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Synoptic flow patterns and large-scale characteristics of flash flood-producing rainstorms over northeast Bangladesh

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Abstract

Flash flood and related hazards occurred over the Haor (wetland) areas of northeast Bangladesh during 17–18 April 2010. Prediction of this sudden incident is challenging when it happened on the high terrain of Meghalaya Plateau and adjoining Bangladesh. Flash flood event occurred when convective cells assembled into a mesoscale convective system (MCS) over the steep edge of the Plateau. The MCS obtained its extreme point after getting moisture support from the southerly flow of the Bay of Bengal (BoB). This study investigated the synoptic flow patterns and large-scale characteristics of the flash flood-producing storm and its associated tropospheric conditions in northeast Bangladesh using the Weather Research and Forecasting (WRF) model. The model used a 3-nested domain with the horizontal resolution of 27 km, 9 km, and 3 km, respectively. The study revealed that the model underestimated the strength of the flash flood in general in respect of rainfall. The 48-h simulated rainfall was about 152 mm for outer domain-1, about 195 mm for inner domain-2 and about 209 mm for the innermost domain-3 whereas actual rainfall was 223 mm as recorded by Bangladesh Meteorological Department (BMD). The southerly wind was strong at 950 hPa and the westerly wind prevailed at 500 hPa level. The model simulated results show that cloud water mixing ratio was 1.8 mg m^{-3} and extended vertically up to 17 km. Ice water mixing ratio was 200 mg m^{-3} and found in between 12 and 20 km, indicating the formation of ice in the upper troposphere. The maximum values of x, y, and z-wind components over Cherrapunji were -11 ms^{-1}, -21 ms^{-1} and -2.8 ms^{-1}, respectively which indicated the strengthening of the convective system to produce flash flood.

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1 Introduction

The wetland areas of the northeastern parts of Bangladesh, locally known as "Haor", experiences frequent flash floods during the pre-monsoon season. These flash floods occur due to the heavy rainfall associated with severe thunderstorms/Mesoscale Convective Systems (MCSs) within a

short span of time in the hilly areas in the northeastern part of Bangladesh. However, it becomes critical if flash floods arrive before harvesting of the major crop (Boro rice) of that area (CEGIS 2012). Accurate flash flood forecasting with sufficient lead time can reduce the damage to crops. A timely forecasting of flash flood might prevent loss of properties and lives. Therefore, an accurate early warning of flash flood forecasting mechanism of those areas is crucial.

However, flash flood forecasting is challenging as the event is short in duration and cloud convection is formed rapidly. The causes of formation of thunderstorms over the northeast areas of Indo-Bangla region are presented in many studies (Das 2010; Das et al. 2006, 2014, 2015a, b, c, d, 2017; Dimri et al. 2015, 2016a, b; Karmakar and Alam 2005; Karmakar et al. 2017; IMD 1944). A southerly low level moist and warm winds impending from the Bay of Bengal (BoB) occurred during this season which often conjugate with the advection of cold and dry north-westerly winds aloft. The thunderstorm events cause flash flood and landslides which are associated with squalls, heavy rain showers, lightning, thunder, hails and downbursts. On many occasions, the outburst of clouds when a passing westerly trough at 500 hPa is superimposed over the Low-Level Jet (LLJ). Usually, the spatial extent of these thunderstorms is a few kilometers and their lifespan is less than an hour (Houze 1975, 1997, 2004, 2014). The development of multi-cell thunderstorms due to established strong convection may have a life duration of several hours and move a few hundred kilometers (Dimri 2013; Islam et al. 2005; Islam and Uyeda 2008). These MCSs grow rigorously when continental air mass meets moist warm air mass from the ocean (Houze et al. 2017). The understanding and forecasting of the extreme weather events challenging to atmospheric researchers. The influx of moisture from the Bay of Bengal (BoB) energizes the MCS (Medina et al. 2010; Murata et al. 2011; Rajeevan et al. 2010; Rasmussen and Houze 2012; Tyagi et al. 2011, 2013; Virts and Houze 2016) as it passes over Meghalaya and northern parts of Bangladesh and thus produces heavy convective and stratiform rain over Meghalaya and the surroundings areas.

The extreme rainfall and runoff are the root causes of the flash flood (Basher et al. 2017; Khan et al. 2019; Mohammed et al. 2017; Nowreen et al. 2014; Roy et al. 2019) in the stretches of valley and highland. The valley and plateaus of the Indo-Bangla region is the wettest place on planet earth. The topography of the north-eastern region of Bangladesh is flat plain, which is situated in the south of the Meghalaya high land. Whenever there is severe thunderstorm during the pre-monsoon season, copious rainfall occurs over Meghalaya and runoff of the rain over the flat terrain causes flash floods in this area. Recent flash floods occurred in 2004, 2010, 2016 and 2017. All four rainstorm events devastated

huge amount of crops and had great impacts on the livelihoods of the people.

In the past, many studies showed that the non-hydrostatic mesoscale models are capable for simulation of high impact weather systems which lead to heavy rainfall episodes over South Asia (Deb et al. 2008; Kumar et al. 2008, 2014; Mohanty et al. 2012; Routray et al. 2005, 2010; Vaid 2013). Conversely, there are also some limitations of forecast skills of rainfall of Numerical Weather Prediction (NWP) models (Das et al. 2008; Rama Rao et al. 2007; Roy and Prasad 2001; Sikka and Rao 2008). Considering these limitations, there is a requirement for efforts to develop NWP model ability in a short-range prediction of convective storms which are responsible for heavy rainfall events causing flash floods and related hazards. A few numerical studies have examined the simulation characteristics of heavy rainfall over Bangladesh using mesoscale models with a horizontal grid size of 9 km or higher resolution (Abhilash et al. 2007; Das and Debsarma 2012; Hasan and Islam 2018; Dimri et al. 2017; Dube et al. 2014; Houze et al. 2011; Webster et al. 2010). Those studies have revealed that numerical models simulate the quantity of rainfall and rain band quite well. It is also mentioned in these studies that the favorable synoptic situation associated with heavy rainfall over Bangladesh, such as the incursion of warm humid air to the storm area by southerly flows, is necessary for the formation of severe thunderstorms. The presence of upper-level jets in the north and low-level jets in the south are typically strengthen the south-north baroclinicity in the mid-troposphere. To investigate such processes, it is important to simulate NWP model at a higher resolution (~3 km) suitable for the convective system to resolve cloud. In the past, such kinds of experiments using NWP model have not been accomplished for high impact weather events over the northeast regions of Bangladesh. Moreover, understanding the large-scale processes for torrential rain over the northeast (NE) area of Bangladesh is an important for flash flood forecasting. Hence, it has become essential to improve the accuracy of rainfall forecasting during the pre-monsoon season using any mesoscale models such as the widely-used community model Weather Research and Forecasting (WRF). WRF is a mesoscale model, which is capable of solving the compressible, non-hydrostatic Euler equations in 3-dimensions (Skamarock et al. 2008, 2019) and designed for both operational applications and atmospheric research. WRF is selectively used in research and operational institutions in Bangladesh for academic research and weather forecasting including high-impact weather simulations.

In this context, this study has investigated the skill of the WRF model to reproduce the flash flood producing heavy rainfall that occurred over the NE region of Bangladesh using cloud-resolving scales (~3 km). WRF has been simulated for heavy rainfall occurred on 17th and 18th April

2010. A double nested WRF model with the highest resolution of 3 km horizontal grid spacing is integrated with conventional analysis data. This study made an attempt to identify and apprehend the various small to large scale wind circulation that resulted in the localized flash-flood-producing heavy rainfall over the NE region of Bangladesh.

