Thunderstorm and Its Features Simulation using WRF-ARW Model over Sylhet, Bangladesh

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Abstract

An attempt has been made to simulate a Thunderstorm event over Sylhet (25.73°N, 89.25°E), Bangladesh occurred from 1900 UTC to 1930 UTC on 15-17 April 2016 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 15 April 2016 to 0000 UTC of 17 April 2016 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 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 said that, model simulated result is good enough to predict thunderstorms over Bangladesh.

1. Introduction

Most of the weather events occurring over Bangladesh and its neighborhood are mesoscale or regional scale phenomena. These mesoscale phenomena is called TSs, 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).Thunder storms 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 Bay of Bengal. 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 Bay of Bengal 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 this region 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]. Karmokar et al., 2011 analyized 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 a TS event over Sylhet, Bangladesh on 15-17 April 2016 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 2016 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.

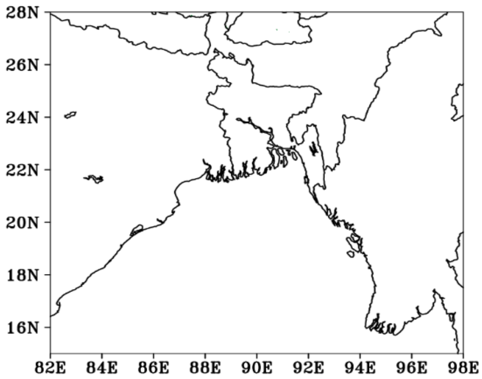

Figure 1: WRF model domain configuration

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 event occurred over Sylhet, Bangladesh on 15-17 April 2016. Model was run using six hourly NCEP-GFS datasets from 0000 UTC of 15 April 2016 to 0000 UTC of 17 April 2016 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. The thunderstorm became mature stage and passed through the country from 1000 UTC to 1200 UTC as per BMD observation. For the validation of the model performance, values of several parameters were compared with the observed value collected from BMD.

3. Results and Discussion

The analysis of the model output using cumulus physics scheme-1 (Cu_1) is discussed in this section. Comparison of the model outcome with observed output is also included here.

3.1 Analysis of Mean Sea Level Pressure

The analysis of Sea Level Pressure from 0000 - 1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 15 and 16 April, 2016 which is shown in figure 2 and figure 3 respectively. The analysis indicates that a tough of low (1003 - 1008 hPa) extends up to NE part of Bangladesh from West Bengal. The model has also simulated the high pressure area over Meghalaya and Eastern Part of Bangladesh. As the NE part is Hilly region and buoyancy occurred in the wind side of the Hilly region. So, it is the supportive condition for the formation of orographic cloud. It is also mentionable that a belt of pressure gradient found to the right side of the trough. So, there is a possibility of incursion of huge amount of moisture towards NE part of Bangladesh from the Bay of Bengal which is source of energy to accelerate the buoyancy process in wind side. At 1200 UTC on 17 April, 2016 the lowest sea level pressure of magnitude 1004 - 1006 hPa found over Sylhet and adjoining area based on 48 h and 72 h advanced model run which is the indication of convergence zone and afterwards it starts to increase which is supportive for the divergence.

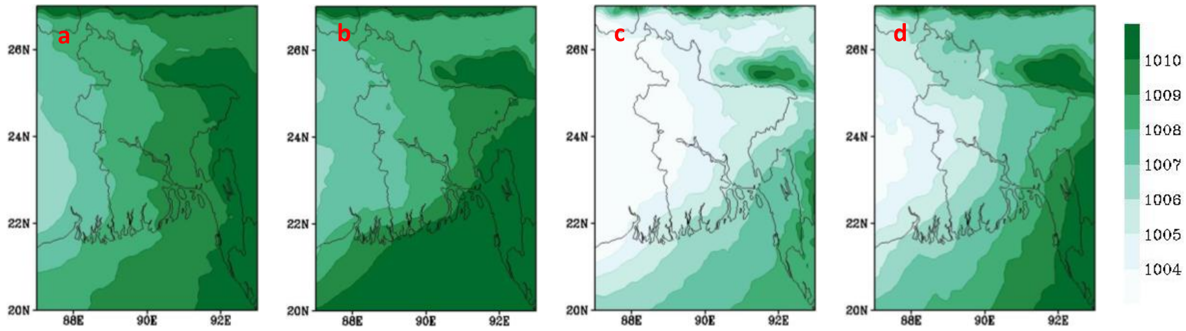

Figure 2: Sea Level Pressure at a) 0000 UTC, b) 0600UTC, c) 1200UTC & d) 1800UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 15 April, 2016 respectively.

