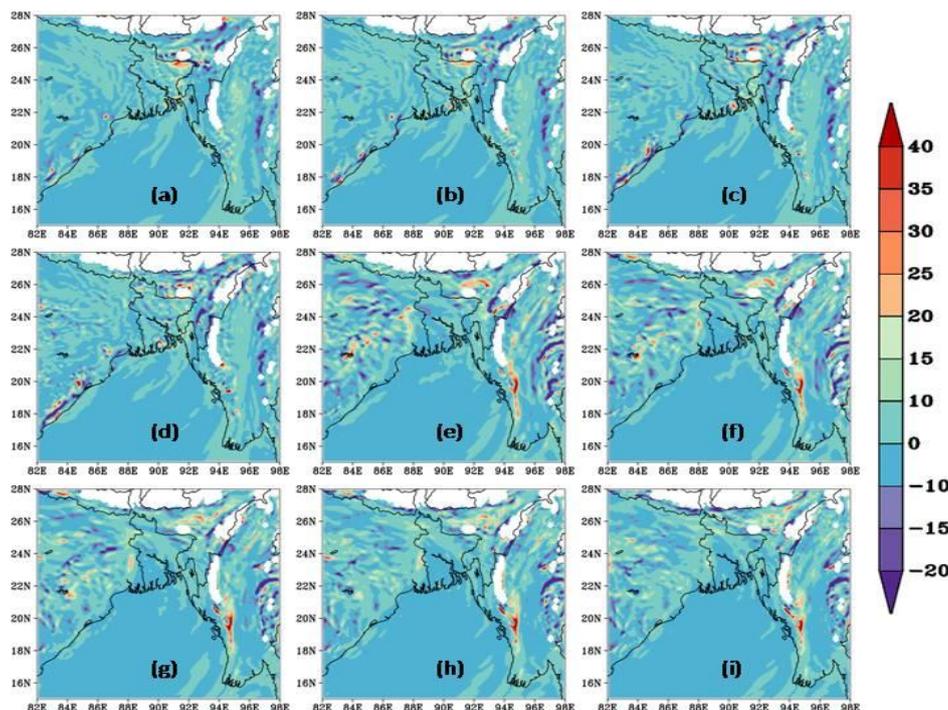


Figure 11 (a-i): ARW model simulated vorticity using Cu_1 and GFS data at (a) 0700 UTC (b) 0800 UTC (c) 0900 UTC (d) 1000 UTC (e) 1700 UTC (f) 1800 UTC (g) 1900 UTC (h) 2000 UTC (i) 2100 UTC on 31 March 2019 based on 0000 UTC 30, March, 2019 initial conditions.