2 Materials and methods

2.1 Heavy rainfall events

Two consecutive rainfall events causing flash flood were selected for investigation based on surface synoptic observations. On 17th April 2010, the 24-h accumulated rainfall was found at Cherapunji and Sylhet were 97 mm and 160 mm respectively. However, the next day, the 24-h accumulated rainfall was found at Cherapunji and Sylhet were 103 mm and 61 mm respectively. This heavy (44–88 mm day^{-1}) to very heavy (> 89 mm day^{-1}) rainfall was responsible for the occurrence of flash flood over the region. This type of flash flood occurs most of the years during pre-monsoon and early monsoon over northeastern Bangladesh (Dimri et al. 2017). On 17 April 2010, northerly wind prevailed with a wind speed of 12.7 ms^{-1} at 0927 UTC and southerly wind at 2338 UTC with a wind speed of 15.6 ms^{-1}. The next day on 18 April 2010, the westerly wind with speed of 20.5 ms^{-1} was observed at 2248 UTC. An upper air trough at 0.9 km above mean sea level and run from central Uttar Pradesh to Gangetic West Bengal across Jharkhand with embedded cyclonic circulations over east Uttar Pradesh. Wind Maxima exist over the region.

2.2 Radar-derived reflectivity and radial wind

The Weather Radar is being used worldwide for observation of various extreme weather events like MCSs, rainstorms, squalls, thunderstorms, tornados, hail storms, the direction of movement of thunderstorms and cyclones. To estimate the rainfall on the real-time basis, Radar has a great potential to enhance the proficiencies of researchers and scientists (Chatterjee et al. 2008; Das et al. 2015c; Pradhan and Sinha 2005). Radar can also measure how fast rain or hail is moving away from or toward the Radar. From a Radar volume scan (series of 360° sweeps, each tilting a little higher than the last); Radar meteorologists can get a complete look at organizations and movements of storms close to the Radar. BMD operates a Radar system consisting of three Doppler Weather Radars (DWRs) and two conventional Radars at different places of the country. The nearest DWR is Moulvibazar (MLV) DWR which is located at 24° 29′ 8″ N, 91° 46′ 30″ E. DWR of Moulvibazar is not operated continuously and there is no other DWR nearby Sylhet and Meghalaya. Therefore, the DWR Moulvibazar data are collected through the SAARC STORM project (Das et al. 2014) and we have processed (Das et al. 2015c) before using them in the analysis. DWR derived reflectivity and radial wind field of the event is analyzed. DWR provides radial wind and reflectivity observations temporally every minute and spatially 10 m resolution. Figure 1a, b represents the reflectivity and radial wind of the event. Rain-gauge data cannot recognize the fact that strong rainfall cores are surrounded by light rainfall regions (Islam et al. 2005). To understand the dimension, forms, extent, propagation, the life cycle of the rainfall the Radar analysis provide useful insights. In this study, DWR
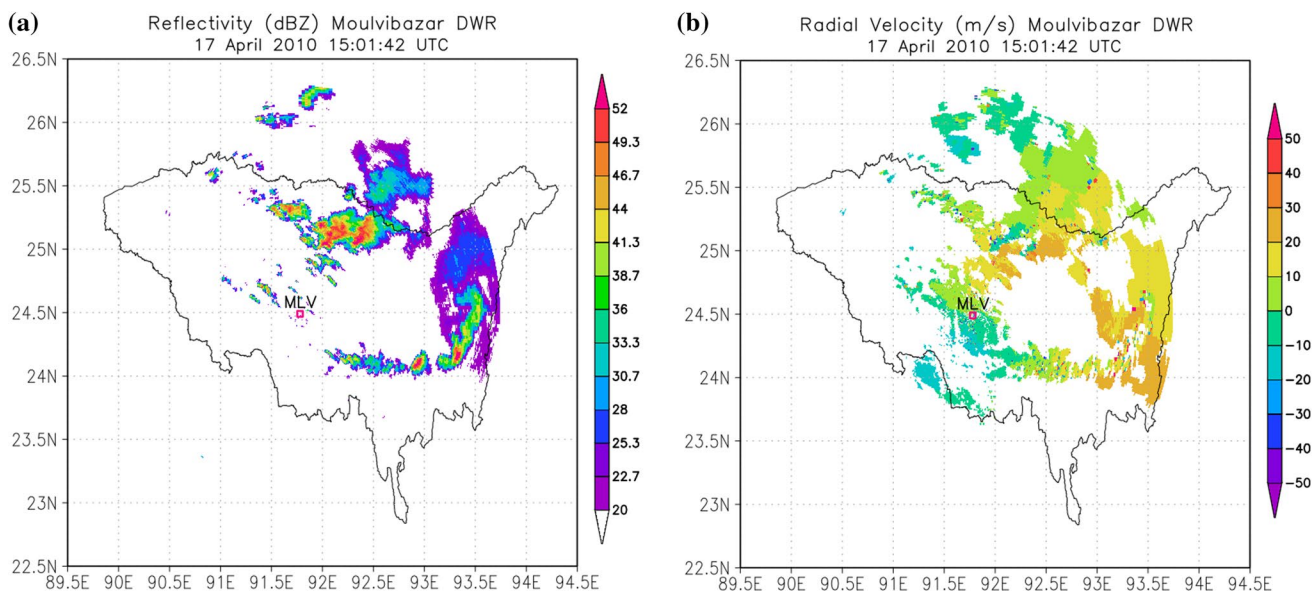
Fig. 1 Moulvibazar DWR derived **a** reflectivity and **b** radial wind on 17 April 2010 at 1501 UTC

reflectivity is correlated with rainfall. MLV DWR recorded reflectivity of 52 dBZ. Bow-type echoes of reflectivity are seen at 1501 UTC on April 17, 2010 (Fig. 1a). This reflectivity indicates heavy rainfall over northeastern Bangladesh and adjoining Meghalaya. The radial wind is correlated with the horizontal wind. Radial velocity between -40 and 50 ms^{-1} is seen during the life cycle of the rainstorm (Fig. 1b). Sun and Crook (1997) study shows that the signal received by DWR is a distribution of velocity which known as Doppler spectrum. The spectrum width is a function of Radar system parameters- pulse width, meteorological parameters and Radar frequency. It defines velocity and hydrometeor density distributions within the scattering volume. Study of Radar data showed that the squalls propagate in the form of parallel bow-shaped squall lines having a horizontal length of more than 50–350 km at the time of the occurrence.
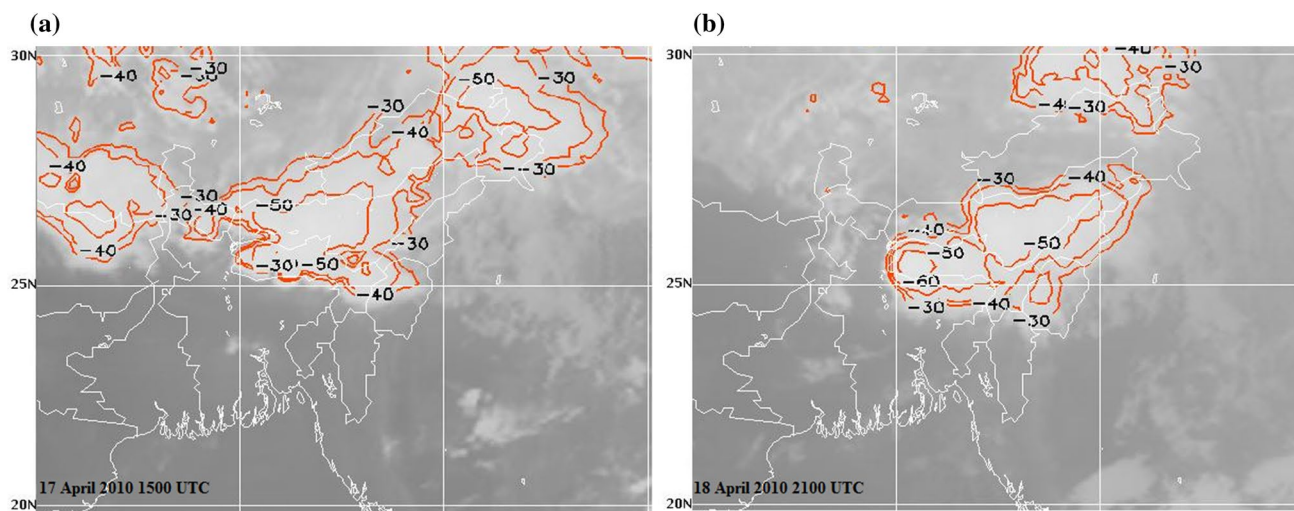
2.3 Satellite-derived cloud top temperature (CTT)