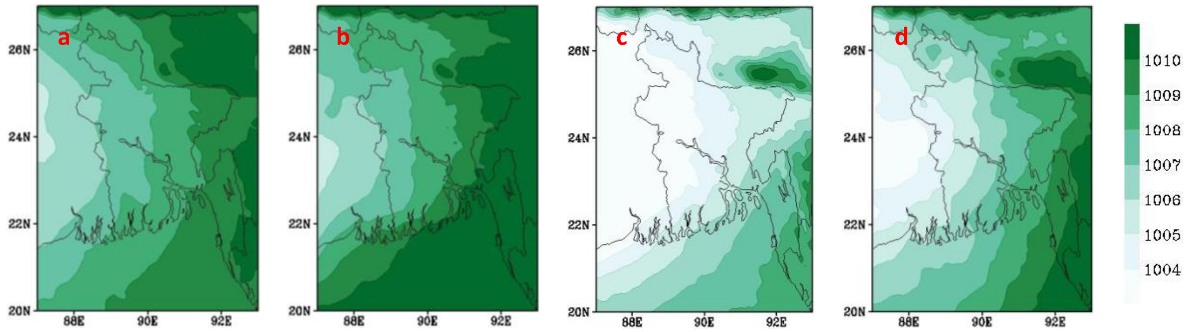

Figure 3: Sea Level Pressure at a) 0000UTV, b) 0600UTC) 1200UTC & d)1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 16 April, 2016 respectively.

3.2 Analysis Wind Pattern at 850 and 500 hPa level

The model simulated wind flow at 850 hPa and 500 hPa level from 0000 - 1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 15 and 16 April, 2016 which is shown in figure 4, figure 5, figure 6 and figure 7 respectively. From the analysis of wind flow at 850 hPa level, it is found that a narrow belt of south-southwesterly wind is blowing from the Bay of Bengal towards the convergence zone of Sylhet and adjoining area and Sylhet through central part of Bangladesh which is shown in figure 4 and figure 5 during 0000 UTC to 1800 UTC of 17 April, 2016 based on 72 hours and 48 hours advanced run respectively. This wind flow carries high amount of moisture towards Bangladesh which is very much related to cloud formation. Due to the orographic effect in the NE part of Bangladesh, this high amount of moisture uplifted and enhanced shallow or deep convection. It is the favourable condition for rainfall processes.

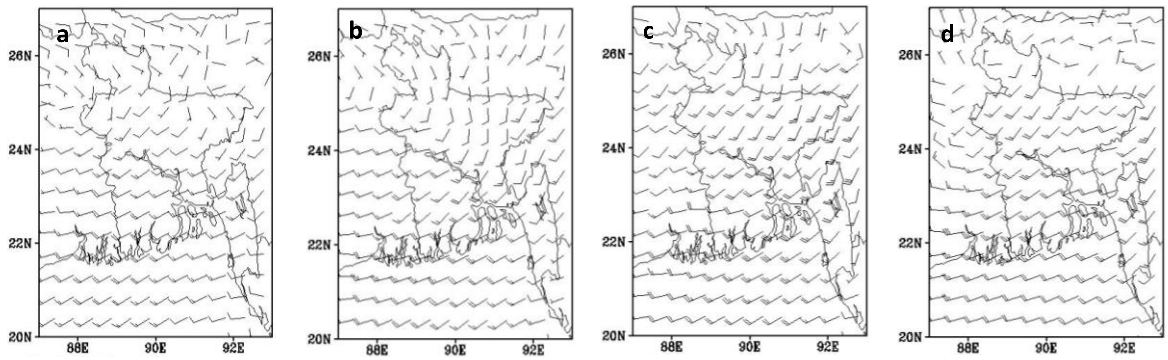

Figure 4: Wind flow analysis at 850 hPa level at a) 0000 UTC, b)0600 UTC, c)1200 UTC & d)1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 15 April, 2016 respectively.

The model predicted wind of 500 hPa level represents west-northwesterly wind flow is pushing towards Sylhet which is shown in figure 6 and figure 7 during 0000 UTC to 1800 UTC of 17 April, 2016 based on 72 hours and 48 hours advanced run respectively.

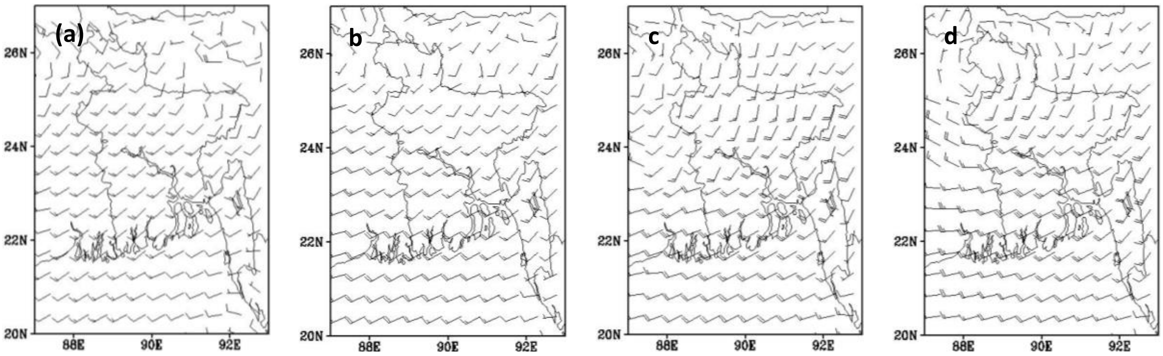

Figure 5: Wind flow analysis at 850 hPa level at a) 0000 UTC,b) 0600 UTC, c)1200 UTC & d)1800UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 16 April, 2016