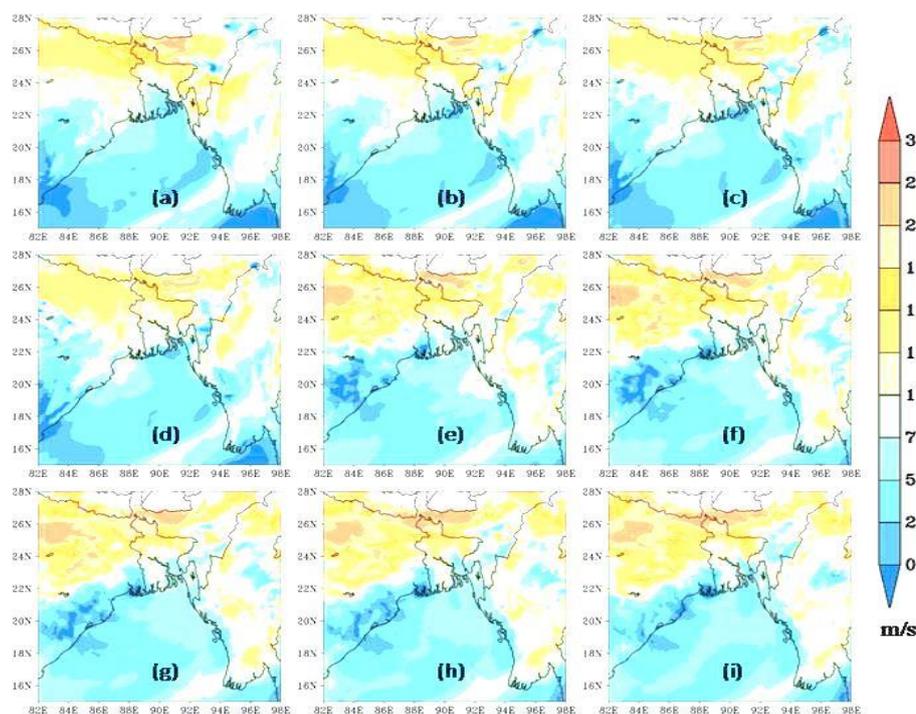


Figure 12 (a-i): ARW model simulated windshear using Cu_1 and GFS data at (a) 0700 UTC (b) 0800 UTC (c) 0900 UTC (d) 1000 UTC (e) 1700 UTC (f) 1800 UTC (g) 1900 UTC (h) 2000 UTC (i) 2100 UTC on 31 March 2019 based on 0000 UTC 30, March, 2019 initial conditions.

3.7 Analysis of MCAPE

From the analysis of model simulated MCAPE, it is found that, the value of MCAPE at most unstable layer from 0700 UTC to 2100 UTC is greater than 1500 j/kg. MCAPE value greater than 1500 j/kg is required for the formation of thunderstorm. From model simulated result, we can see that, in most part of Bangladesh MCAPE value varies from 2000 j/kg to 3000 j/kg from 0700 UTC to 1000 UTC. The value is even much higher in most part of Bangladesh from 1700 UTC to 2100 UTC which varied from 2500 j/kg to 4000 j/kg. So, we can see the

value of MCAPE is greater than 1500 j/kg throughout the country which is the pre-condition of formation of thunderstorms and the model simulate MCAPE very well based on the 0000 UTC 30 March,2019 initial conditions. This is depicted in figure 13 (a-i).

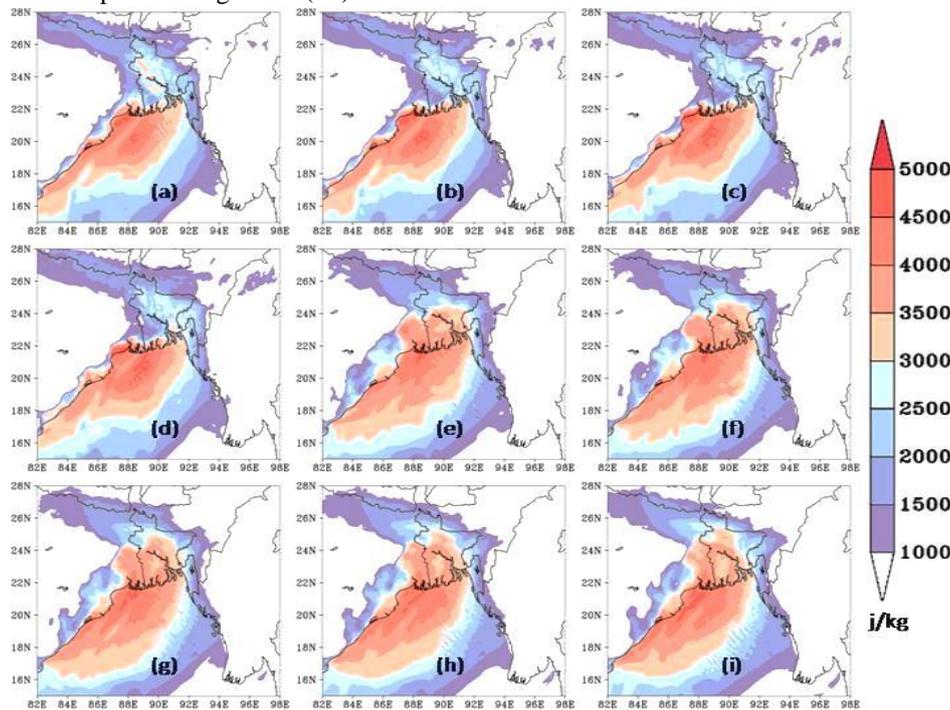


Figure 13 (a-i): ARW model simulated MCAPE using Cu_1 and GFS data at (a) 0700 UTC (b) 0800 UTC (c) 0900 UTC (d) 1000 UTC (e) 1700 UTC (f) 1800 UTC (g) 1900 UTC (h) 2000 UTC (i) 2100 UTC on 31 March 2019 based on 0000 UTC 30, March, 2019 initial conditions.

