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Simulation of Orographic Rainfall and its Associated Thermodynamic Characteristics over Bangladesh using WRF Model

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Abstract
An attempt has been made to simulate the rainfall of 25 June, 2019 over Sylhet, Bangladesh due to orography using WRF model. The model has been run in a single domain of 10 km horizontal resolution for 48-h and 72-h using six hourly global final datasets from 0000 UTC of each initial day of the event as initial and lateral boundary conditionswith NSSL 2-moment microphysics scheme, Kain–Fritsch cumulous scheme and Yonsei University PBL scheme after sensitivity test in terms of RMSE. The model simulated mean sea level pressure, wind, vorticity, wind shear, humidity, CAPE, CIN, Lifted Index, K-index, Total Total Index and rainfall are analyzed. These weather parameters are visualized by GrADS and GIS software andvalidated with observed data of Bangladesh Meteorological Department, TRMMand ECMWF data. The analysis determines thatrelative humidity of 80-100% up to 200 hPa level, positive vorticity of magnitude (8-10) x10^{-5} s^{-1} and CAPE of magnitude 800-1000 J/Kg or more are responsible for the happening of the orographic extreme rainfall and other parameters are well-matched with the observed. This study indicates that the model with an appropriate model set up iscapable to predict the orographicrainfallrealistically well enough.

Keywords: *CAPE, CIN, LI, TTI, TRMM and ECMWF*

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I. Introduction

Bangladesh is situated in the Northeastern part of South Asia. The great Himalayas stand some distance to the North, while in the South lays the Bay of Bengal (BoB). West Bengal borders on the West and in the East lies the hilly and forested regions of India and Myanmar. These nice-lookingtopographicalsettingsof low lying plain of about 1,47,570 square kilometer crisscrossed by many rivers, lakes and streams.The elevation of delta area is not more than 150 m above sea level and most of it belongs to 1-2 m above sea level. Floodwater covers most of the land surface during the rainy season and damages crops and decrease national economy. The Orographic Rainfall (OR) mainly occurs in the Northeastern hilly regions of Bangladesh [1]. When moist air is lifted and moves over a mountain range, OR is produced. As the air rises and cools, convective clouds form due to orographyand serve as the source of the rainfall, most of which falls upwind of the mountain ridge. Some also fall a short distance downwind of the ridge and sometimes called spillover. On the lee side of the mountain range, rainfall is usually low, and the area is assumed to be in a rain sleuth. The influence of mountains upon rain is often profound, generating some of the Earth's wettest places. Orographic effects on rainfall are also responsible for some of the planet's sharpest climatic transitions. The classic example is the so-called 'rain shadow'; for a mountain range oriented perpendicular to the prevailing winds, rainfall is greatly enhanced on the windward side and suppressed in the lee side. However, the full range of orographic influences is much broader than this.Rainfall can be intensified in the lee side, over the crest, or well upwind of a mountain. Almost all orographic influences on rainfall occur due to rising and sinking atmospheric motions forced by topography. These motions can be forced mechanically, as air affecting on a mountain is lifted over it, or thermally, as heated mountain slopes instantaneous buoyancy-driven rotations. Rising motion causes the air to expand and cool, which is significant since the amount of water that may exist as vapor in air is an approximately exponential function of temperature. Thus, if cooling is enough, air saturates and the water vapor condenses into cloud droplets or forms ice-crystals. These droplets and crystals develop by various processes until they become large enough to fall as rain drop. It is important to highlight that moist ascent over topography alone is typically insufficient to make rainfall. These orographic effects generally modify rainfall during pre-existing storms and the interaction of potential instability with topography must be carefully taken into account for success of the OR forecasting by NWP models [2, 3]. Globally, the ARW model is being usually used for the mockup of a variability of weather events, such as heavy rainfall [4, 5, 6, 7] and TCs [7, 8, 9].

So, an effort has been made to forecast the high impact rainfall of 119 mmrecorded over Sylhet, Bangladesh on29 March 2017 by Weather Research and Forecasting (WRF) model and an endeavoris also taken to find out the meteorological features of that event. The most meteorological research questions are being solved by justifying the model performance through this research work.

II. Experimental Setup, Data Used and Methodology

The Advanced Research WRF model, developed at the National Center for Atmospheric Research (NCAR), is one of the two different dynamical hubs of the WRF model. The other core version, the Non-hydrostatic Mesoscale Model (NMM), was developed at the Environmental Modeling Center of the National Centers for Environmental Prediction (NCEP). The NWP model used in this study is the ARW model of version 3.9.1. The WRF model provides a flexible and portable open-source community model for both atmospheric research and operational forecasting [10]. It is a limited-area, non-hydrostatic basic equation model with multiple options for numerous parameterization schemes for different physical methods. The 1^0 resolution FNL data covering the entire globe every 6-h were taken as the initial and lateral boundary condition. 30 sec United States Geological Survey (USGS) dataGTOPO30 were used as topography and 25 categories USGS data weretaken as vegetation/land use (Modis and Hi-Def Lakes) coverage. The observed rainfall data of Bangladesh Meteorological Department (BMD) were used to compare or authenticate the model simulated rainfall. The simulation was done on a single domain of 10 km horizontal resolution and the domain (251×251 grid points with 38 unequally spaced sigma levels) of the NWP study is shown in Fig. 1. The details of the model and domain configuration are listed in Table 1.

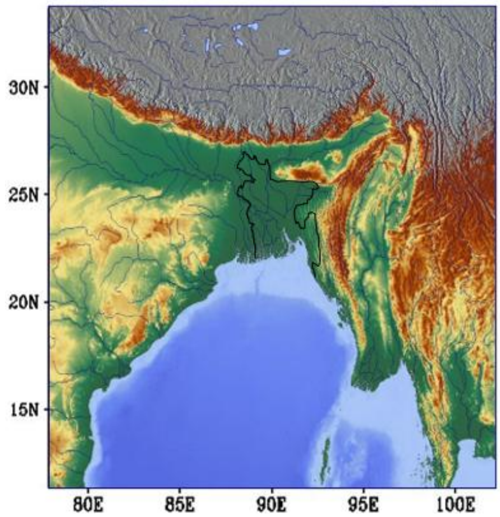


Fig. 1. Domain for the NWP study

Table 1: WRF Model and Domain Configurations

Dynamics	Non-hydrostatic
WRF Version	3.9.1
Number of domains	1
Central points of the domain	23^0 N and 90^0E
Horizontal grid distance	10 km
Number of grid points	251x251
Run time	72 and 48 hours
Time step	25
Map projection	Mercator
Vertical levels	38
Horizontal grid distribution	Arakawa C-grid
Time integration	3rd order Runge-Kutta
Spatial differencing scheme	6th order centered differencing
Initial conditions	Final (FNL: 1° × 1°)
Lateral boundary condition	Specified options for real-data
Top boundary condition	Gravity wave absorbing
Bottom boundary condition	Physical or free-slip
Diffusion and Damping	Simple Diffusion
Microphysics (MP)	NSSL 2-moment Scheme
Cumulus physics (CP)	Kain-Fritsch (KF) Scheme
Land surface parameterization	5 Layer Thermal diffusion scheme
Planetary Boundary Layer (PBL) parameterization	Yonsei University (YSU) Scheme
Radiation scheme	RRTM for long wave and Dudhia for short wave
Surface layer	Monin-Obukhov similarity theory scheme

2.1 Sensitivity Test of the Parameterization Schemes of WRF Model

A sensitivity test is carried out by using fifteen MP options (MP-1, 2, 3, 4, 6, 8, 10, 11, 13, 14, 16, 17, 18, 19 and 21) with the coupling of Kain–Fritsch cumulus parameterization (CP-1) scheme andYonsei University (YSU) planetary boundary layer physics (PBL-1) scheme of WRF model for simulating 24-h rainfall of 30 May, 2015 over Bangladesh and compared with the observed rainfall of BMD and NSSL 2-moment microphysics (hereafter MP-17) is selected in terms of the least Root Mean Square Error (RMSE) of 3 hourly model extracted rainfall at Sylhet, Bangladesh, then seven CP options (CP-1, 2, 3, 5, 6, 11 and 14) of WRF model with the coupling of MP-17 and PBL-1 is made, then MP-17 and CP-1 is compared with the observation and chosen due to the least RMSE for further simulation, afterwards seven PBL physics options (PBL-1, 5, 6, 7, 8, 11 and 12) of the model with the combination of MP-17 and CP-1 scheme is performed and finally MP-17, CP-1and PBL-1 schemes are taken (bold marked) due to the lowest RMSE for the case study of heavy rainfall event of 25 June, 2019 and is depicted in the Table-1 and Fig. 2.

Table. 1: RMSE of 3 hourly simulated rainfall at Sylhet for all combinations.