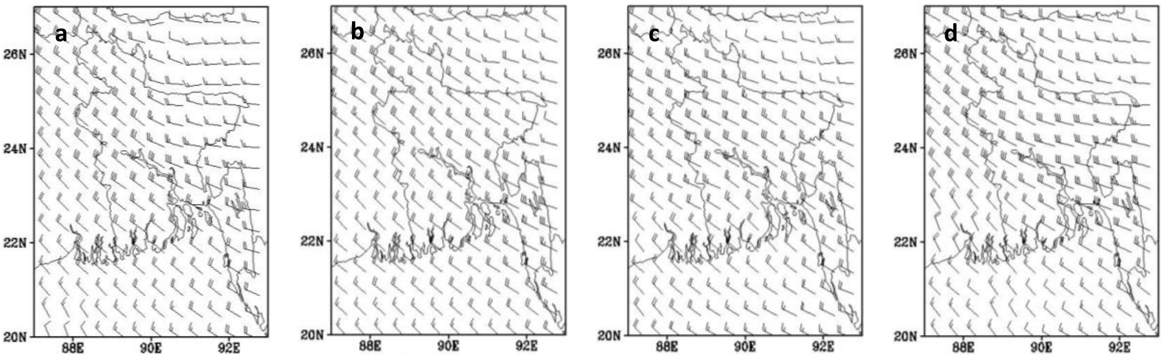

Figure 6: Wind flow analysis at 500 hPa level at a) 0000 UTC, b) 0600 UTC, c)1200 UTC & d)1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 15 April, 2016.

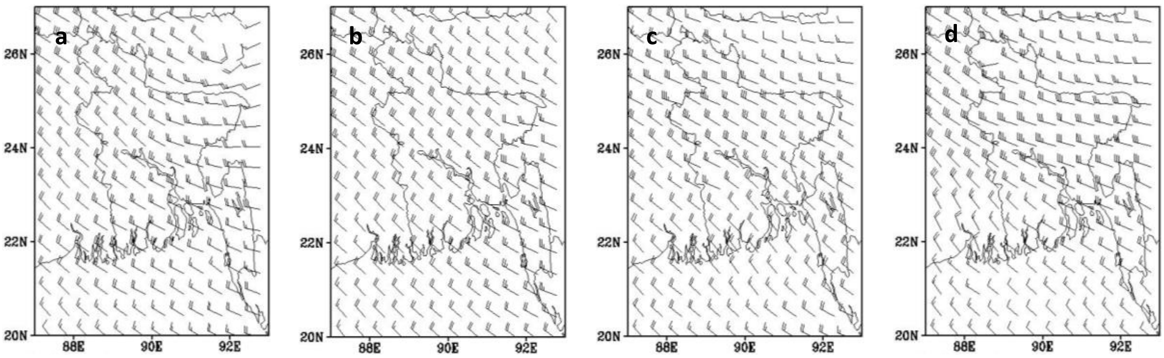

Figure 7: Wind flow analysis at 500 hPa level at a) 0000 UTC, b)0600 UTC, c)1200 UTC & d01800UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 16 April, 2016 respectively.

3.3 Relative Humidity at 2m Height and its Vertical Cross-section

The analysis of relative humidity at 2m height from 0000 - 1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 15 and 16 April, 2016 which is shown in figure 8 and figure 9 respectively. It is found that the relative humidity is 75-100% over Sylhet and adjoining. The high amount of moisture is responsible for buoyant of air and ultimately cloud formation. It is also mentionable that the relative humidity is more than 95% at wind side of the hilly region of Sylhet. The heavy rainfall occurred at the right side of the dry line (border of dry and hot air with moist and warm air).

The vertical cross-section of relative humidity from 0000 - 1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 15 and 16 April, 2016 for zonal (at lat. 24.9^0 N) which is shown in figure 10 and figure 11 and for meridional (at lon. 91.9^0 E) which is shown in figure 12 and figure 13 respectively. The model simulated vertical cross-section of zonal relative humidity indicates that 60-80% of moisture is extended up to 500 hPa level along $88\text{-}90^0$ E and 80-100% of moisture is extended up to 200 hPa level along $91\text{-}93^0$ E, whereas the meridional relative humidity indicates that 80-100% of moisture is extended up to 200 hPa level along $23\text{-}27^0$ N. It is clear that initially the relative humidity is uplifted from a single cell. It also indicates that the vertically uplifted moisture is responsible for cloud formation and it is the indication of occurring heavy rainfall.

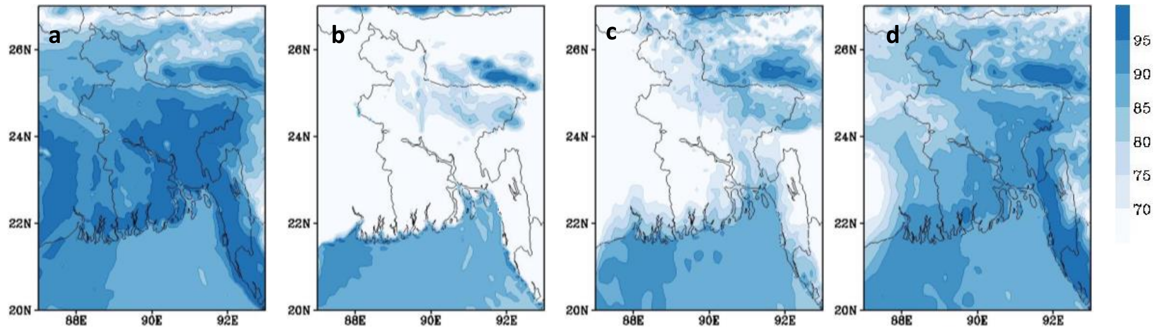

Figure 8: Relative Humidity at 2m height on a) 0000 UTC, b) 0600 UTC, c)1200 UTC & d)1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 15 April, 2016