3.8 Analysis of Accumulated Heat Flux

From the analysis of model simulated accumulated heat flux, it is found that, there were significant heat flux field over west Bengal and adjoining area of Bangladesh before occurring or before formation of thunderstorm events.

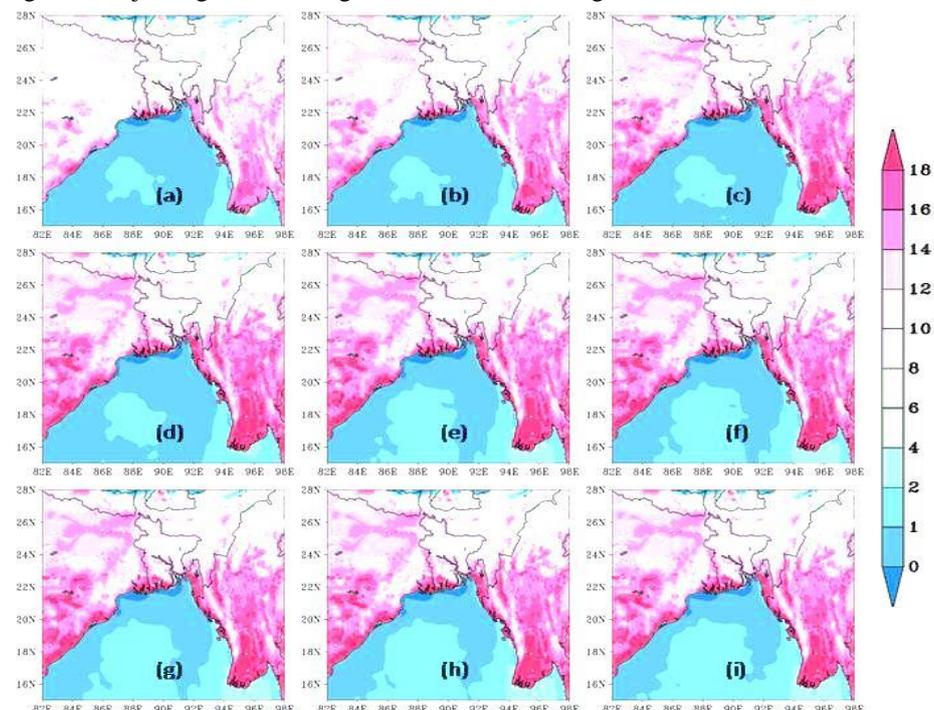


Figure 14 (a-i): ARW model simulated accumulated heat flux using Cu_1 and GFS data at (a) 0700 UTC (b) 0800 UTC (c) 0900 UTC (d) 1000 UTC (e) 1700 UTC (f) 1800 UTC (g) 1900 UTC (h) 2000 UTC (i) 2100 UTC on 31 March 2019 based on 0000 UTC 30, March, 2019 initial conditions.

It means, there was sufficient heat available for making the lower tropospheric levels unstable as well as uplifting the air parcels for supporting convective activity over or near the thunderstorm events. This situation also helps to carry moisture to mid tropospheric level where convective cloud cells formed for generation of thunderstorm, as depicted to figure 14 (a-i).

Magnitude of the maximum heat flux within the range $(8-14) \times 10^6$ found over west Bengal and adjoining western part of Bangladesh. So, we can say, the model simulated accumulated heat flux very well based on the 0000 UTC 30 March, 2019 initial conditions.

3.9 Analysis of Latent Heat Flux

Analysis of the simulation of latent heat flux at surface level indicates that, before during thunderstorm as well as afterwards of the thunderstorm event, latent heat flux was maximum over Bangladesh and adjoining areas with the range of $(1-2.5) \times 10^6$.