S. L	Combinations	RMSE of 3 hourly rainfall (mm)
Combination-01	MP-01+CP-01+PBL-01	34.75702
Combination-02	MP-02+CP-01+PBL-01	43.56455
Combination-03	MP-03+CP-01+PBL-01	30.51648
Combination-04	MP-04+CP-01+PBL-01	45.4927
Combination-05	MP-06+CP-01+PBL-01	43.46087
Combination-06	MP-08+CP-01+PBL-01	16.59829
Combination-07	MP-10+CP-01+PBL-01	20.71503
Combination-08	MP-11+CP-01+PBL-01	21.532
Combination-09	MP-13+CP-01+PBL-01	20.76344
Combination-10	MP-14+CP-01+PBL-01	30.72084
Combination-11	MP-16+CP-01+PBL-01	29.14872
Combination-12	**MP-17+CP-01+PBL-01**	**11.00821**
Combination-13	MP-18+CP-01+PBL-01	24.1331
Combination-14	MP-19+CP-01+PBL-01	42.13469
Combination-15	MP-21+CP-01+PBL-01	47.12375
Combination-16	MP-17+CP-02+PBL-01	20.98264
Combination-17	MP-17+CP-03+PBL-01	50.08925
Combination-18	MP-17+CP-05+PBL-01	22.79465
Combination-19	MP-17+CP-06+PBL-01	12.01264
Combination-20	MP-17+CP-11+PBL-01	22.58245
Combination-21	MP-17+CP-14+PBL-01	23.93825
Combination-22	MP-17+CP-01+PBL-05	11.86629
Combination-23	MP-17+CP-01+PBL-06	12.17116
Combination-24	MP-17+CP-01+PBL-07	17.42767
Combination-25	MP-17+CP-01+PBL-08	39.81076
Combination-26	MP-17+CP-01+PBL-11	31.21597
Combination-27	MP-17+CP-01+PBL-12	15.53288

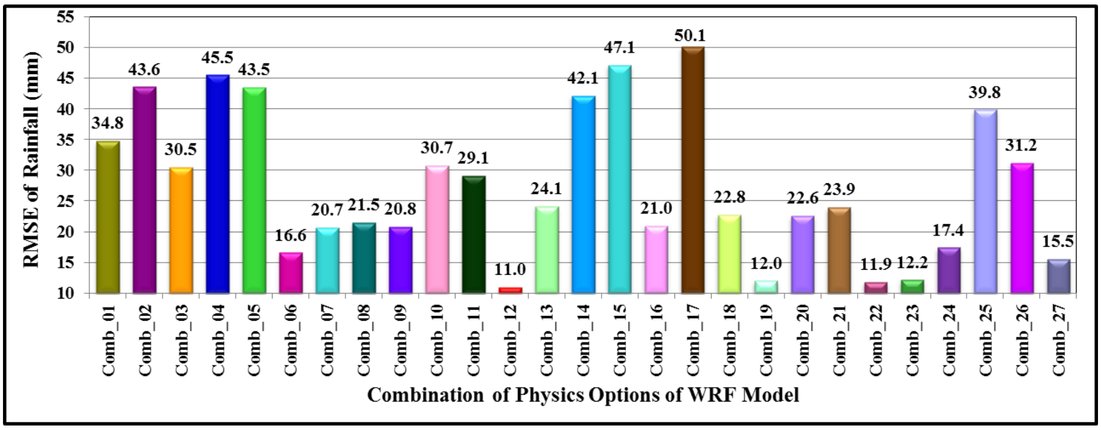


Fig. 2: RMSE of 3 hourly extracted simulated rainfall of 29-30 May, 2015 for twenty-seven combinations of MP, CP and PBL.

III. Result and Discussions

A thunderstorm was passed over Sylhet and adjoining area during 1730 UTC to 2200 UTC of 25 June, 2019 followed by another thunderstorm over the vicinity of north Rangpur, Bangladesh that was not passed over Sylhet region. At 1400 UTC of 25 June, 2019, there is no deep convection over Sylhet and adjoining area which is shown in Fig. 2 (a). This thunderstorm was developed at 1730 UTC of 25 June, 2019 and at 1730 UTC of 25th, it reached in mature stage which is shown in Fig. 2 (b). At 1900 UTC of 25 June,2019, it wasdissipating which is shown in Fig. 2 (c). At 2200 UTC of 25 June, 2019, it is reached weakening stage which is shown in Fig. 2 (d).

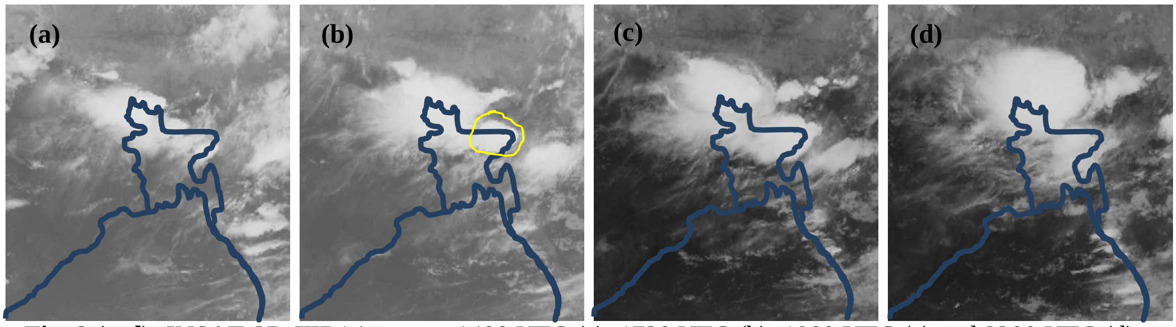
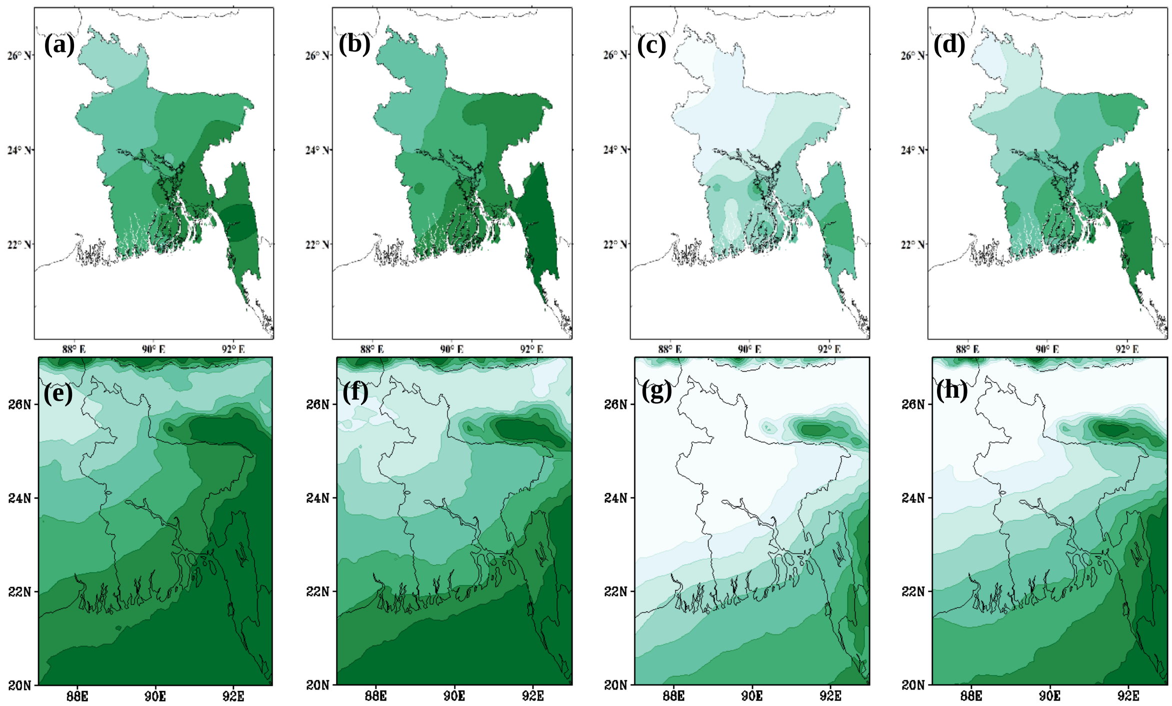


Fig. 2 (a-d): INSAT-3D-TIR1 image at 1400 UTC (a), 1730 UTC (b), 1900 UTC (c) and 2200 UTC (d) of 25 June, 2019.

3.1 Mean Sea Level Pressure Analysis

The analysis of MSLP on 0000, 0600, 1200 and 1800 UTC of 25 June, 2019 based on the initial condition of 0000 UTC of 23 and 24 June, 2019 is compared with observed MSLP on 0000, 0600, 1200 and 1800 UTC of 25 June, 2019 which is presented in Fig. 3 (a-l). The analysis indicates that a tough of low extends up to NE part of Bangladesh from West Bengal. The convergence zone lies along the trough. The model has also simulated the high-pressure area over Meghalaya and Eastern Part of Bangladesh which is very closed to the observation. The wind blows from the high-pressure area towards the trough which carries moisture.