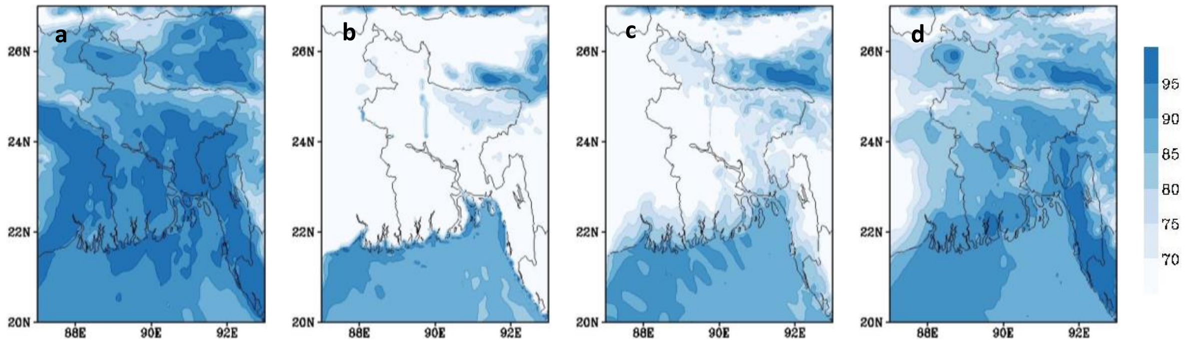

Figure 9: Relative Humidity at 2m height at at) 0000UTC, b) 0600UTCUTC, c)1200 & d)1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 16 April, 2016.

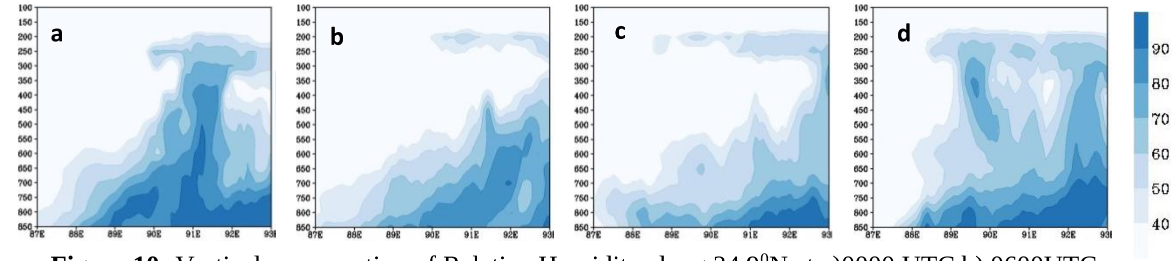

Figure 10: Vertical cross-section of Relative Humidity along 24.9^{0}N at a)0000 UTC,b) 0600UTC, c)1200UTC & d)1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 15 April, 2016

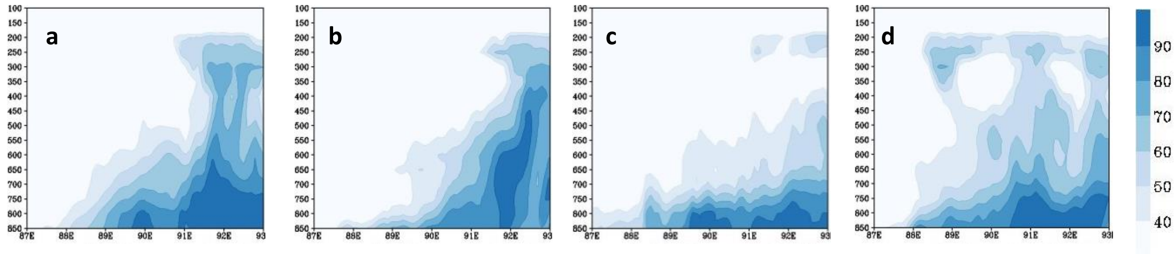

Figure 11: Vertical cross-section of Relative Humidity along 24.9^{0}N at a) 0000 UTC, b) 0600UTC, c)1200UTC & d)1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 16 April, 2016.

The vertical cross-section of relative humidity from 0000 - 1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 15 and 16 April, 2016 for zonal (at lat. 24.9^0 N) which is shown in figure 10 and figure 11 and for meridional (at lon. 91.9^0 E) which is shown in figure 12 and figure 13 respectively. The model simulated vertical cross-section of zonal relative humidity indicates that 60-80% of moisture is extended up to 500 hPa level along 88-90^0 E and 80-100% of moisture is extended up to 200 hPa level along 91-93^0 E, whereas the meridional relative humidity indicates that 80-100% of moisture is extended up to 200 hPa level along 23-27^0 N. It is clear that initially the relative humidity is uplifted from a single cell. It also indicates that the vertically uplifted moisture is responsible for cloud formation and it is the indication of occurring heavy rainfall.