In the study made by Lazri et al. (2013), it is mentioned that there is a relationship between CTT and rainfall probability and intensity, which can be applied for the detection and classification of rainfall areas. In the present study hourly, satellite imageries are analyzed to understand the initiation, maturity and rainfall intensity of the rainstorms. It is found that initiation of the convection, as indicated by CTT, started in the afternoon and became intense during the night up to 2200 UTC on both the days. Only diagrams of the mature stage are presented here (Fig. 2a, b). Moderate (CTT <-30 °C) to strong convection (CTT <-50 °C) was found over the region where rainstorms associated with squalls were reported. It is found that all the systems are aggregate of numerous cloud convections which have strengthened persistently and propagated on the way to

Meghalaya of India and Sylhet of Bangladesh area. The CTT amplified thereafter and the convection became significant at 2100 UTC of 18th April 2010 (Fig. 2b). Otkin and Greenwald (2008) showed that the CTT from the satellite is used to exhibit the advanced capabilities for prediction of convective weather. CTT was found to be -30 °C to -60 °C (Litta et al. 2012) for all the times which indicate the vertical extension of cumulonimbus (Cb) cloud in between 6 and 15 km or more. The cloud extended vertically upward and was more intense. This higher convection was responsible for heavy to very heavy rainfall causing the flash flood.
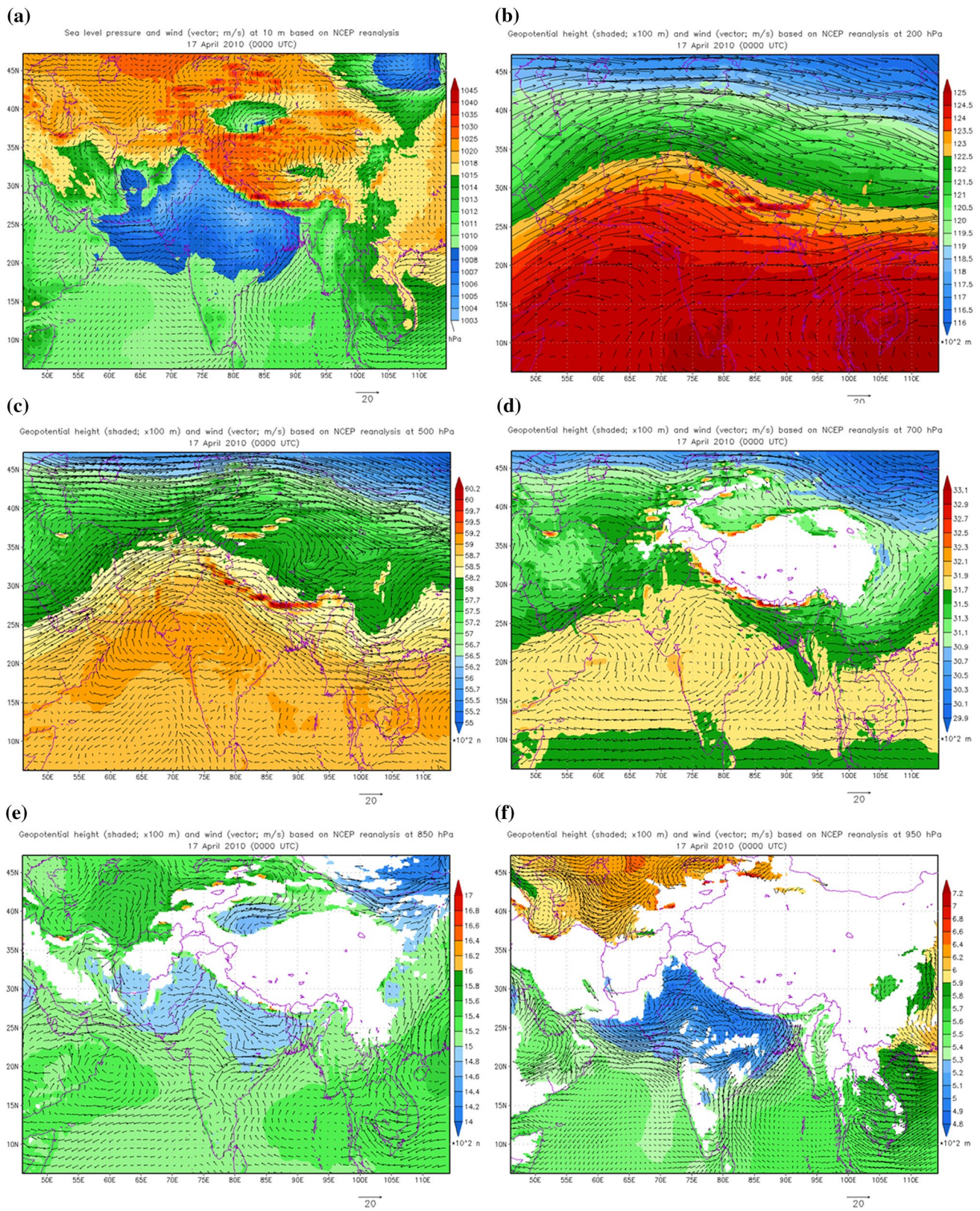
2.4 NCEP reanalysis data for analysis of large scale synoptic processes

The large scale synoptic process and forcing with sea level pressure and wind flow at 10 m is shown in Fig. 3a. The geopotential height in meter and wind flow pattern at 200, 500, 700, 850 and 950 hPa are presented in Fig. 3b–f. The analyses are based on the National Centers for Environmental Prediction (NCEP) reanalysis (NCEP 2000) on 0000 UTC 17 April 2010. A trough of low pressure is extended towards the northeastern part of Bangladesh as shown in Fig. 3a. There is a southwest moist flow at the 10 m level over the country and converging over sub-Himalayan West Bengal with an extended Trough towards the northeast (Fig. 3a). The wind speed is about 20 ms^{-1} over the north BoB. In Fig. 3a, b ridge of the westerly jet is present over the north Arabian Sea, Pakistan, and north India at 200 hPa level. There is a strong trough of both geopotential height and wind circulation over northern Bangladesh and north of it, extending over the Meghalaya region. The geopotential height over the northeast region is 12,250 m, which is lower relative to the surrounding areas and is responsible for the formation

Fig. 2 Cloud top temperature (°C) retrieved from Kalpana-1 satellite **a** 17 April 2010 at 1500 UTC and **b** 18 April 2010 at 2100 UTC

(a)

Sea level pressure and wind (vector; m/s) at 10 m based on NCEP reanalysis
17 April 2010 (0000 UTC)

(b)

Geopotential height (shaded; ×100 m) and wind (vector; m/s) based on NCEP reanalysis at 200 hPa
17 April 2010 (0000 UTC)

(c)

Geopotential height (shaded; ×100 m) and wind (vector; m/s) based on NCEP reanalysis at 500 hPa
17 April 2010 (0000 UTC)

(d)

Geopotential height (shaded; ×100 m) and wind (vector; m/s) based on NCEP reanalysis at 700 hPa
17 April 2010 (0000 UTC)

(e)

Geopotential height (shaded; ×100 m) and wind (vector; m/s) based on NCEP reanalysis at 850 hPa
17 April 2010 (0000 UTC)

(f)

Geopotential height (shaded; ×100 m) and wind (vector; m/s) based on NCEP reanalysis at 950 hPa
17 April 2010 (0000 UTC)

Fig. 3 Large scale process based on NCEP reanalysis on 0000 UTC 17 April 2010 **a** Sea Level Pressure (shaded; hPa) and wind vector (ms^{-1}) at 10 m. Geopotential height (shaded; ×100 m) and wind vector; (ms^{-1}) at **b** 200 hPa, **c** 500 hPa, **d** 700 hPa, **e** 850 hPa and **f** 950 hPa

of the thunderstorm. The sub-tropical westerly jet (SWJ) is embedded in the upper level at 200 hPa; this SWJ also favors the formation of thunderstorms.