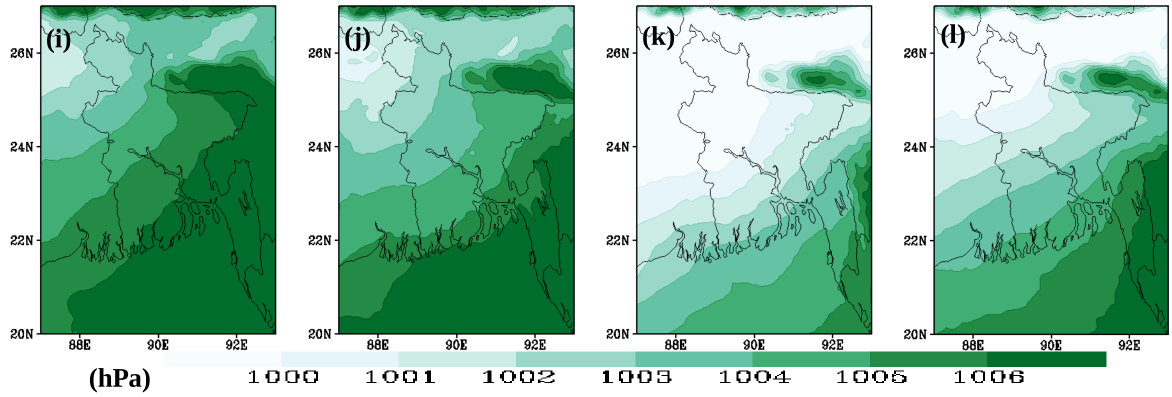


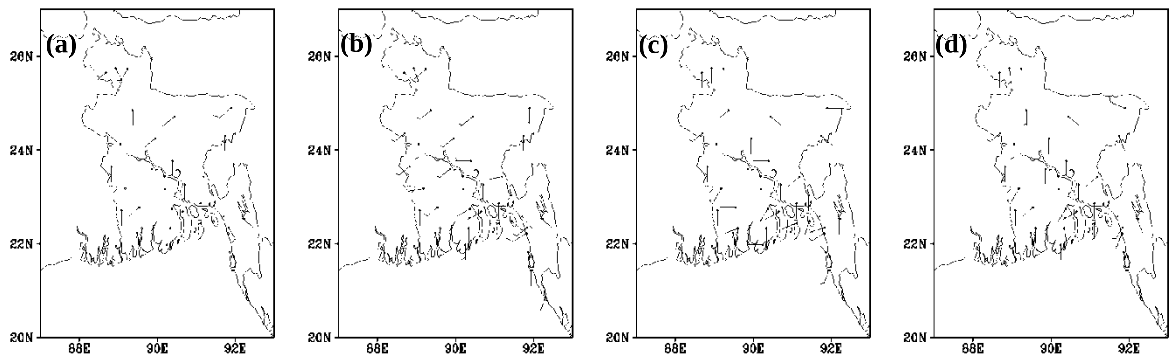
Fig. 3 (a-l): Observed MSLPon 0000, 0600, 1200 & 1800 UTC of 25June, 2019 (a-d); Predicted MSLPon 0000, 0600, 1200 and 1800 UTC of 25June, 2019 based on the initial condition of 0000 UTC of24 June, 2019 (e-h) and 23June, 2019 (i-l) respectively.

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 narrow belt of pressure gradient is found to the right side of the trough. So, there is a probability of invasion of huge amount of moisture towards NE part of Bangladesh from the BoB which is the source of energy to accelerate the buoyancy process in wind side. At 1200 UTC of 25 June, 2019 the lowest MSLP of magnitude 1000 - 1002 hPa was found over Sylhetand adjoining area based on 48 h and 72 h advanced model run which is the sign of formation convergence zone and afterwards it starts to increase and is supportive for the divergence.

3.2 Wind Flow Analysis at 10m Height, 850 and 500 hPa Level

The model simulated wind flow at 10-meter height on 0000, 0600, 1200 and 1800 UTC of 25June, 2019 based on 0000 UTC of 23 and 24June, 2019 is compared with BMD's observed wind flow at 10-meter height on 0000, 0600, 1200 and 1800 UTC of 25June, 2019 which is shown in Fig. 4 (a-l).The model simulated wind flow at 850 and 500 hPa level on 0000, 0600, 1200 and 1800 UTC of 25June, 2019 based on the initial condition of 0000 UTC of 23 and 24June, 2019 is shown in Fig. 5 (a-h) and Fig. 6 (a-h) respectively. From the analysis of wind flow at 10-meter height, it is found that south-southwesterly wind is blowing from the BoB towards Sylhet through central part of Bangladesh which is matched to the observation. Also, the analysis of wind flow at 850 hPa level, it is found that south-southwesterly wind is blowing from the BoB.

This wind flow brings high amount of moisture towards Bangladesh. 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 over those regions. The model predicted wind flow at 500 hPa level represents north-westerly wind which is blowing towards Sylhet is dry and cold. Owing to the mixing of this cold wind and the uplifting moist wind, cloud formation occurs over Sylhet and adjoining area.



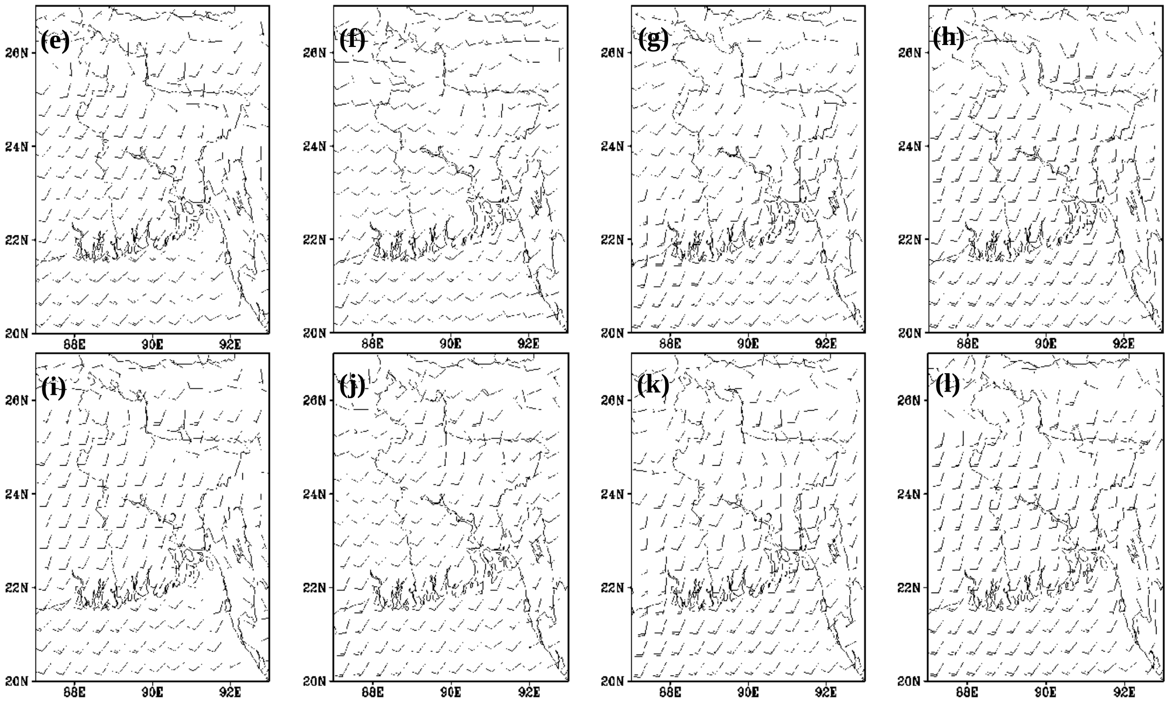


Fig. 4 (a-l): Observed wind flow at 10mheight on 0000, 0600, 1200 & 1800 UTC of 25June, 2019 (a-d); Predicted wind flow at 10mheight on 0000, 0600, 1200 and 1800 UTC of 25June, 2019 based on the initial condition of 0000 UTC of 24 June, 2019 (e-h) and 23June, 2019 (i-l) respectively.

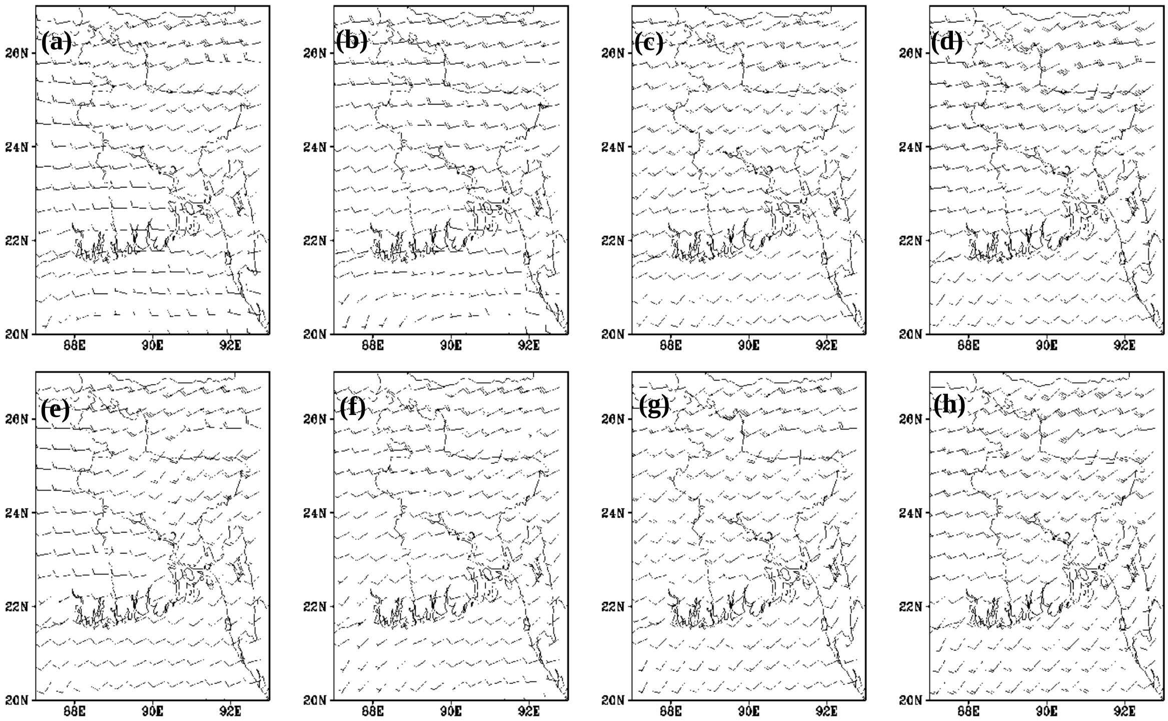


Fig. 5 (a-h): Predicted wind flow at 850 hPa level on 0000, 0600, 1200 and 1800 UTC of 25 June, 2019 based on the initial condition of 0000 UTC of24 June, 2019 (a-d) and 23 June, 2019 (e-h) respectively.