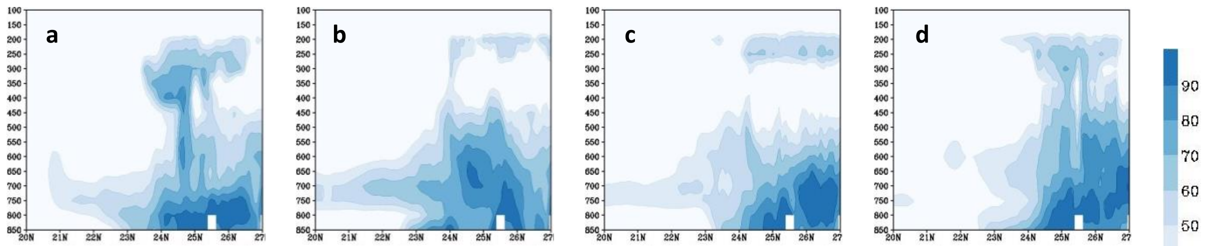

Figure 12: Vertical cross-section of Relative Humidity along 91.9^{0}E at a)0000UTC, b) 0600UTC, c)1200UTC & d)1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 15 April, 2016.

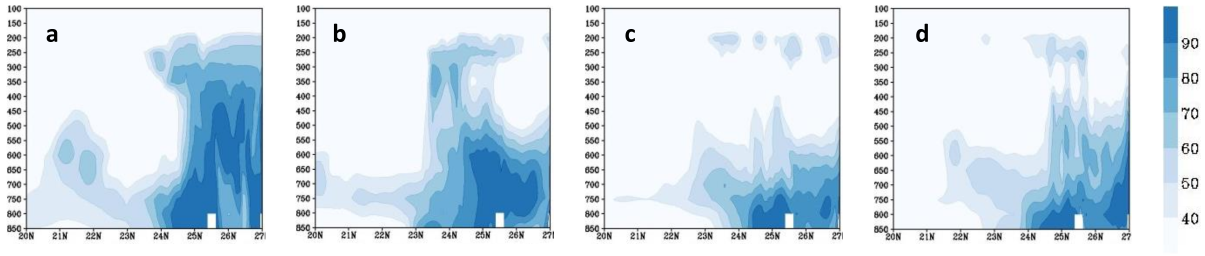

Figure 13: Vertical cross-section of Relative Humidity along 91.9^{0}E at a) 0000 UTC, b) 0600UTC, c)1200UTC & d)1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 16 April, 2016

3.4 Wind Shear Analysis

The wind shear analysis ($u_{500} - u_{850}$) from 0000 - 1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 15 and 16 April, 2016 which is shown in figure14 and figure 15 respectively. Positive value of wind shear is related to updraft and negative value of wind shear dominates downdraft. From the analysis, it is found that the wind shear over sylhet and adjoining area is positive from 0000 to 0600 and 1800 UTC of 17 April, 2016 which is shown in figure14 (a-b, d) and figure 15 (a-b, d) based on 72 hours and 48 hours advanced run respectively; whereas at 1200 UTC it is negative depicted in figure14 (c) and figure15 (c) based on 72 hours and 48 hours advanced run respectively. The updraft and downdraft occurs simultaneously which is predicted by the model very well.

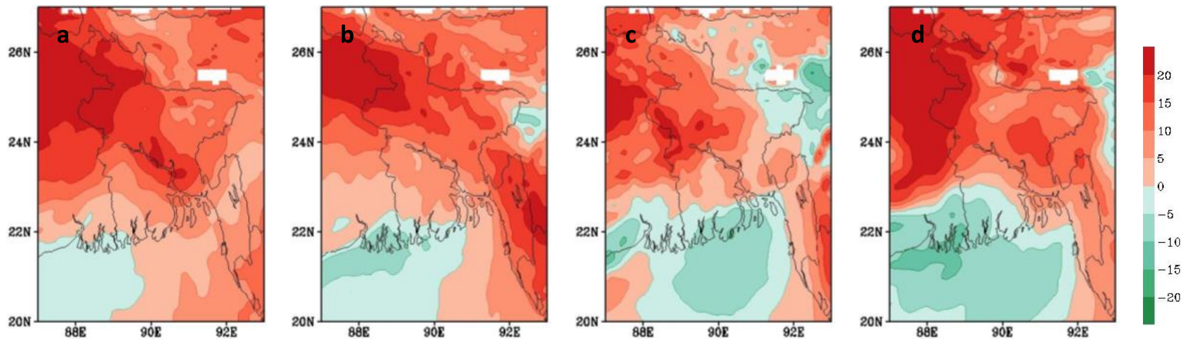

Figure 14: Wind Shear analysis ($u_{500} - u_{850}$) at a) 0000 UTC, b) 0600UTC, c)1200UTC & d)1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 15April, 2016.