The northwesterly wind flow, advecting cold and dry air over Bangladesh and adjoining area at 500 hPa level are presented in Fig. 3c. This cold air advection at 500 hPa from the northwest is important for producing instability after mixing with the warm and moist air at a low level. An anticyclonic circulation is present over central India and the Arabian Sea region. The geopotential height varies at the northeast area from 5825 to 5850 m, having a trough in the northeast region. At 700 hPa level, the strong trough of circulation is found to persist over northern Bangladesh and further north of the country (Fig. 3d). Simultaneously, a strong anticyclonic circulation is found to prevail, covering the area of central India, the Arabian Sea, and the western BoB. A COL area is found near southeast of Bangladesh and adjoining BoB. The relatively lower geopotential height in the northeast region is 3150 m. The strong trough is favorable for MCS formation.

Low geopotential height is found at 850 hPa over West Bengal and adjoining Bangladesh with a value of 1400 m and a trough of low geopotential is extended to northeast Bangladesh (Fig. 3e). At the same time, there exists a strong circulation, converging over the low geopotential height and having an extended trough over the northeast region. The circulation is associated with a strong south-southwesterly moist flow over Bangladesh and adjoining area from the BoB, and there is a northwesterly dry flow in West Bengal and sub-Himalayan West Bengal region. These two types of wind flow are very much conducive to the formation of Cb cloud systems (Fig. 2). Geopotential height varies from 1480 to 1500 m over the northeast region. The presence of strong southwesterly flow from the BoB to the Meghalaya Plateau through Bangladesh was found at 950 hPa level on 17 April

2010 (Fig. 3f). An elongated strong trough exists over the northeastern region, making the environment favorable for generating convection over the region. Analysis of geopotential height showed a strong low height region over West Bengal and adjoining Bangladesh with a trough extending to the northeast with lower geopotential height between 530 and 540 m over the northeastern region.

It can be summarized from the above analysis that there are signs for the growth of convection within the forcing of large scale. The event is localized, having the direct impact of large scale forcing. This direct impact is often hard to find as the trigger of the event; it is absent in the observation as well as initial and boundary conditions (Chaudhuri et al. 2015; Dimri et al. 2017). Interestingly, moist flow from the Arabian Sea and the BoB is found to reach up to the Himalaya region with an extended trough of circulation over northeast Bangladesh and the Meghalaya Plateau. Yatagai et al. (2012a, b) suggested that the convection is the result of wave energy transport of the jet stream in the Himalayan region. A jet stream with a wave like a pattern has been found in Fig. 3b.

2.5 Rainfall retrieved from TRMM

The spatial distributions of rain intensities retrieved from TRMM 3B42RT (Huffman 2016) for the flash flood event over Bangladesh that occurred on 17 April and 18 April 2010 are shown in Fig. 4. Three hourly rainfall starting from 0000 UTC and ending at 0000 UTC of next day are shown in Fig. 4a, b respectively. The rainfall area covers almost the north, northeast and east of Bangladesh. In the morning, there are two rainfall areas over the north and northeast Bangladesh (Fig. 4a). But from 1200 UTC on 17 April 2010, the small areas are aggregated into one intense and large rainfall area which continued up to 2100 UTC, the maximum
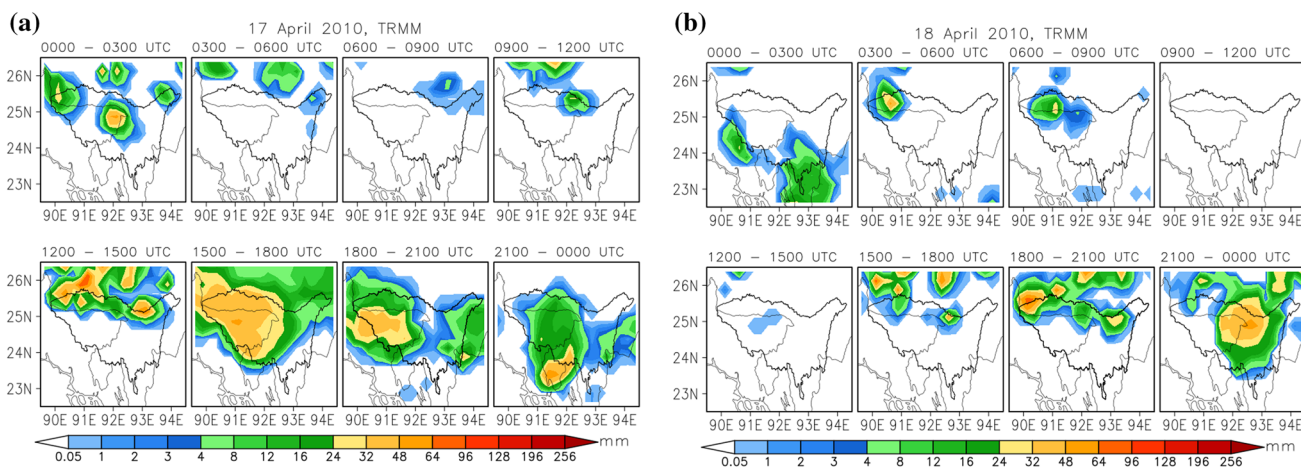

Fig. 4 Accumulated 3 hourly rainfall retrieved from TRMM on **a** 17 April 2010 and **b** 18 April 2010

intensity being found during 1500–1800 UTC. Rainfall amount of 32 mm day^{-1} and 64 mm day^{-1} from 1500 UTC of 17 April to 0000 UTC of 18 April 2010. The rainfall amount is found decreased from 0300 to 0900 UTC with its position shifted slightly northeastward. Later, rainfall areas are found over the northeastern region of Bangladesh and the Meghalaya region with an amount greater than 64 mm. On 18 April 2010, the whole country becomes rainfall free during 0900–1200 UTC as can be shown in Fig. 4b. From 1200 UTC, some systems are found to develop over Assam and adjoining areas and the system has intensified and moved to the south/southeastward when heavy rainfall might have occurred over the Meghalaya Plateau and adjoining northeastern Bangladesh over the Haor areas. The rainfall area of the 1st day is more expanded compared to 2nd day which also indicates more rainfall had occurred on 17 April 2010.