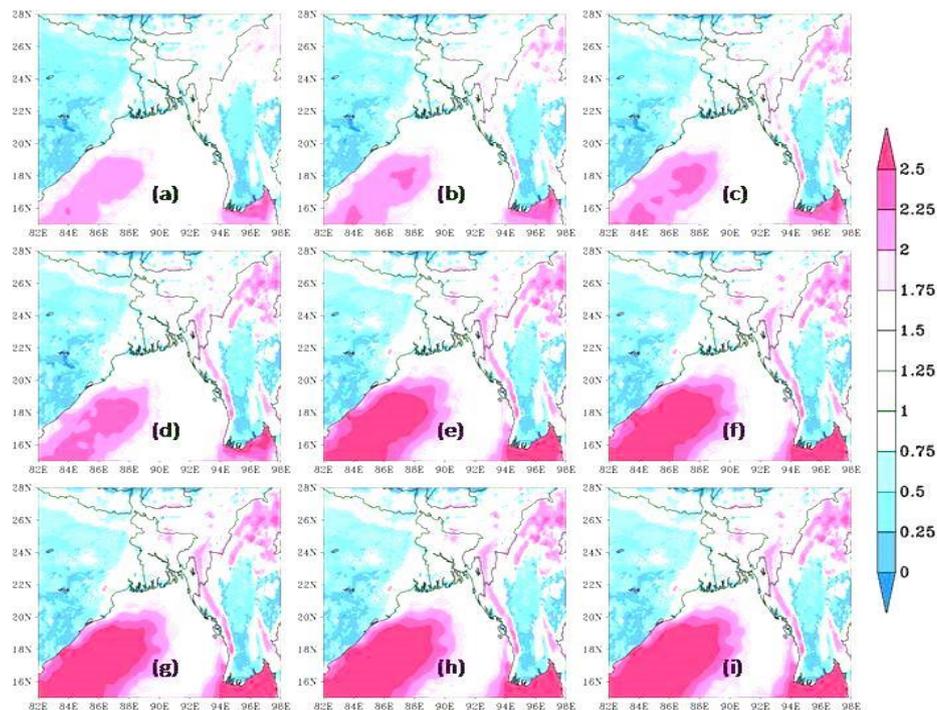


Figure 15 (a-i): ARW model simulated latent heat flux using Cu_1 and GFS data at (a) 0700 UTC (b) 0800 UTC (c) 0900 UTC (d) 1000 UTC (e) 1700 UTC (f) 1800 UTC (g) 1900 UTC (h) 2000 UTC (i) 2100 UTC on 31 March 2019 based on 0000 UTC 30, March, 2019 initial conditions.

It means, when the thunderstorm event moved over Bangladesh due to releasing heat from the thunderstorm cloud, lower troposphere over Bangladesh becoming warmer and warmer. It means, thunderstorm event passes over Bangladesh with the sufficient thunderstorm activities as well as releasing heat which helped to increase the lower tropospheric temperature of Bangladesh as shown in figure 15 (a-i).

3.10 Analysis of Rainfall

When downdraft starts to dominate over updraft, thunderstorm gradually dies through heavy rain. So, rainfall plays an important role in thunderstorm. From the analysis of model simulated 3 hourly rainfall, it is found that, model simulated very little amount of rainfall at Rajshahi and Sayerpur during the day. Model simulated 6 mm rainfall at Rangpur from 0600 UTC to 0900 UTC and 9 mm rainfall found from 0900 UTC to 1200 UTC. Moderate rainfall simulated over Sylhet, Habiganj and adjoining area from 0000 UTC to 0300 UTC which is 15 mm to 40 mm and model simulated similar amount of rainfall from 0300 UTC to 0600 UTC. A very low amount of rainfall simulated over Rangpur, Dinajpur and adjoining area from 0900 UTC to 1200 UTC which is about 1 mm to 9 mm. Little amount of rainfall was found by model simulation over Habiganj and adjoining area from 1500 UTC to 2100 UTC. This is shown in figure 16 (a-h).

For the validation of model simulated rainfall, a comparison is made between the model simulated 24 hour rainfall using Cu_1 and GFS dataset combination and the observed rainfall data recorded by BMD. The comparison is shown in figure 17.