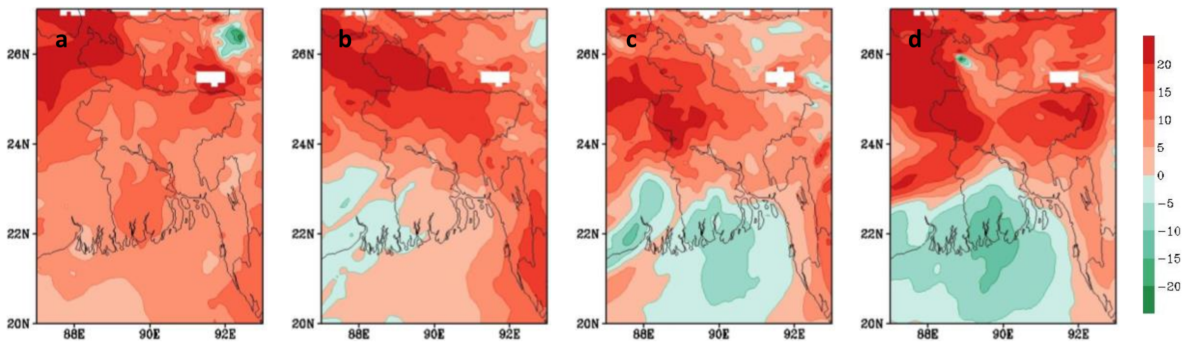

Figure 15: Wind Shear analysis ($u_{500} - u_{850}$) at a) 0000UTC, b) 0600UTC, c)1200UTC & d)1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 16 April, 2016.

3.5 Vorticity Analysis at 850 hPa and 500 hPa level

The vorticity analysis at 850 hPa and 500 hPa level from 0000 - 1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 15 and 16 April, 2016 which is shown in figure16, figure17, figure18and figure19 respectively. Positive vorticity is related to uplift and negative vorticity governs downdraft. From the analysis, it is found that the vorticity at 850 hPa level over Sylhet and adjoining area is positive of magnitude (6-10) x10^{-5} s^{-1} and negative of magnitude (6-8) x10^{-5} s^{-1} which is shown in figure16 and figure17 based on 72 hours and 48

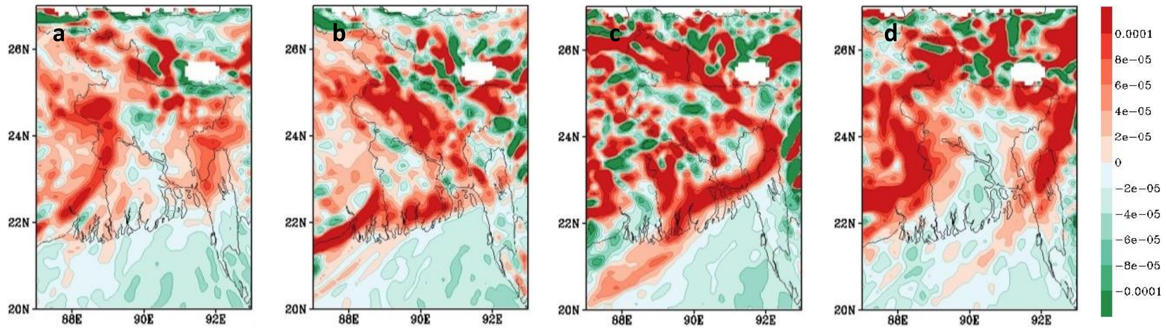

Figure 16: Vorticity analysis at 850 hPa level at a) 0000UTC, b) 0600UTC, c)1200UTC & d)1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 15April, 2016.

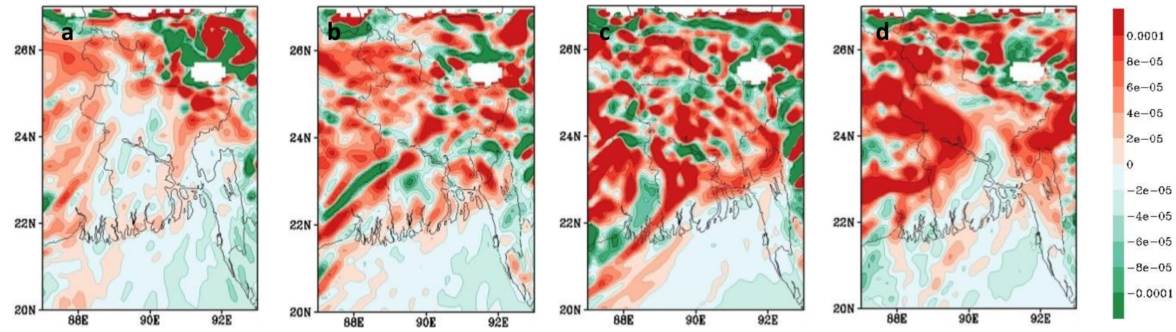

Figure 17: Vorticity analysis at 850 hPa level at a) 0000UTC, b) 0600UTC, c)1200UTC & d)1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 16 April, 2016 respectively.

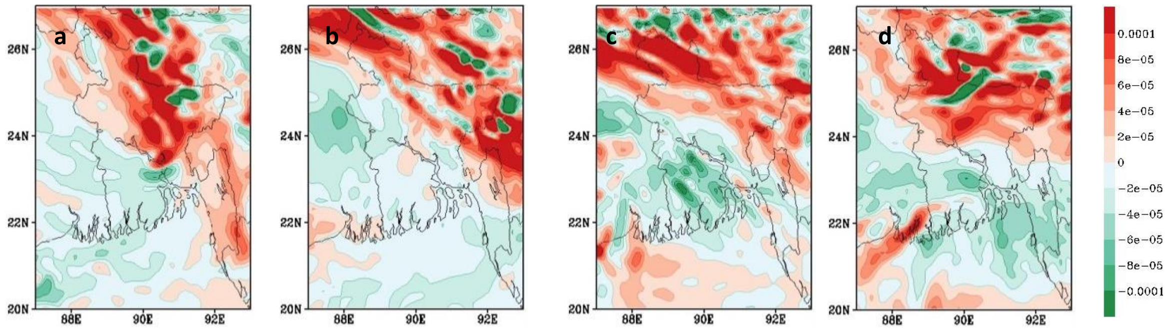

Figure 18: Vorticity analysis at 500 hPa level at a) 0000UTC, b) 0600UTC, c)1200UTC & d)1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 15 April, 2016 respectively.