2.6 Weather Research and Forecasting (WRF) model

Numerical weather prediction (NWP) is the state-of-art for seamless weather forecasting at all spatial and temporal scales. The NWP model has the ability to predict micro as well as mesoscale weather phenomena. The numerical model provides information over a study domain from which we can assess an approximation and probability of various weather phenomena and extremes. Mountainous highlands have scanty data where it is difficult to forecast rainfall. In this aspect, the WRF model is an excellent technique to predict weather phenomena where the data is scanty. The forecast products are very useful to the end user as well as different communities. WRF model is capable to simulate short range (hourly basis) to medium range (5–10 days) and

long range (more than 10 days) forecast products for various use. These kind of simulated outputs are very essential for decisions making in weather forecasting. The limitation of the model is the location and time specific error of the forecast for which various parameterization experiments are needed to validate the model simulated event and season wise forecast. A lot of developmental work is required in this area including assimilation of a wide variety of observations from different sources such as surface and upper air observations, Radar, aircraft and satellite observations, ocean observations from floating buoys, and various other remote sensing platforms. Development of physical parameterization schemes, ensemble, and probabilistic forecasting is another important aspect that is continuously evolving. Therefore, it is very important that the research activity is continued for finalizing the appropriate WRF modelling system. Flash flood producing rainstorm in a high terrain region is a sudden convective event and often very localized event. The high-resolution domain setup with the combination of sophisticated physical scheme helps to predict the event and rainfall amount. The rainfall amounts are used in the hydrologic model for water level and discharge forecasting. Hence, the WRF model simulated precise rainfall amount is very important for agriculture and hydrological planners. The Advanced Research Weather Research and Forecasting model (ARW), version 3.7.1 (Skamarock et al. 2008) is used in this study. WRF is a three-dimensional, fully compressible, non-hydrostatic model. In the study, the domain is considered with a nested domain with 27, 9 and 3 km horizontal spatial resolution as shown in Fig. 5. The $1.0° \times 1.0°$ gridded NCEP FNL (Final) Operational Global Analysis and Global Forecast System (GFS) data are used as
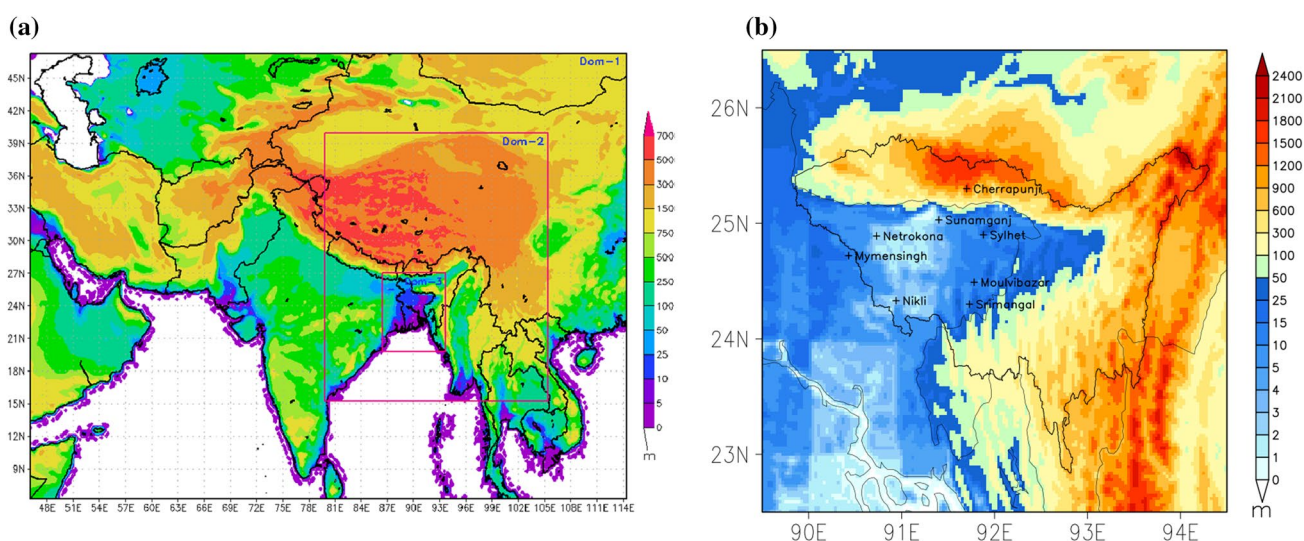
Fig. 5 Geographic map of the study area along with the terrain heights **a** Triple nested domain and **b** Northeastern Bangladesh and the Meghna Basin

initial and Lateral Boundary Conditions (LBC) of the model. The main features of the model employed for this study are summarized in Table 1.

3 Results and discussion

The WRF model was simulated for a period of 96 h, starting at 0000 UTC on 15 April 2010, as initial values. The structure of the flash flood-producing storm is obtained by the model and compared with observations available from synoptic observations, ground-based Radar, and TRMM. We will discuss the results obtained from the model simulations in the following sub-sections.

3.1 Maximum reflectivity (dBZ) and rainfall

The model simulated reflectivity of hydrometeor in the atmosphere at different synoptic hours on 17 and 18 April 2010 are presented in Fig. 6a. It has found that the reflectivity becomes maximum and distinct from 0600 to 1800 UTC on 17 April 2010 and from 0600 to 1200 UTC on 18 April 2010 over the place of occurrence as shown in Fig. 6a. The model simulated reflectivity value is more than 50 dBZ, indicating severe thunderstorm and intensive rainfall which is comparable (Fig. 1a) to BMD MLV DWR derived reflectivity.

The model simulated three hourly rainfalls, which is comparable with the spatial distribution of rainfall derived from TRMM (Fig. 4a, b) is shown in Fig. 6b. While the model results show the shifting of the areas of rainfall both in time and locations, the intensities of rainfall rates are simulated very well. From the spatial pattern of rainfall, it can be clearly found that rainfall amount and spread are well

Table 1 Features of numerical model configurations

Model	WRF version 3.7.1
Map projection	Mercator
Horizontal resolution	Nest: 27, 9 and 3 km
Vertical levels	40
Land cover	USGS
Time integration	Semi implicit
Vertical differencing	Arakawa's Energy Conserving Scheme
Convection	Kain-Fritsch (new Eta) scheme (Kain 2004)
Planetary boundary layer	Yonsei University Scheme (YSU)
Cloud microphysics	WRF single-moment 6-class (WSM6) (Hong and Lim 2006)
Surface layer	Monin–Obukhov
Radiation	RRTM (LW), SW (Dudhia 1989)
Land surface processes	Unified NOAH Land Surface Model
Horizontal grid scheme	Arakawa C-grid

captured for the event (Fig. 4a, b). The model has simulated the maximum rainfall of 128 mm day^{-1}, which is very near to the observed rainfall of BMD.

The model underestimated rainfall over the region during the flash flood event. Recorded 48-hour rainfall accumulated during 17–19 April 2010 at the synoptic observatory of Sylhet was 222.6 mm. For the domain 1–3, 48-hours rainfall amount differs with observations and are 152 mm, 195 mm and 209 mm respectively over the Sylhet region. TRMM retrieved 48-h rain amount is 139 mm, which also underestimates the rain gauge recordings. There is also 7 mm difference in rainfall between BMD rain gauge at Sylhet and special observation taken by Kyoto University of Japan team by using Automatic Weather station (AWS) at Sylhet International Airport which is about 5 km north of BMD rain gauge. The statistical analysis shows that the root means square error (RMSE) compared to BMD rain gauge station with TRMM is 17 mm and with the model simulated rainfall is about 22, 29 and 31 mm respectively for domain 1, 2 and 3. Although the root-mean-squared error for domain 3 is higher it simulates heavy rainfall event quite well. The model domain 3 has underestimated 5.9% whereas domain 2 has underestimated 12.2% and domain 3 has underestimated 31.7%. Three hourly rainfalls from the surface observatory, TRMM 3B42RT derived, model-simulated and their statistical analysis is shown in Table 2. It is also noted that from 0000 to 0600 UTC of 17 April 2010, the recorded rainfall is 124 mm in Sylhet station. Such a heavy rainfall plays a significant role in producing a flash flood event.