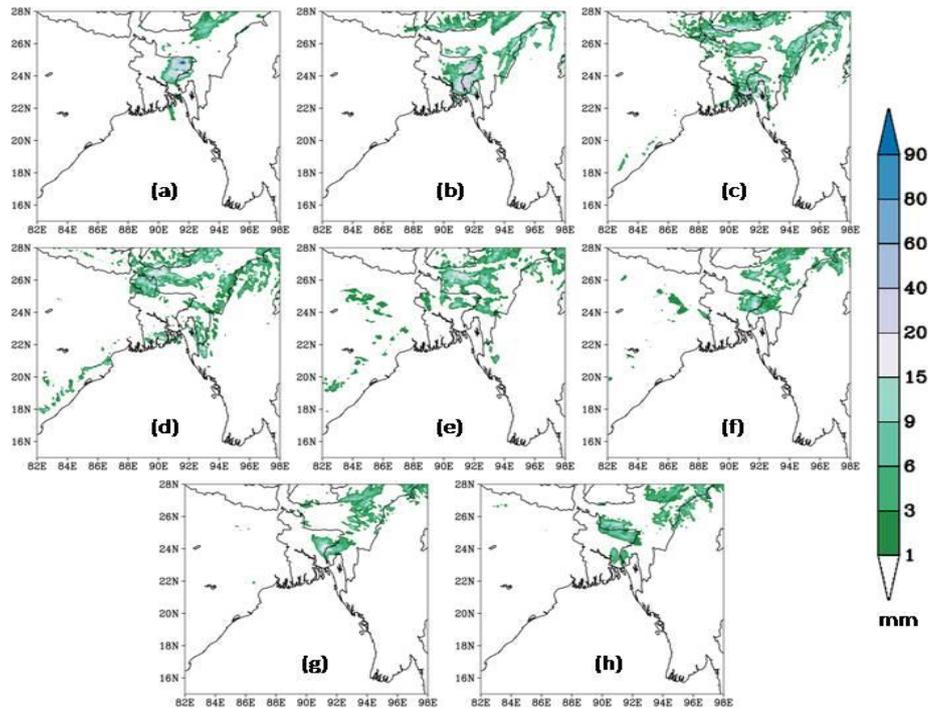


Figure 16 (a-h): ARW model simulated rainfall using Cu_1 and GFS data at (a) 0000-0300 UTC (b) 0300-0600 UTC (c) 0600-0900 UTC (d) 0900-1200 UTC (e) 1200-1500 UTC (f) 1500-1800 UTC (g) 1800-2100 UTC (h) 2100-0000 UTC on 31 March 2019 based on 0000 UTC 30, March, 2019 initial conditions.