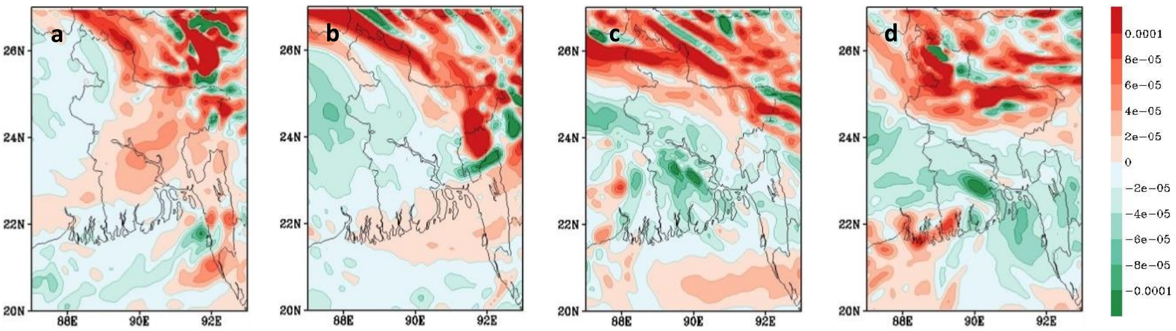

Figure 19: Vorticity analysis at 500 hPa level at a) 0000UTC,b) 0600UTC, c)1200UTC & d)1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 16 April, 2016.

hours advanced run respectively. This positive and negative vorticity is supportive for occurring of heavy rainfall. On the other hand, the vorticity at 500 hPa level over Sylhet and adjoining area is dominated by negative vorticity which is the indication of priority of downdrafts depicted in figure16 and figure17 based on 72 hours and 48 hours advanced run respectively. This negative vorticity hinders the further updraft of the system.

3.6 CAPE Analysis

The model simulated Maximum Convective Available Potential Energy (MCAPE) from 0000 - 1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 15 and 16 April, 2016 which is shown in figure 20 and figure 21 respectively. From 0000 to 0600 UTC of 17 April, 2016 MCAPE is found 1000 – 1500 J/KG over Sylhet and adjoining area based on the initial condition of 15 and 16 April, 2016 at developing stage of the system. Then it is started to increase till 1200 UTC 17 April, 2016 of magnitude 1500 – 2500 J/Kg. Afterwards it is decreasing over that region. So the model predicted that the system is a short spell phenomenon. The value of 1500 J/Kg or more is the indication of the unstable condition of the atmosphere and favourable condition for the convection. The high amount of rainfall over the orographic region, Sylhet was recorded, 161 mm (BMD) which is consistent to the MCAPE value.

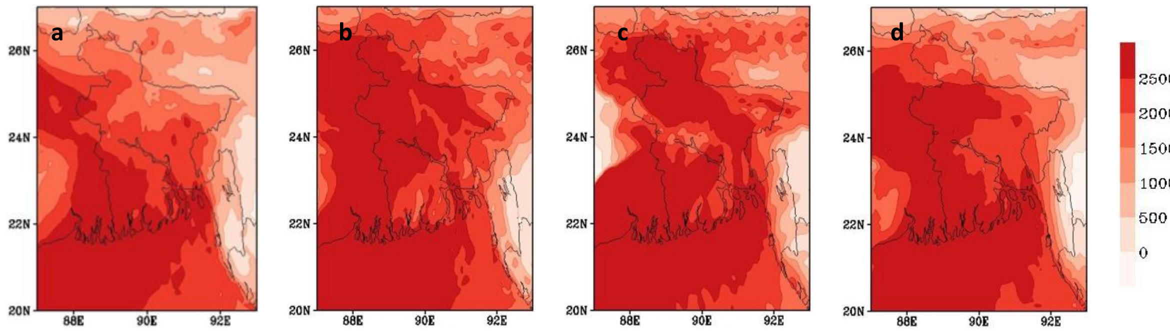

Figure 20: MCAPE analysis a) 0000UTC, b) 0600UTC, c)1200UTC & d)1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 15 April, 2016 respectively.

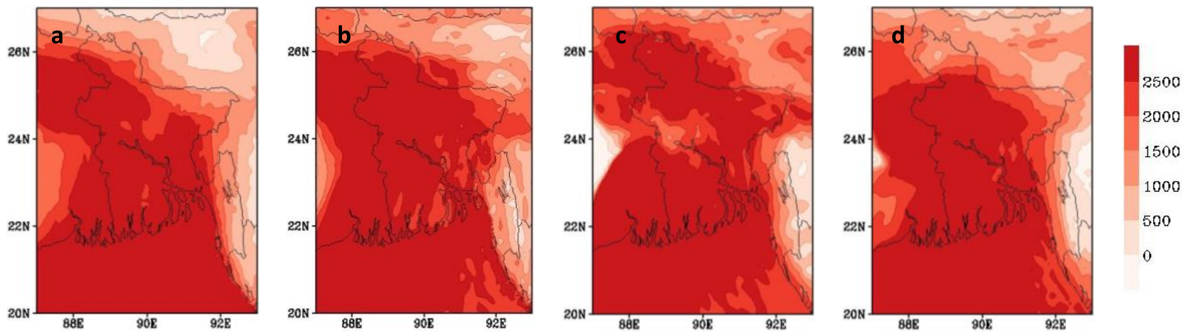

Figure 21: MCAPE analysis a) 0000UTC, b) 0600UTC, c)1200UTC & d)1800 UTC of 17 April, 2016 based on the initial condition of 0000 UTC of 16 April, 2016 respectively.