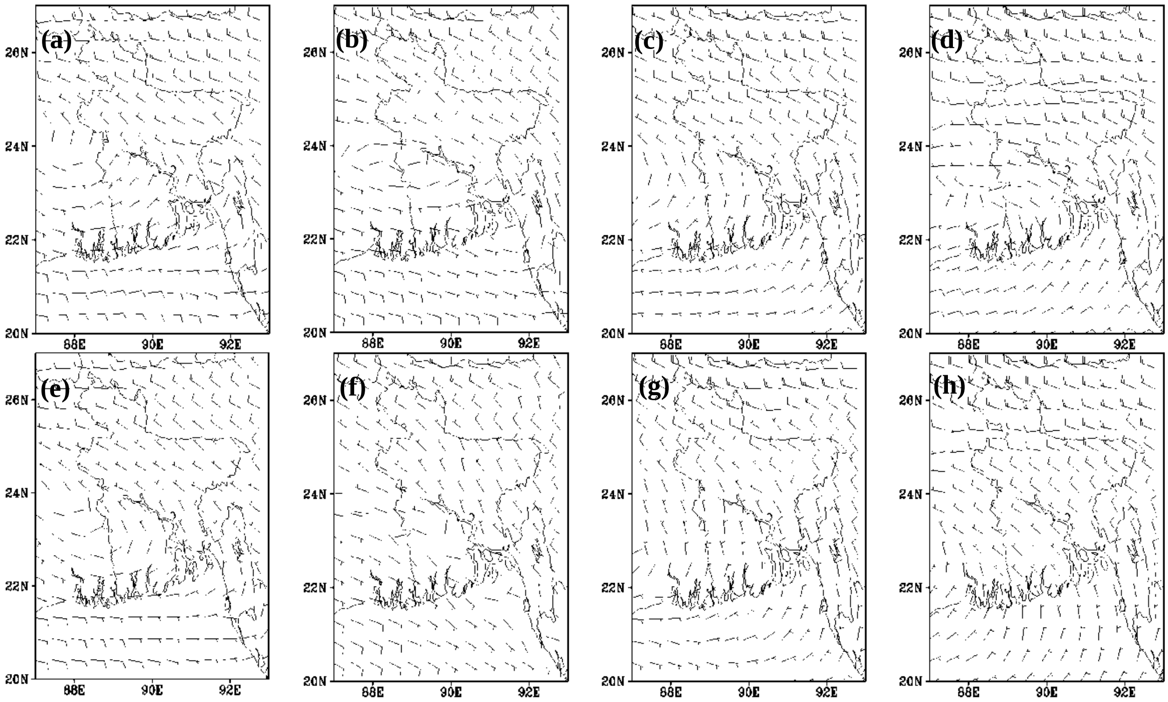


Fig. 6 (a-h): Predicted wind flow at 500 hPa level on 0000, 0600, 1200 and 1800 UTC of 25 June, 2019 based on the initial condition of 0000 UTC of 24 June, 2019 (a-d) and 23 June, 2019 (e-h) respectively.

3.3 Analysis of Relative Vorticity at 850 and 500 hPa Level

The model simulated relative vorticity at 850 and 500 hPa level on 0000, 0600, 1200 and 1800 UTC of 25June, 2019 based on the initial condition of 0000 UTC of 23 and 24June, 2019 is displayed in Fig. 7 (a-h) and Fig. 8 (a-h) respectively. Positive vorticity is related to updraft and negative vorticity is correlated to downdraft. From the analysis, it is found that the vorticity at 850 hPa level over Sylhet and adjoining area is positive of magnitude $(8\text{-}10)\times10^{-5}$ s^{-1} and negative of magnitude $(6\text{-}10)\times10^{-5}$ s^{-1}. 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 negativevorticity which is the indication of priority of downdrafts.

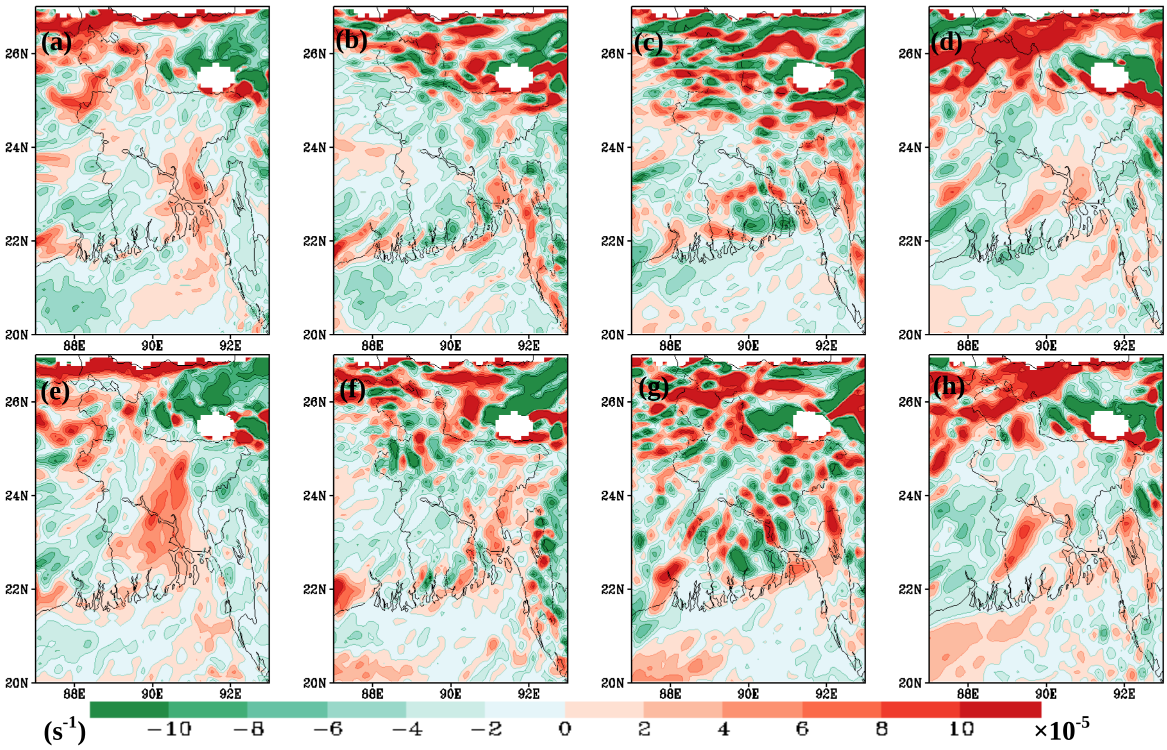


Fig. 7 (a-h): Predicted relative vorticity at 850 hPa level on 0000, 0600, 1200 and 1800 UTC of 25 June, 2019 based on the initial condition of 0000 UTC of 24 June, 2019 (a-d) and 23 June, 2019 (e-h) respectively.

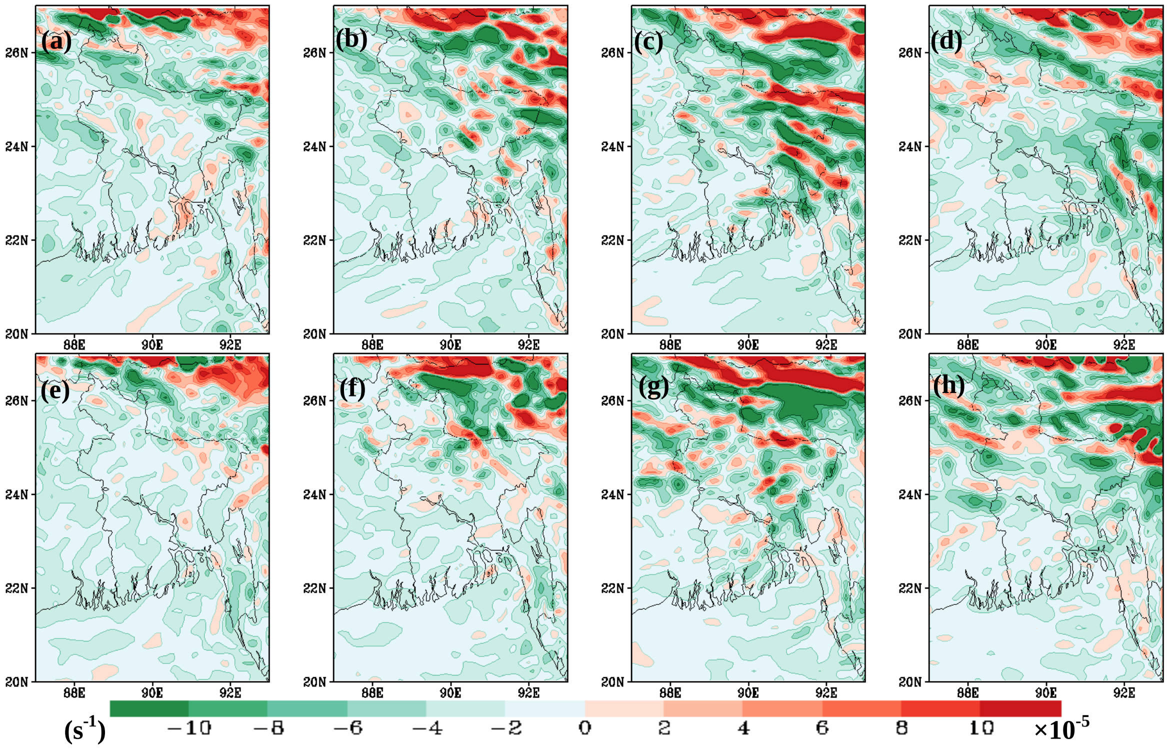
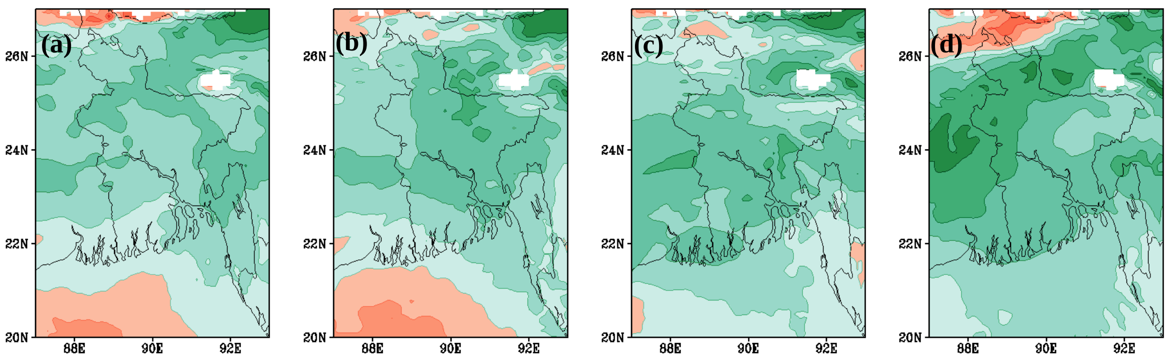