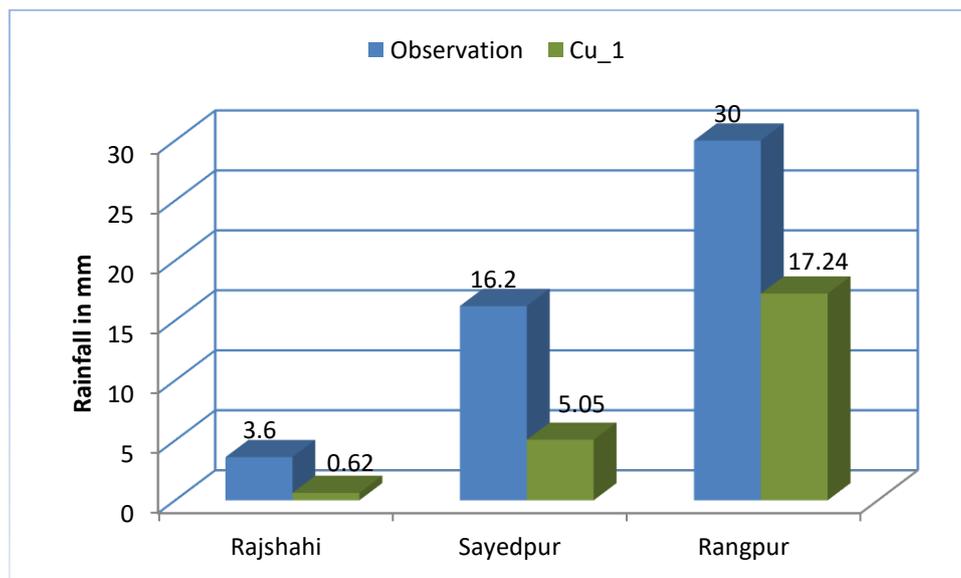


Figure 17: Comparison of model simulated rainfall and observed rainfall

From the above figure, it is found that, model simulated rainfall is less than the observed rainfall in all three thunderstorm events. So, in this case, model simulated rainfall underestimate compared to the observed rainfall. But the model is capable to capture the rainfall in the thunderstorm events and its surrounding area.

4. Conclusion

The following conclusions can be made on model performance for capturing thunderstorm event over Bangladesh.

- The WRF model has simulated the westerly trough of low very well which is the main supportive condition for the formation of thunderstorms. It is found, the value of MSLP is about 1002 to 1011 hPa from 0700 UTC to 2100 UTC during the thunderstorm at 0600 UTC to 1200 UTC with capturing the sharp fall of pressure over Rajshahi, Rangpur and Sayedpur.
- Model is capable to capture the strong wind speed over Bangladesh at 850 hPa and 200 hPa. The well-organized convergence zone is found in foot hill of the Himalaya and adjoining north Bihar and it tilted south-eastwards. A divergence zone is found on the BoB which pushes high winds towards Bangladesh

and carries high amount of moisture. It is favorable for the development of cumulonimbus cloud which triggers thunderstorm over Bangladesh and adjoining area.

- Model is good enough to capture the sudden fall of temperature during the thunderstorm over Rajshahi, Rangpur and Sayedpur. It is the prime indication of occurring cold precipitation from towering clouds. It is good sign for the development of thunderstorm.
- The RH is quite low at the left side of the dry-line and higher in the right side. Dry-line is the region where dry and hot air mass conjugates with moist and warm air mass. So, the thunderstorm occurs at the vicinity of the dry-line. Model is good enough to capture the dry-line. The signature of model simulated three hourly RH and observed RH of BMD is reasonably well.
- The value of vorticity is $(0-20) \times 10^{-5} \text{ s}^{-1}$ from 0700 UTC to 2100 UTC over Rajshahi, Rangpur and Sayedpur of Bangladesh. Model captures the positive value of vorticity during the thunderstorm which is the pre-condition of formation of thunderstorms.
- The value of vertical wind shear is positive throughout the country ($10-20 \text{ ms}^{-1}$) and very high in some part of Rajshahi, Rangpur and Sayedpur during 0700 to 2100 UTC which is the pre-condition of formation of thunderstorms and the model simulates vertical wind shear very well.
- The MCAPE is the measurement of potential energy over the high unstable regions and found 2000 j/kg to 3000 j/kg from 0700 UTC to 1000 UTC. The value is even much higher in most part of Bangladesh from 1700 UTC to 2100 UTC which varied from 2500 j/kg to 4000 j/kg throughout the country during the thunderstorm. It is the pre-condition of formation of thunderstorms and the model has simulated MCAPE precisely well.
- Model captures the availability of sufficient heat flux for making the lower tropospheric level unstable and the range of accumulated heat flux is $(8-16) \times 10^6$ over Bangladesh during the thunderstorm. So the model simulates accumulated heat flux well enough.
- The value of latent heat flux in the range of $(1-2.25) \times 10^6$ is found during the thunderstorm over Bangladesh. This range of value is supportive for the formation of deep convective clouds which is important for system intensification. So, it can be concluded that, latent heat flux captured by the model is also good enough for the system prediction.
- Model simulated 24 hour rainfall was 0.62 mm over Rajshahi, 5.05 mm in Sayedpur and 17.24 mm over Rangpur. The model underestimates the rainfall compared to the observation rainfall of BMD. But the model is capable to capture the rainfall of the thunderstorms though it has some biases.

From the above discussion and conclusion, it can be decided that, the WRF-ARW model is capable to predict the thunderstorm events over Bangladesh though it consists of some errors and biases.

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