3.7 Rainfall Analysis

The model predicted 24 hour rainfall of 17 April, 2016 based on the initial condition of 0000 UTC of 15 and 16 April, 2016 which is shown in figure22, which is compared with 24 hour observed rainfall shown in figure 23.

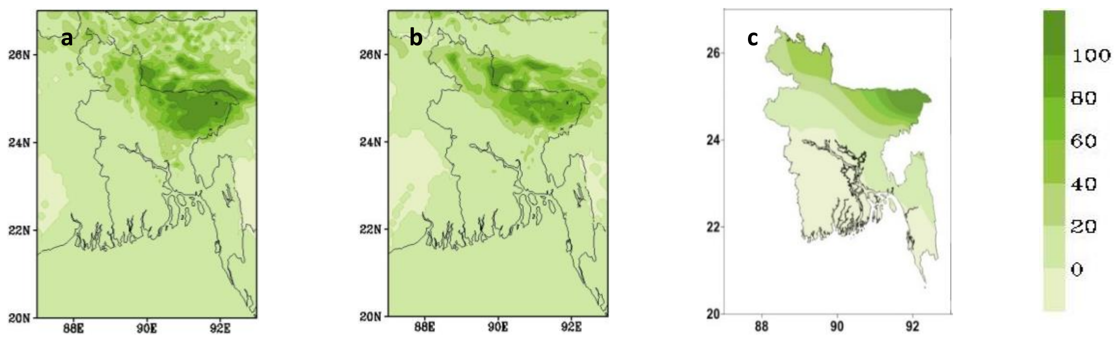

Figure 22: Model predicted 24 hour rainfall of 17 April, 2016 based on the initial condition of a) 0000 UTC of 15April and of b) 0000 UTC 16 April 2016 and c) observed rainfall of 17 April, 2016

The computational 24 hour observed rainfall of Sylhet of 17 April, 2016 is compared with model simulated rainfall based on 72 hours and 48 hours advanced run which is shown in figure160. The signature of the spatial distribution of model and observed rainfall is well matched. From the computational analysis, it is clear that the model simulated 24 hour rainfall is underestimated by 72 hour and 48 hour advanced run. But in both cases very heavy rainfall is predicted by the model reasonably well over the wind side of orographic region, Sylhet.

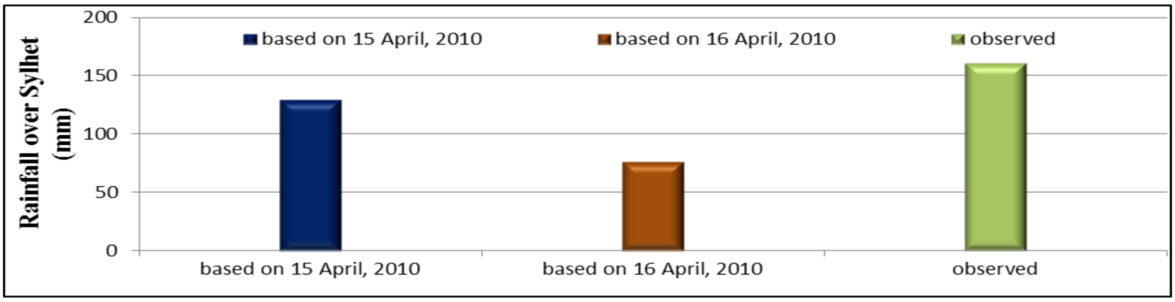

Figure 23: Bar Graph of model predicted 24 hour rainfall at Sylhet of 17 April, 2016 based on the initial condition of 0000 UTC of 15 and 16 April 2016 and observed rainfall at Sylhet of 17 April, 2016.

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 1003 hPa to 1008 hPa during the thunderstorm at 1000 to 1500 UTC with capturing the sharp fall of pressure over Sylhet.
- 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 Bay of Bengal which pushes high winds towards Bangladesh and carries high amount of moisture. It is favorable for the development of cumulonombus cloud which triggers thunderstorm.
- Model is good enough to capture the sudden fall of temperature during the thunderstorm over Sylhet. 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)$\times 10^{-5}\ s^{-1}$ from 1000 UTC to 1500 UTC over Bangladesh. Model captures the positive value of vorticity during the thunderstorm is the pre-condition of formation of thunderstorms.
- The value of vertical wind shear is positive throughout the country (greater than 10 ms^{-1}) and very high in some part of the country 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 greater than 3000 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 16.2 mm over Sylhet. The model underestimates the rainfall compared to the observation. But the model is capable to capture the rainfall of the thunderstorms though it has 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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