Rainfall evaluated from the model at an observatory location can give a partial picture. Hence, we have plotted a time series of areal average rainfall calculated over a 1° lat-lon box around Sylhet station in Fig. 6c. The spatial distribution of the rainfall is also presented in Supp. Figure 1a, b. From the time series and spatial distribution, it is evident that the higher resolution of the computation domain leads to rainfall that is higher in amount and spatial resolution. Since for flash flood, information of basin-wide rainfall is more important than rain recorded in a single point, we argue that higher domain resolution can provide a better estimation of basin rainfall.
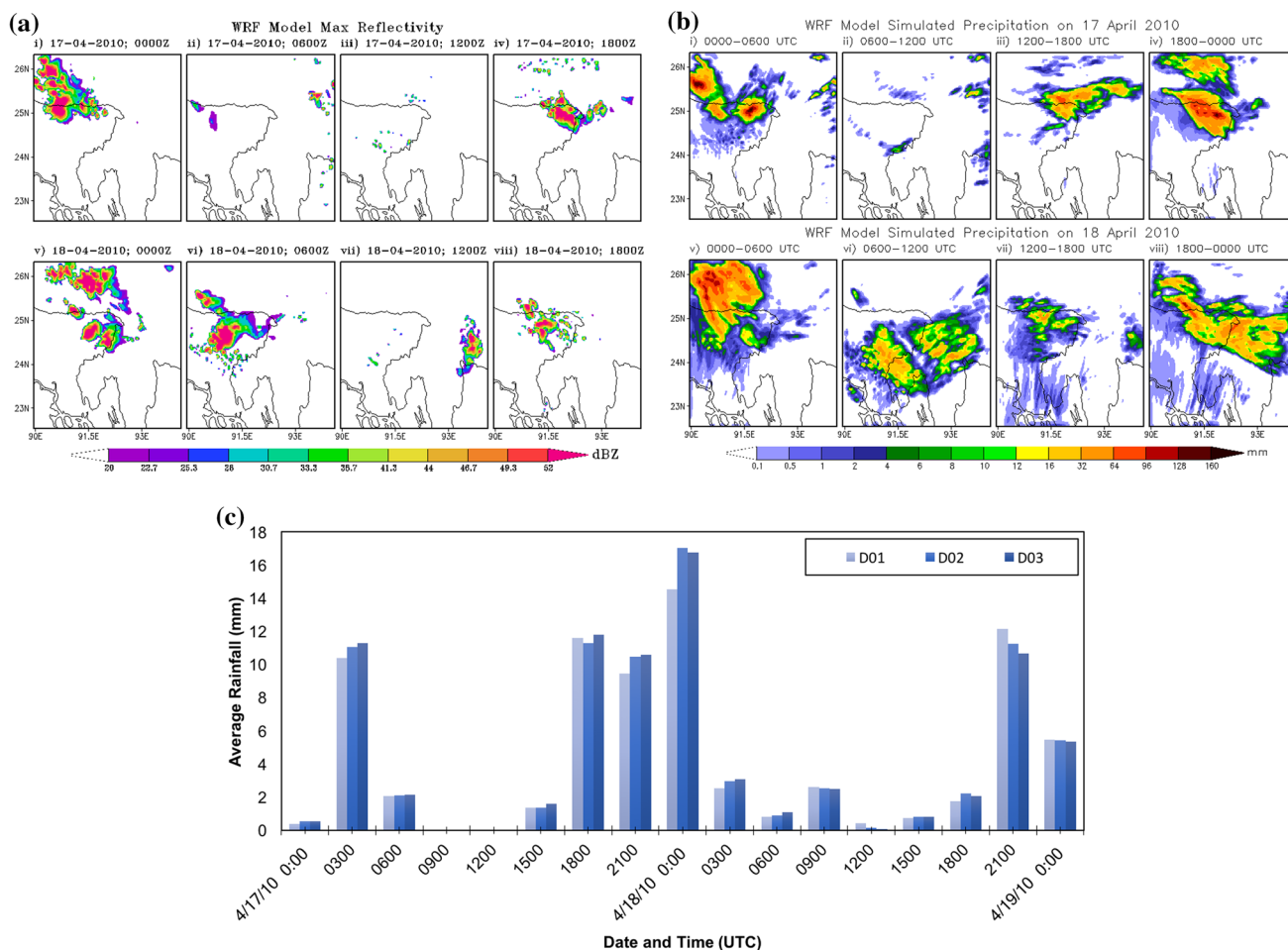
3.2 Wind, SLP, vorticity, and RH

The model simulated vector wind at 950 hPa and wind speed at 10 m level are shown in Fig. 7a. The wind speed of 6–10 ms^{-1} at 10 m level in the northeast region of Bangladesh at 0600 UTC and 1800 UTC on 17 April 2010 and 0600 UTC on 18 April 2010. There is a strong cyclonic circulation at 950 hPa level over West Bengal and adjoining Bangladesh with a prominent trough extending towards the northeast. The 950 hPa horizontal wind shows strong southerly flow through southern Bangladesh with a trough

Fig. 6 WRF model simulated **a** reflectivity, **b** accumulated 6 hourly rainfall and **c** areal average rainfall calculated over a 1° lat-lon box around Sylhet station

extending over the north and north-eastern part of Bangladesh (Fig. 7a). There exists a micro-circulation during 0000–1200 UTC on both 17 and 18 April 2010 over the north-northeast area of Bangladesh as can be found from Fig. 7a. Such a micro-circulation has been responsible for the generation of a severe thunderstorm with higher rainfall. The model simulated feature is consistent with surrounding radiosonde observations. The strong southerly flow incurs the moisture in the lower levels. For triggering a convective activity, the stronger south-southwesterly wind flow is important which has helped deliver moisture convergence over the convective zone.

The time evolution of SLP at the flash flood reporting stations is shown in Fig. 7b. Solar insolation causes strong surface heating and forms heat low at the surface. SLP seems to be less than 1002 hPa over the western part of Bangladesh and adjoining West Bengal, which is due to the existence of heat low during the pre-monsoon season (Dalal et al. 2012). Figure 7b shows that the mean sea level pressure is relatively lower over the northeastern part of the country at 1200 UTC

on 17 April 2010, having a micro low of 1004 hPa over Sylhet region. This micro low over northeast region of Bangladesh has been conducive and responsible for the occurrence of the severe convection.

The model simulated the vorticity field at 850 hPa is shown in Fig. 7c. In the lower level, the vorticity is positive during the event over Bangladesh and adjacent region. Severe activity is observed during 0000 and 1800 UTC of 17th April having vorticity as high as 400×10^{-5} s^{-1}. The high value of vorticity is favorable for the thunderstorm to occur and supports condensation of the available moisture, and the resultant latent heat helped (Holton 1994) to further increase instability leading to convection. Strong convergence and divergence are found in the simulation at a lower atmosphere during the thunderstorm period (Fig. 7c).

The distribution of relative humidity at 2 m simulated by the WRF model over Bangladesh is shown in Fig. 7d at every six hours on 17 and 18 April 2010. The dry and moist lines are found to intersect at the place of occurrence of the storm as shown in Fig. 7d. This point of intersection shows

Table 2 Statistical analysis of three hourly observed, TRMM derived, model simulated rainfall

Date	Time (UTC)	Rainfall (mm)					
		BMD	AWS	TRMM 3B42RT	WRF model		
					Dom-1	Dom-2	Dom-3
17 April 2010	0000–0300	65.4	93.1	48.3	45.8	15.9	8.3
	0300–0600	58.8	38.0	0	6.5	9.9	8.6
	0600–0900	0	0	0	0	0	0
	0900–1200	0	0	0	0	0	0
	1200–1500	0	0.4	0	0	0	0
	1500–1800	34.4	17.2	34.5	28.4	38.5	51.8
	1800–2100	2.2	19.4	3.7	39.1	68.6	68.5
	2100–0000	1	1.7	13.9	18.9	44.5	50.1
18 April 2010	0000–0300	0	0	0	0.2	0	0
	0300–0600	0	0	0	2.0	1.0	0.8
	0600–0900	4.2	9.5	3.4	0.3	0.4	1.0
	0900–1200	0	0	0	0	0	0
	1200–1500	0	0	0	2.7	5.5	6.7
	1500–1800	0	0.5	0	1.9	4.7	4.7
	1800–2100	0	0.9	1.4	4.9	3.9	6.8
	2100–0000	56.6	35.2	33.7	1.5	2.2	2.0
Total		222.6	215.9	138.8	152.1	195.3	209.4
% of underestimation (%)			3.0	37.6	31.7	12.3	**5.9**
RMSE			11.9	16.7	22.3	29.8	31.6

the place of occurrence of the severe storm which caused the flash flood.