Fig. 8 (a-h): Predicted relative vorticity at 500 hPa level on 0000, 0600, 1200 and 1800 UTC of 25 June, 2019 based on the initial condition of 0000 UTC of 24 June, 2019 (a-d) and 23 June, 2019 (e-h) respectively.

3.4 Analysis of Vertical Wind Shear

The model regenerated wind shear between 500 and 850 hPa level ($u_{500} - u_{850}$) on 0000, 0600, 1200 and 1800 UTC of 25June, 2019 based on the initial condition of 0000 UTC of 23 and 24June, 2019 is depicted in Fig. 9 (a-h). Positive value of vertical wind shear of the order of (0-5) knots is connected to updraft and negative value of vertical wind shear of the order of (0-15) knots governs downdraft over Sylhet and adjoining area. From the analysis, it is found that the negative vertical wind shear is dominant over Sylhet and adjoining area and downdraft occurs which is predicted by the model very well.



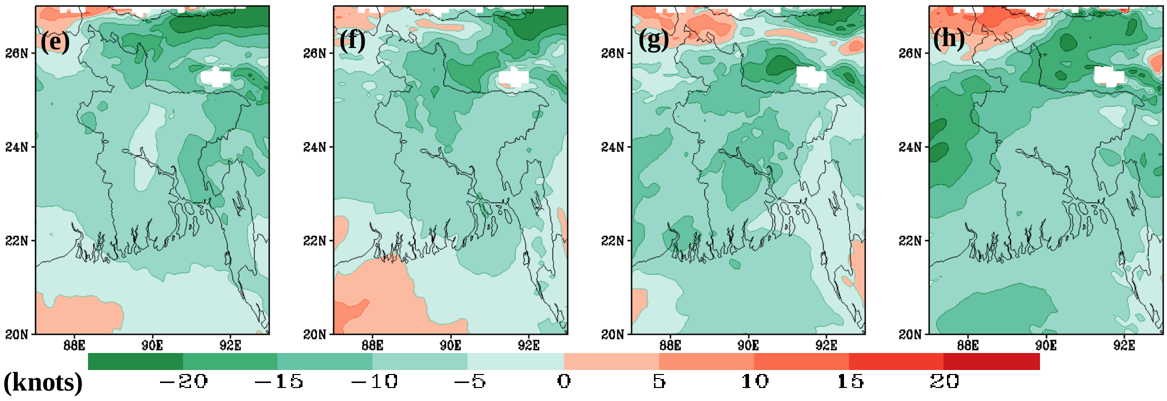
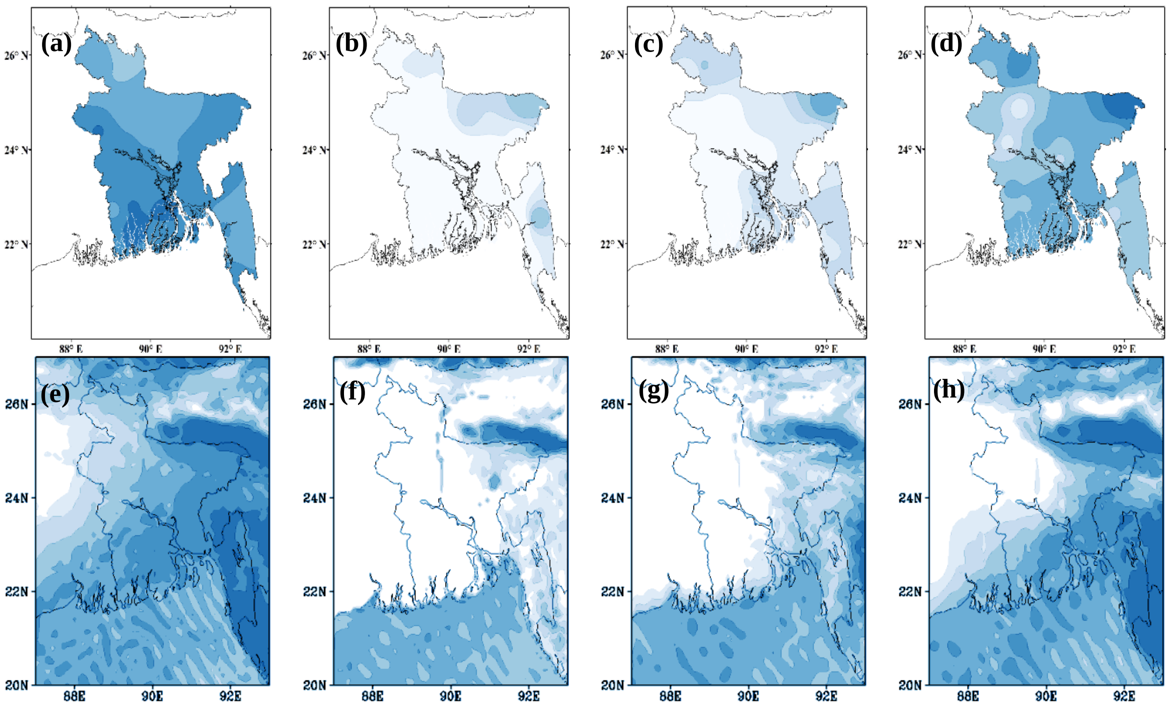


Fig. 9 (a-h): Predicted vertical wind shear between 500 and 850 hPa level on 0000, 0600, 1200 and 1800 UTC of 25 June, 2019 based on the initial condition of 0000 UTC of 24 June, 2019 (a-d) and 23 June, 2019 (e-h) respectively.

3.5 Analysis of Relative Humidity at 2m Height and its Vertical Cross-Section

The model simulated rh at 2m height on 0000, 0600, 1200 and 1800 UTC of 25June, 2019 based on the initial condition of 0000 UTC of 23 and 24June, 2019 is compared with observed rh at 2m height on 0000, 0600, 1200 and 1800 UTC of 25June, 2019 shown in Fig. 10 (a-l). The model generated rhis about 75-100% over Sylhet and adjoining area which is consistent to the observation. The high amount ofmoisture is responsible for buoyancy of air and finally cloud formation. It is also mentionable that rh is more than 95% at the wind side of hilly region of Sylhet and adjoining area which trigger precipitation processes over that regions. The heavy rainfall occurred at the right side of the dry line (border of dry and cold air with moist and warm air).

The model simulated vertical cross-section of rh on 0000, 0600, 1200 and 1800 UTC of 25June, 2019 based on the initial condition of 0000 UTC of 23 and 24June, 2019 for latitudinal (at Lat. 24.9^0 N) is shown in Fig. 11(a-h) and for longitudinal (at Lon. 91.9^0 E) is shown in Fig. 12 (a-h) respectively. The model simulated latitudinal cross-section of rh along 24.9^0 N indicates that 60-100% of moisture is extended up to 500 hPa level along $87\text{-}90^0$ E and 60-100% of moisture is extended up to 200 hPa level along $91\text{-}93^0$ E, whereas the longitudinal cross-section of rh along 91.9^0 E indicates that 60-80% of moisture is extended up to 600 hPa and 400 to 200 hPa level along $20\text{-}23^0$ N and 60-100% of moisture is extended up to 250 hPa level along $23\text{-}27^0$ N. It is clear that initially the moisture is uplifted from the different individual single cloud cell; afterwards they emerged as a single cell and becomes stronger and vigorous. It also indicates that the vertically uplifted moisture is responsible for cumuli-form of cloud formation and occurring of heavy rainfall.



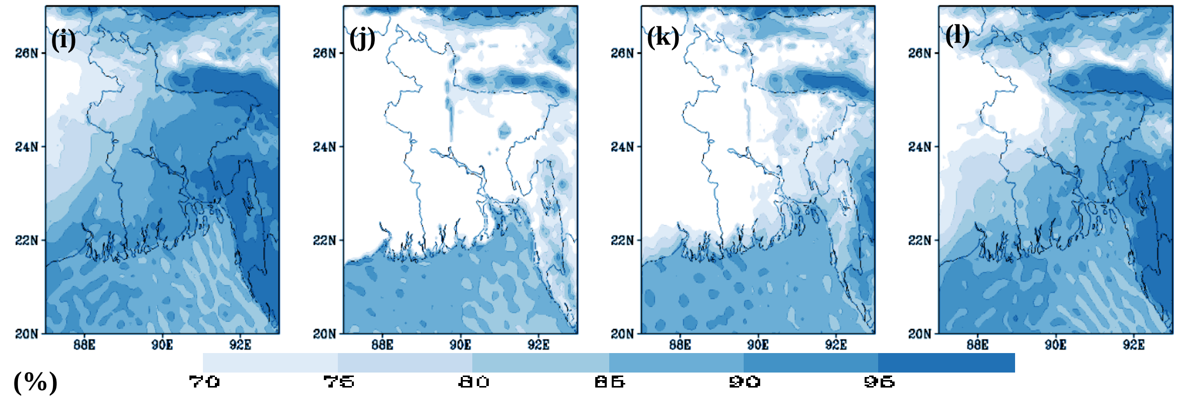


Fig. 10 (a-l): Observed rh at 2mheight on 0000, 0600, 1200 & 1800 UTC of 25June, 2019 (a-d); Predicted rh at 2mheight on 0000, 0600, 1200 and 1800 UTC of 25June, 2019 based on the initial condition of 0000 UTC of 24 June, 2019 (e-h) and 23June, 2019 (i-l) respectively.

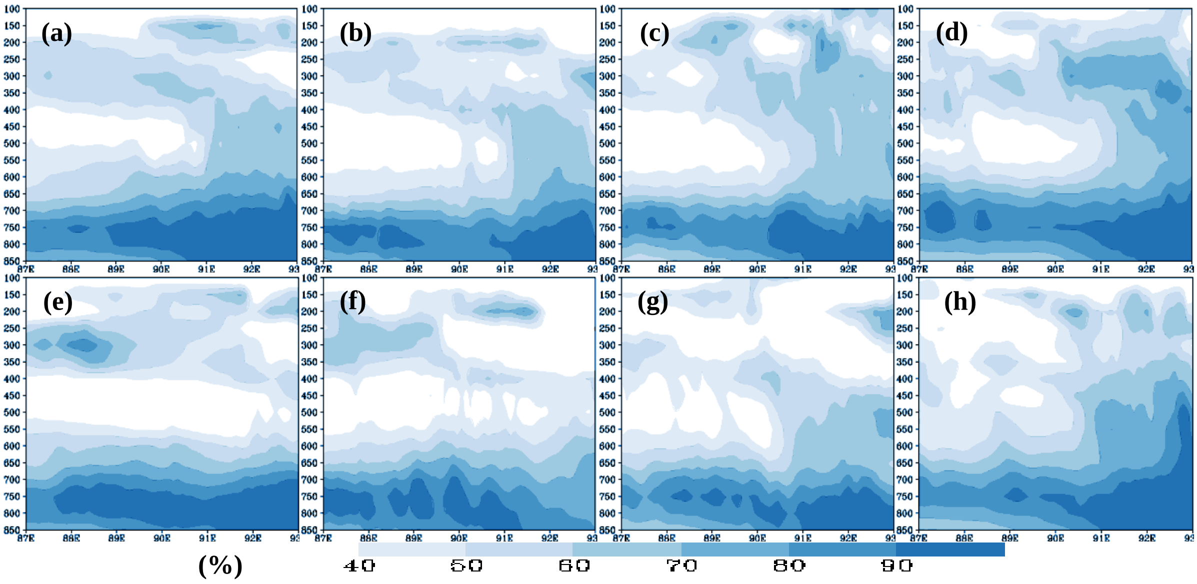
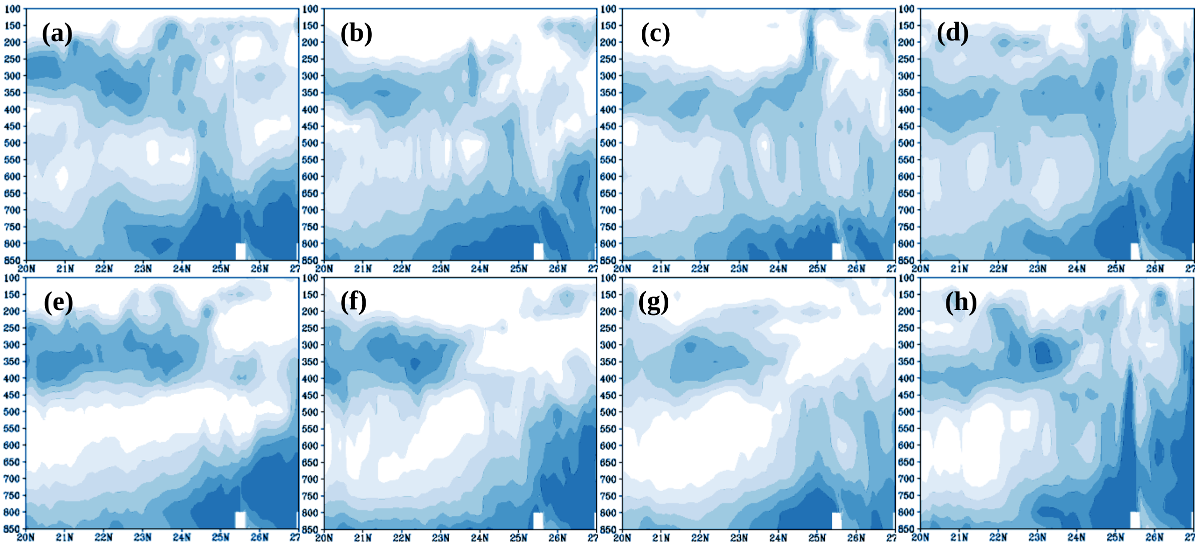


Fig. 11 (a-h): Predicted latitudinal (at lat. 24.9° N) cross-section of rh on 0000, 0600, 1200 and 1800 UTC of 25 June, 2019 based on the initial condition of 0000 UTC of 24 June, 2019 (a-d) and 23 June, 2019 (e-h) respectively.



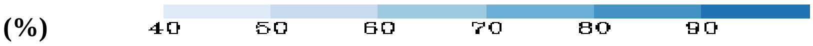


Fig. 12 (a-h): Predicted longitudinal (at lon. 91.9° E) cross-section of rh on 0000, 0600, 1200 and 1800 UTC of 25 June, 2019 based on the initial condition of 0000 UTC of 24 June, 2019 (a-d) and 23 June, 2019 (e-h) respectively.

3.6 Analysis of CAPE at 850 hPa Level

The model simulated CAPE at 850 hPa level on 0000, 0600, 1200 and 1800 UTC of 25June, 2019 based on the initial condition of 0000 UTC of 23 and 24June, 2019 is shown in Fig. 13 (a-h). The model simulated CAPE is found 400 – 800 J/Kg over Sylhet and adjoining area at 0000 and 0600 UTC at developing stage of the system. Afterwards the numeric value of CAPE is increasing to 1000 J/Kg or more over the study region. The value of CAPE is 1000 J/Kg or more is liable for moderate unstable [11] condition of theatmosphere which enhanced heavy to very heavy rainfall. The amount of 24h rainfall over Sylhet was recorded, 887 mm (BMD) which is consistent to the model simulated CAPE value.

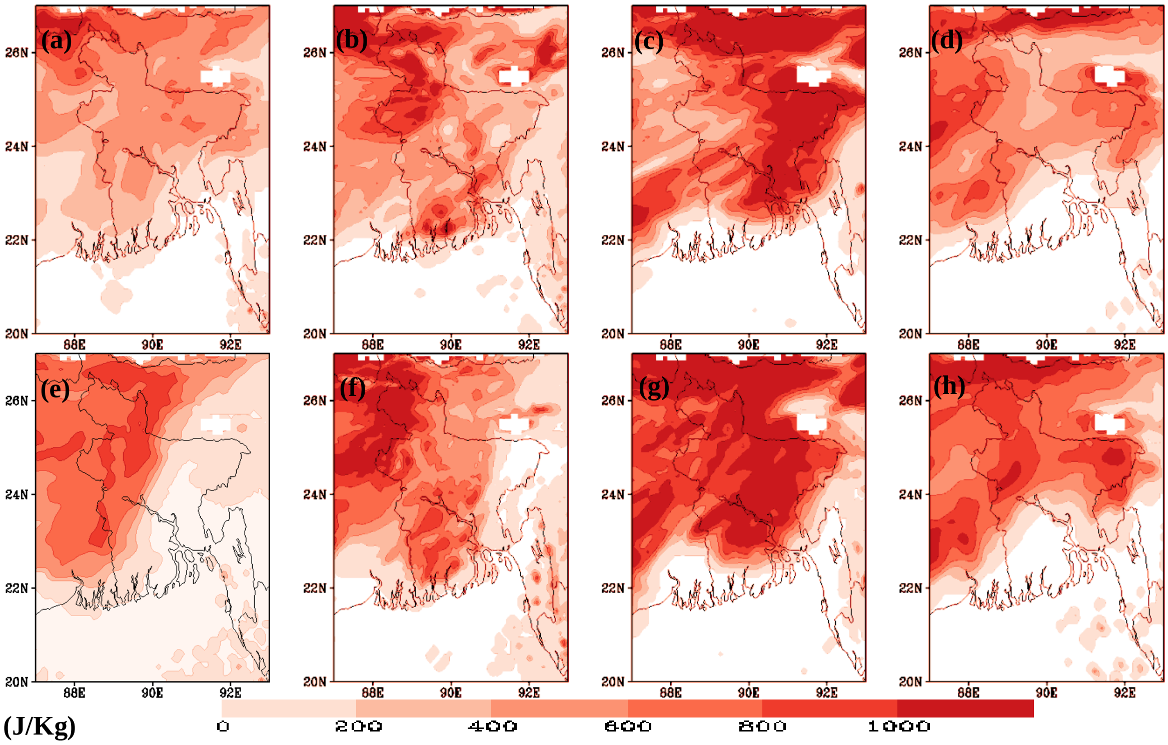


Fig. 13 (a-h): Predicted CAPE at 850 hPa level on 0000, 0600, 1200 and 1800 UTC of 25June, 2019 based on the initial condition of 0000 UTC of24 June, 2019 (a-d) and 23June, 2019 (e-h) respectively.