3.3 Time-pressure cross section of RH, cloud water mixing ratio and Ice water mixing ratio

Time-pressure cross section of relative humidity (%) on the days of the flash flood at different locations is shown in Fig. 8a. All the figures of the panel of Fig. 8a show 90–95% relative humidity up to about 200 hPa (approx.12 km) and this humidity is found to extend up to the top of the troposphere at all stations during 1800 UTC on 17 April and 0600 UTC on 18 April 2010, when the maximum heavy rain is assumed to occur over the northeastern part of the country. This indicates the relative humidity increases throughout the troposphere extending to upper troposphere prior to the occurrence of the thunderstorm.

The vertical cross-section of the cloud water mixing ratio is given for places such as Mymensingh, Netrokona, Nikli, Sunamganj, Cherrapunji, Srimangal, Moulvibazar, and Sylhet is shown in Fig. 8b. It has found that the advection of the cloud/convection with a variation of height moved from the west to east. Prominent cloud water mixing ratio was found over the northern part of Bangladesh and extend up to 300 hPa (Fig. 8b). Mixing of cloud water is found to start from the lower troposphere. The value of cloud water mixing ratio is 500–700 mg m^{-3}. The cloud water mixing ratio

is found to be prominent between 0000 and 1800 UTC and it has extended up to 350 hPa or more (Fig. 8b). It may be noted that the cloud water mixing ratio does not have the continuous vertical extension; rather it has broken patches at all times. The reason is not known but it may be due to the orographic effects where eddy flow of winds occurs.

The ice water mixing ratio is simulated by the numerical model, WRF is shown in Fig. 8c. The ice water mixing ratio persists from 0000 to 1800 UTC between 600 and 150 hPa on 17 April 2010. On the 2nd day, it was existing from 0000 to 0600 UTC. Mixing of ice and water is found to start from about 600 hPa in most of the places. The maximum value of ice water mixing ratio for the 1st day is 180 mg m^{-3} and the 2nd day it is 140 mg m^{-3}. The ice water mixing ratio over Sunamganj, Sylhet, and Cherrapunji is more prominent lasting for a longer time in the upper troposphere and indicates more hails associated with the thunderstorms under study. Ice water mixing ratio plays a significant role in the formation of large hail storms in the extreme thunderstorms.

3.4 Wind structure simulated over Cherrapunji and Sylhet

The zonal, meridional and vertical wind components are computed from the model simulated results for the Cherrapunji and Sylhet stations on 17–19 April 2010. The
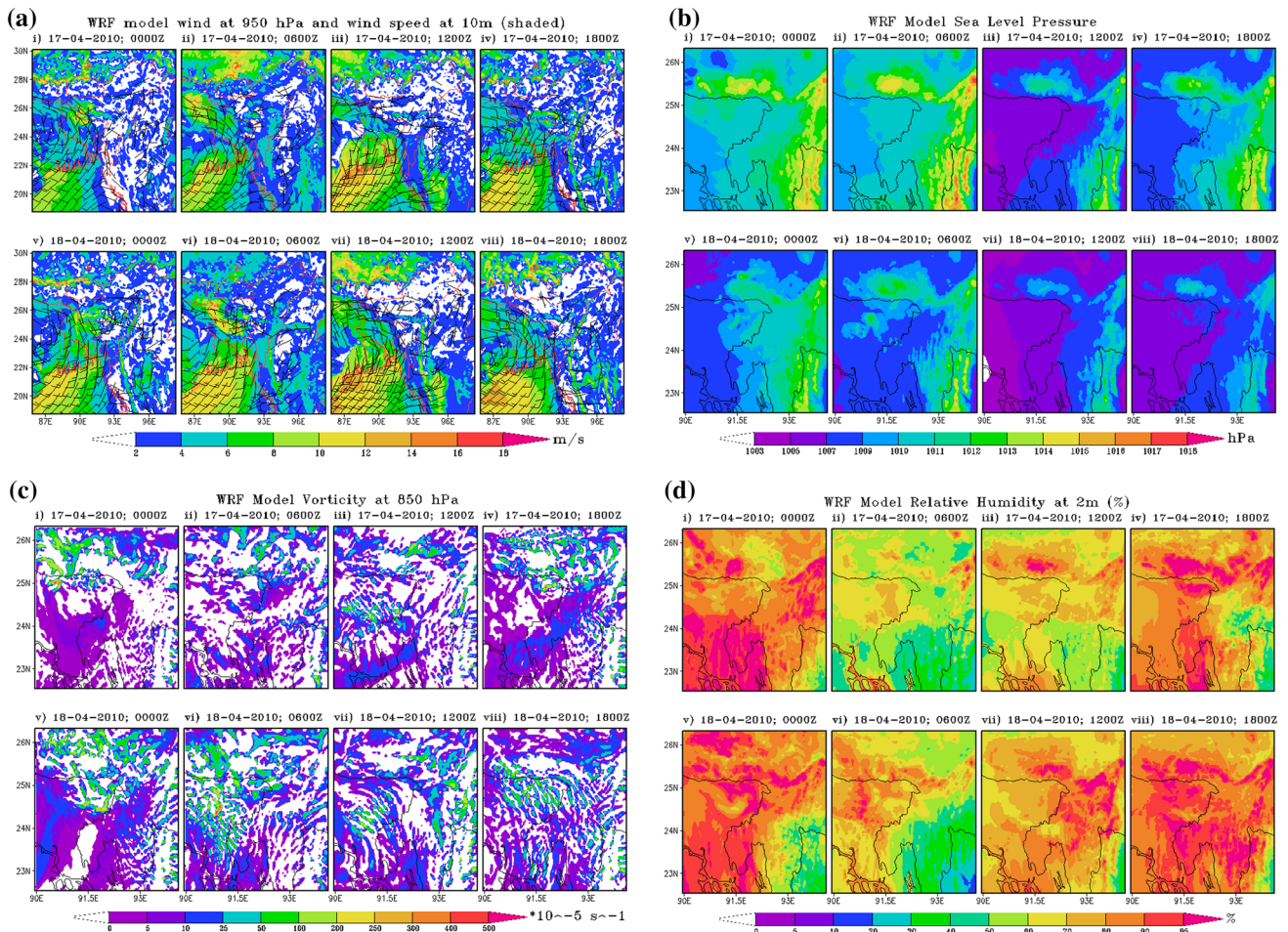
Fig. 7 WRF model simulated **a** wind at 950 hPa and wind speed at 10 m (shaded), **b** Sea Level Pressure (SLP), **c** Vorticity ($\times 10^{-5}$ s^{-1}) at 850 hPa and **d** spatial distribution of relative humidity at 2 m (%)

vertical structures of the simulated wind components (u, v and z) in terms of vertical-time cross-sections are shown in Fig. 9a–f.