3.7 Analysis of CIN at 850 hPa Level

The model simulated CIN at 850 hPa level on 0000, 0600, 1200 and 1800 UTC of 25June, 2019 based on 0000 UTC of 23 and 24June, 2019 is shown in Fig. 14 (a-h). The model simulated CIN is found 0 – 20 J/Kg over Sylhet and adjoining area at 0000 UTCon developing stage of the system. Afterwards it is 0-30 J/Kg over the said region. The value of CIN is supportive for potentially unstable [11] atmospheric condition and it is the favourable condition for the convection and afterwards occurring of very heavy rainfall over Sylhet and adjoining area.

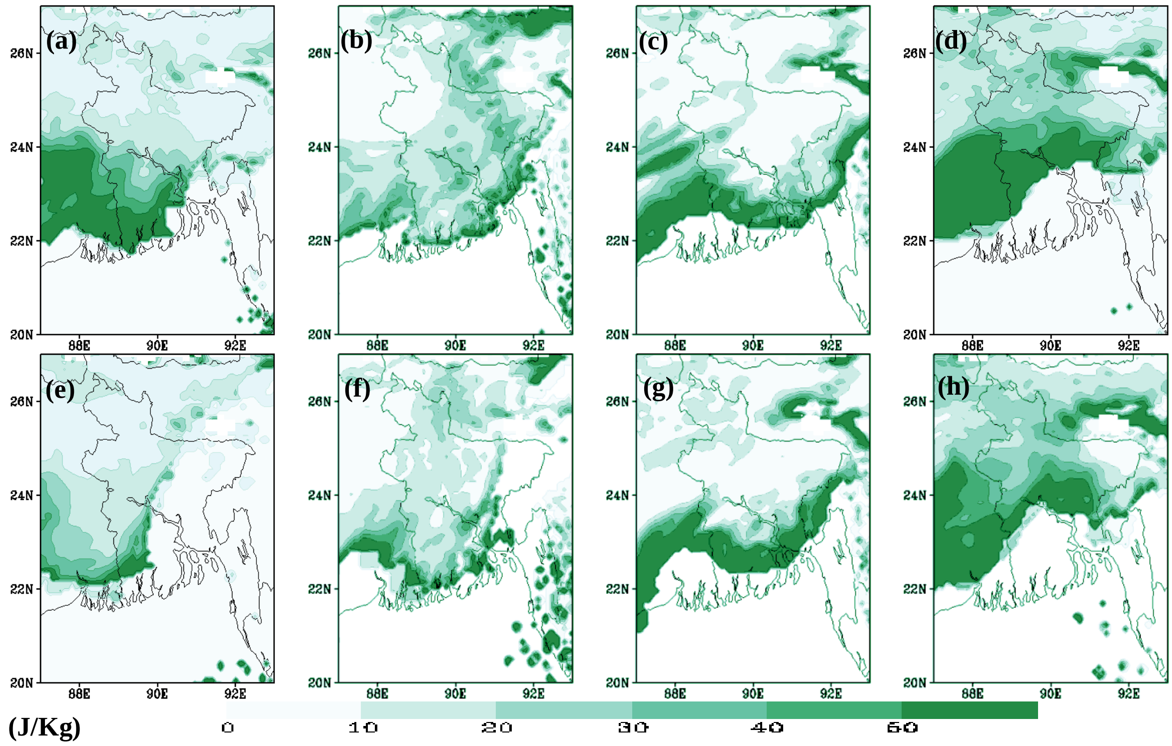


Fig. 14 (a-h): Predicted CIN at 850 hPa level on 0000, 0600, 1200 and 1800 UTC of 25June, 2019 based on the initial condition of 0000 UTC of 24 June, 2019 (a-d) and23 June, 2019 (e-h) respectively.

3.8 Analysis of Different Indices of Thermodynamic Diagram

The model simulated thermodynamic parameters as well as thermodynamic diagram (Skew T-log p diagram) at Sylhet, Bangladesh on 0000 UTC of 25June, 2019 based on 0000 UTC of 23 and 24June, 2019 is compared with BMD's thermodynamic parameters and diagram on 0000 UTC of 25June, 2019 which is shown in Fig. 15 (a-c). Here, black, blue and pink lines indicate T, Td and rh sounding line respectively.The model predicted sounding diagram of T and Td sounding lines are very close to the observation and it is the indication of unstable atmosphere. Different thermodynamic indices are described as follows:

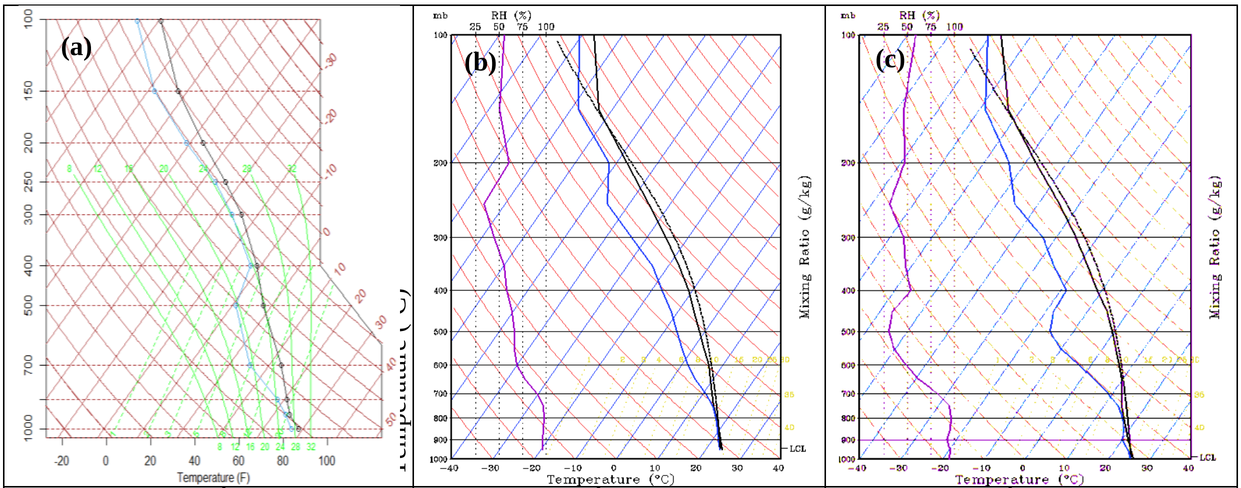
The model simulated LI is found negative (-1^0C for 48h and 72h model run) and the observed LI is found also negative (-4.35^0C) which is the marginal unstable to large instability of the atmospheric condition [12].

The model predicted K-index is found 39^0C for 48h and 35^0C for 72h model run and the observed K-index is found 33.27^0C which is the Moderate convective potential of the atmospheric condition [12]. This thermodynamic index is predicted by the model good enough and it is consistent to the observation. So that the WRF model can be used for predicting this parameter even 72 h before of the event occurrence.

The model generated TT is found 42^0C for 48h and 39^0C for 72h model run and the observed TT is found 43.36^0C which is not supportedfor the formation of thunderstorm [12].

The spatial distribution of CAPE is analyzed in chapter 3.7. The model predicted CAPE at Dhaka is found 580 J/Kg for 48h and 623 J/Kg for 72h model run and the observed CAPE is found 1203.21 J/Kg which is liable for marginal to moderate unstable [11] condition of the atmosphere. The model predicted CIN at Dhaka is found 4 J/Kg for 48h and 0 J/Kg for 72h model run and the observed CIN is found 5.07 J/Kg which is supportive for potentially unstable [11] condition of the atmosphere.

These thermodynamic indices indicate to favourable condition for occurring heavy to very heavy rainfall.

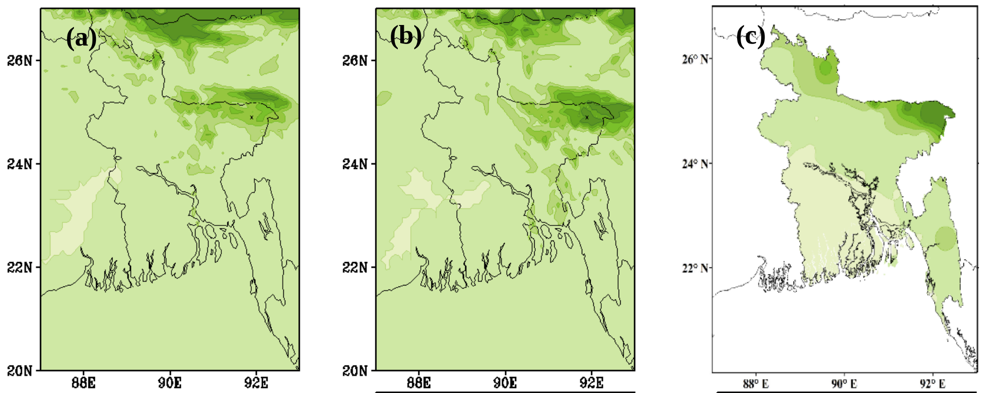


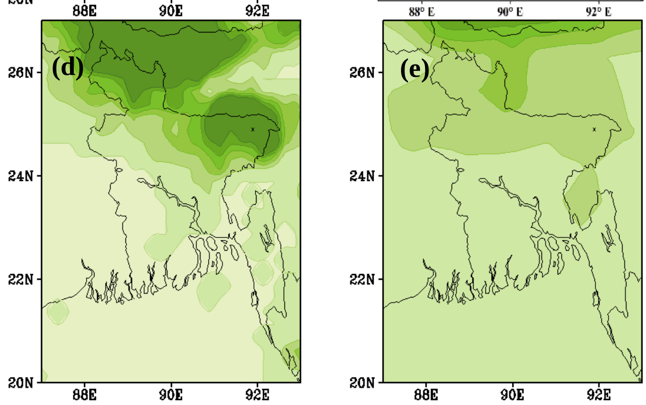
K-index = 33.27 ^{0}C; TT index = 43.36 ^{0}C; LI = -4.35 ^{0}C; CAPE = 1203.21 J/Kg; CIN = 5.07 J/Kg	K-index = 39 ^{0}C; TT index = 42 ^{0}C; LI = -1 ^{0}C; CAPE = 580 J/Kg; CIN = 4 J/Kg	K-index = 35 ^{0}C; TT index = 39 ^{0}C; LI = -1 ^{0}C; CAPE = 623 J/Kg; CIN = 0 J/Kg

Fig. 15 (a-c): Observed thermodynamic diagram and thermodynamic parameters at Sylhet, Bangladesh on 0000 UTC of 25 June, 2019 (a); Predicted thermodynamic diagram and thermodynamic parameters on 0000 UTC of 25 June, 2019 of 0000 UTC of 24 June, 2019 (b) and 23 June, 2019 (c) respectively.

3.9 Rainfall Analysis

The model predicted accumulated 24-hour rainfall of 25June, 2019 based on 0000 UTC of 23 and 24June, 2019 is compared with observed, TRMM and ECMWF accumulated 24-hour rainfall of 25June, 2019 which is shown in Fig. 16 (a-e). The signature of the spatial distribution of WRF model is well-matched to the observed rainfall than that of TRMM and ECMWF. In both cases very heavy rainfall is predicted by the WRF model reasonably well over the wind side of orographic region, Sylhet. The WRF model simulated rainfall is very close to the observation but TRMM is overestimated and ECMWF is underestimated over Bangladesh than that of WRF model.





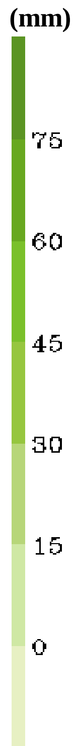


Fig. 16(a-e): Predicted 24 hour accumulated rainfall of 25June, 2019 based on 0000 UTC of 23June, 2019 (a) and 24June, 2019 (b); Observed (c), TRMM (d) and ECMWF (e) 24 hour accumulated rainfall of 25June, 2019 respectively.

At different station nearby Sylhet, Bangladesh listed in table-2, the model predicted 24-hour computational rainfall of 25June, 2019 based on the initial condition of 0000 UTC of 23 and 24June, 2019 is compared with 24-hour observed, TRMM and ECMWF rainfall of 25June, 2019which is shown in Fig. 17(a-e). From the computational analysis, it is clear that the model simulated 24-hour rainfall by 48-hour advanced run is closer than TRMM, ECMWF and 72-hour advanced run. From the validation of the model compared to the observed, it is clear that the model performance is well enough to predict the rainfall. The model output gives the better result with the minimization of the lead time.

Table-2: computational rainfall of 25 June, 2019

	Station Name	Lat.	Lon.	Observed	wrf_48h	wrf_72h	TRMM	ECMWF
St-01	Sylhet (BMD)	24.9	91.8833	88	76.5	36.5	149.8	21
St-02	Srimangal (BMD)	24.3	91.7333	0	22.5	1.2	30.3	15.4
St-03	Mymensingh (BMD)	24.7167	90.4333	0	26.5	31.2	40.9	18.9
St-04	B. Baria (FFWC)	23.9900	91.1200	0	7.9	8.1	3.9	14.1
St-05	Mymensingh (FFWC)	24.6779	90.4651	0	23.4	12.3	40.9	16.7
St-06	Bhairab Bazar (FFWC)	24.0527	91.0019	0	0.1	0	45.8	13.6
St-07	Durgapur (FFWC)	25.1176	90.6707	74.5	31.7	47.5	48.3	20.9
St-08	Jariajanjail (FFWC)	24.9800	90.6200	0	23.4	12.3	40.9	16.7
St-09	Sylhet (FFWC)	24.8882	91.8525	88	70.1	42.7	149.8	21.1
St-10	Kanaighat (FFWC)	25.0038	92.2683	170	87.8	49.2	88.7	19.6
St-11	Sunamganj (FFWC)	25.0710	91.4085	85	51.4	47.7	232	20.7
St-12	Lourergorh (FFWC)	25.1926	91.2500	40	37	40.3	232	21.3
St-13	Habiganj (FFWC)	24.3920	91.4133	0	15.7	6.8	34.1	15.7
St-14	Moulvi Bazar (FFWC)	24.4950	91.7779	0	5.8	11	42.5	17.9

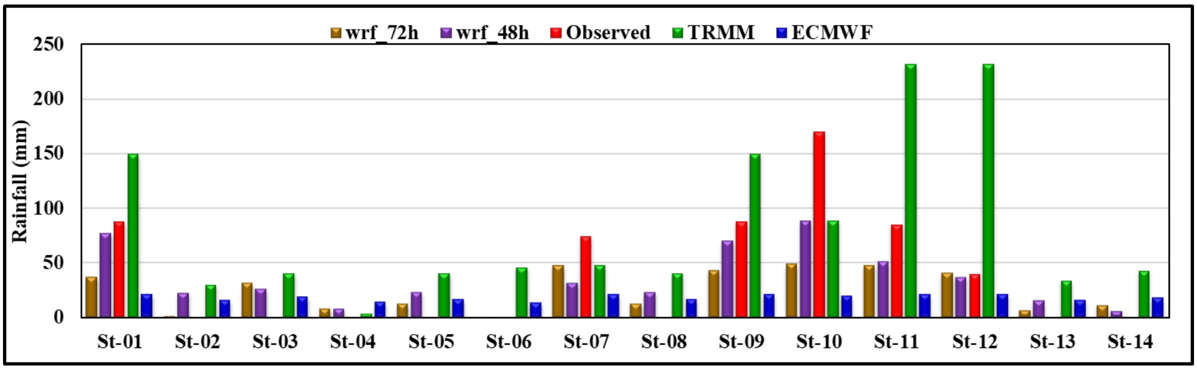


Fig. 17 (a-e): Predicted 24-hour computational rainfall of 25June, 2019 at Sylhet based on the initial condition of 0000 UTC of 23June, 2019 (wrf_72h) and 24June, 2019 (wrf_48h); 24-hour computational observed, TRMM and ECMWF rainfall of 29 March, 2017 at different station nearby Sylhet, Bangladesh respectively.

IV. Conclusion

The parameterization schemes-NSSL 2-moment microphysics with coupling to the Kain–Fritsch Scheme and YSU scheme options of WRF model produces representative results in both spatial and quantitative evaluations. Therefore, these schemes have been considered as the best for prediction of thunderstorm which passes over NE part of Bangladesh. The model predicted lowest MSLP of the thunderstorm is about 1001-1003hPa for 48-h, and 72-h model run. The model captured the south-westerly wind flow at 10-m height and 850 hPa level which transports abundant moisture of (75-100) % from the enormous area of the BoB towards the NE part of Bangladesh and neighborhood, this south-westerly wind bends to easterly by the confrontation of hills. One of its components uplifted and conjugate with the west-northwesterly dry and cold wind at 500 hPa level which is very close to the observation. The model predicted vorticity over NE part of Bangladesh at 850 hPa level is positive of magnitude (08-10)$\times10^{-5}$ s^{-1} and negative of magnitude (6-10)$\times10^{-5}$ s^{-1} for 48-h and 72-h model run which directs updraft and downdraft. At 500 hPa level, negativevorticityis dominant, is the indication of hinderthe updrafts of the system. The model predicted negative vertical wind shear of the order of (0-15) knots is governingand it is the indication of further updraft of the system. The rh is found 75-100% over Sylhet and adjoining area which is very close to the observation and 60-100% moisture is extended up to 600-200 hPa levels. The model simulated CAPE is found 400 – 800 J/Kg at developing stage and 800-1000 J/Kg or more at mature stage over Sylhet and adjoining area which is moderately liable for unstable condition of the atmosphere. The model simulated LI is negative (-1^{0}C to -4 ^{0}C), K-index lies between33^{0}C to 39^{0}C and TT is found 39^{0}C to

43^{0}C at Dhaka which are close to the observation and responsible for the marginal unstable to large instability of the atmosphericcondition. The model captured the rainfall event reasonably well enough though some spatial and computational error exits. The bias correction may increase the competency of the model for prediction of ORand may be forecasted more precisely and accurately.

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