The westerly wind dominates (positive u-component) the whole troposphere from 0300 UTC of 17 April 2010 to 0000 UTC of next day roughly from 850 hPa to top of the troposphere (Fig. 9a). The wind speed of about 5–12 ms^{-1} is found in the level 800–350 hPa. The westerly wind is found to increase in the upper troposphere between 300 to 100 hPa. Maximum wind speed of about 25–35 ms^{-1} is found at about 150 hPa from 0000 to 0900 UTC indicating the presence of westerly jet in that level. On 18 April 2010, the westerly wind has become weak at 0000 UTC and the weak easterly wind has appeared between 800 and 500 hPa from 0300 to 0600 UTC. Then the westerly wind has again reappeared from 800 hPa to the top of the troposphere having wind speeds of about 10 ms^{-1} in 800–300 hPa and 15–30 ms^{-1} aloft. The westerly jet stream of about 25–30 ms^{-1} is at 150 hPa between 0000 to 0600 UTC of 18 April 2010. The presence of easterly wind indicates a change (break) in the

rainfall pattern, which is also evident in Fig. 4a, b when there was no rainfall.

The vertical structure of the zonal wind over Sylhet is shown in Fig. 9b. It can be found that westerly wind is present throughout the troposphere with a little exception at the surface when there is a feeble easterly wind at 1500–2100 UTC on 17 April 2010. The westerly wind of 5–15 ms^{-1} is found to dominate from 800 hPa to about 250 hPa between 0300 and 1500 UTC on 17 April 2010. The same is found on 18 April 2010 with the exception that there is an easterly wind in the layer 650 hPa to 400 hPa during 0300 UTC to about 1200 UTC. The westerly wind is found to intensify again afterward with dominant speeds of 10–15 ms^{-1} between 800 hPa to the top of the troposphere. Maximum westerly wind of 25–35 ms^{-1} or more is found at around 150 hPa in the morning of 17 and 18 April 2010 which may be due to the higher temperature gradient in the morning as compared to that of the afternoon. It is evident from Figs. 4a, b and 9b that rainfall is found to cease with the weakening of the westerly wind.
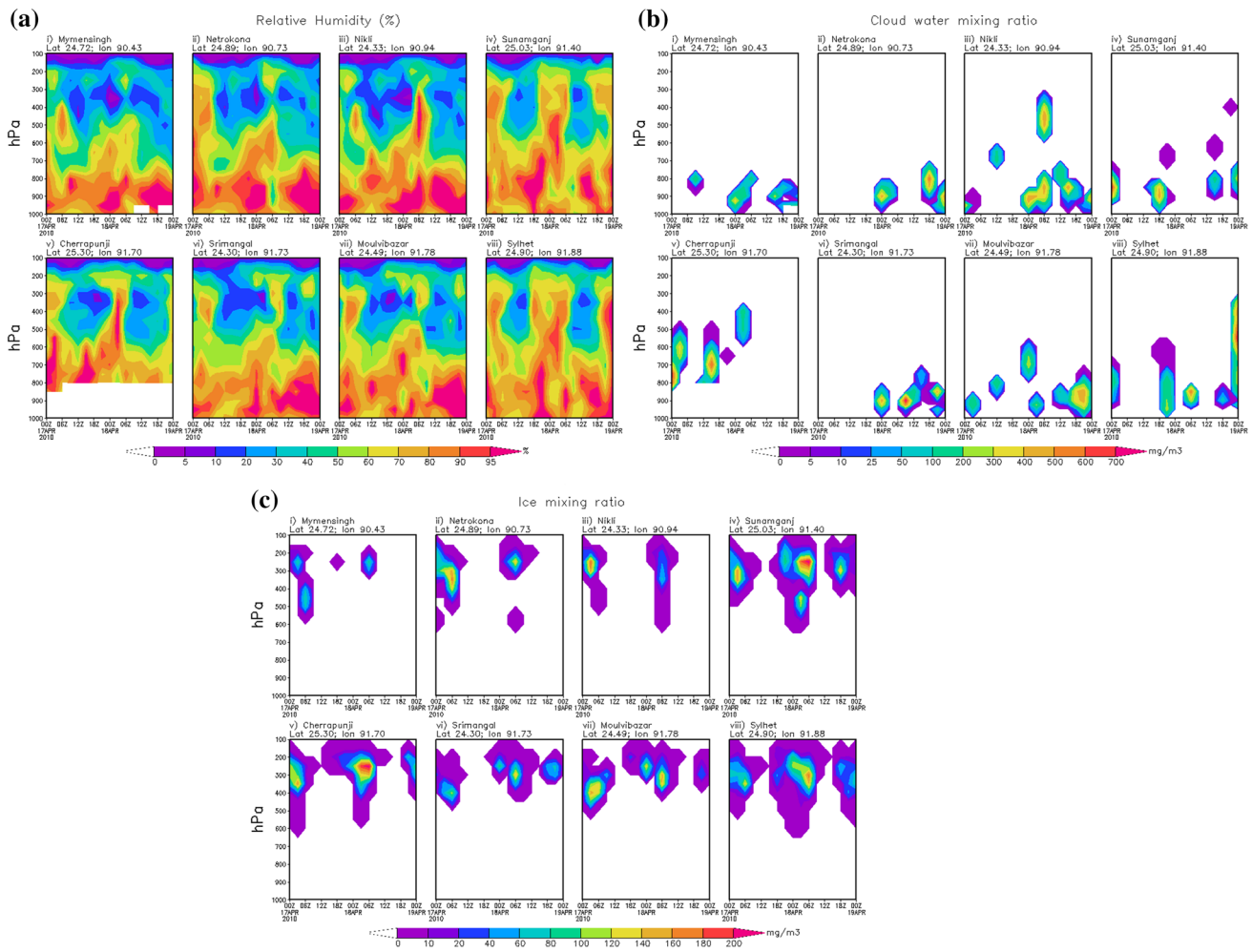
Fig. 8 Vertical profile of **a** relative humidity (%), **b** cloud water mixing ratio and **c** ice water mixing ratio for different locations during flash flood

The vertical structure of the v-component of Cherrapunji is shown in Fig. 9c. It has been found from Fig. 9c that there is southerly wind (positive v-component) at 840 hPa to about 540 hPa level during 0000 UTC of 17 April 2010 to about 0000 UTC on 18 April 2010. The maximum wind speed is 9 ms^{-1} at around 0300 UTC near 800 hPa to 760 hPa on 17 April 2010. Above 500 hPa level to about 100 hPa level there is dominance of northerly wind (negative v component) during 0000 to 1800 UTC of 17 April 2010 except the level 320 hPa to 180 hPa at about 0300 UTC and the level 250 to 220 hPa level at around 2100 UTC when there are southerly winds on 17 April 2010. It is also found that northerly wind exists from about 680 hPa to about 250 hPa at 2100 UTC on 17 April 2010. Then northerly wind speed of 3 to 12 ms^{-1} is found to be dominant from 800 to 580 hPa level and a cell of southerly wind in the layer 500 hPa to about 300 hPa in between 0300 to 0500 UTC on 18 April 2010. Afterward, the southerly wind has appeared in the lower troposphere

with the maximum speed of 9 ms^{-1} at 0600 UTC. Simultaneously northerly wind is found to be dominant in the upper troposphere with the maximum wind speeds of 9 to 15 ms^{-1} in the layer 500 to 100 hPa. The appearance of northerly wind with the interruption of the southerly wind 2100 UTC of 17 April to 0600 UTC of 18 April 2010 may be thought of being responsible for the cessation of rainfall at Cherrapunji.

The vertical structure of v-component of wind (meridional wind component) over Sylhet is shown in Fig. 9d. There is southerly wind (positive v-component) from the surface to 700 hPa during 0000 UTC of 17 April to 0000 UTC of 19 April 2010 and the maximum value is 9 ms^{-1}. There is dominant northerly wind (negative v-component) above 420 hPa from 0000 to 0600 UTC of 17 April 2010. The dominance is more prominent at 0900 UTC, and 2100 UTC of 17 April and during 0600–2100 UTC of 18 April 2010 above 500 hPa extending to the top of the troposphere. The maximum value of the northerly wind is 18 ms^{-1}.
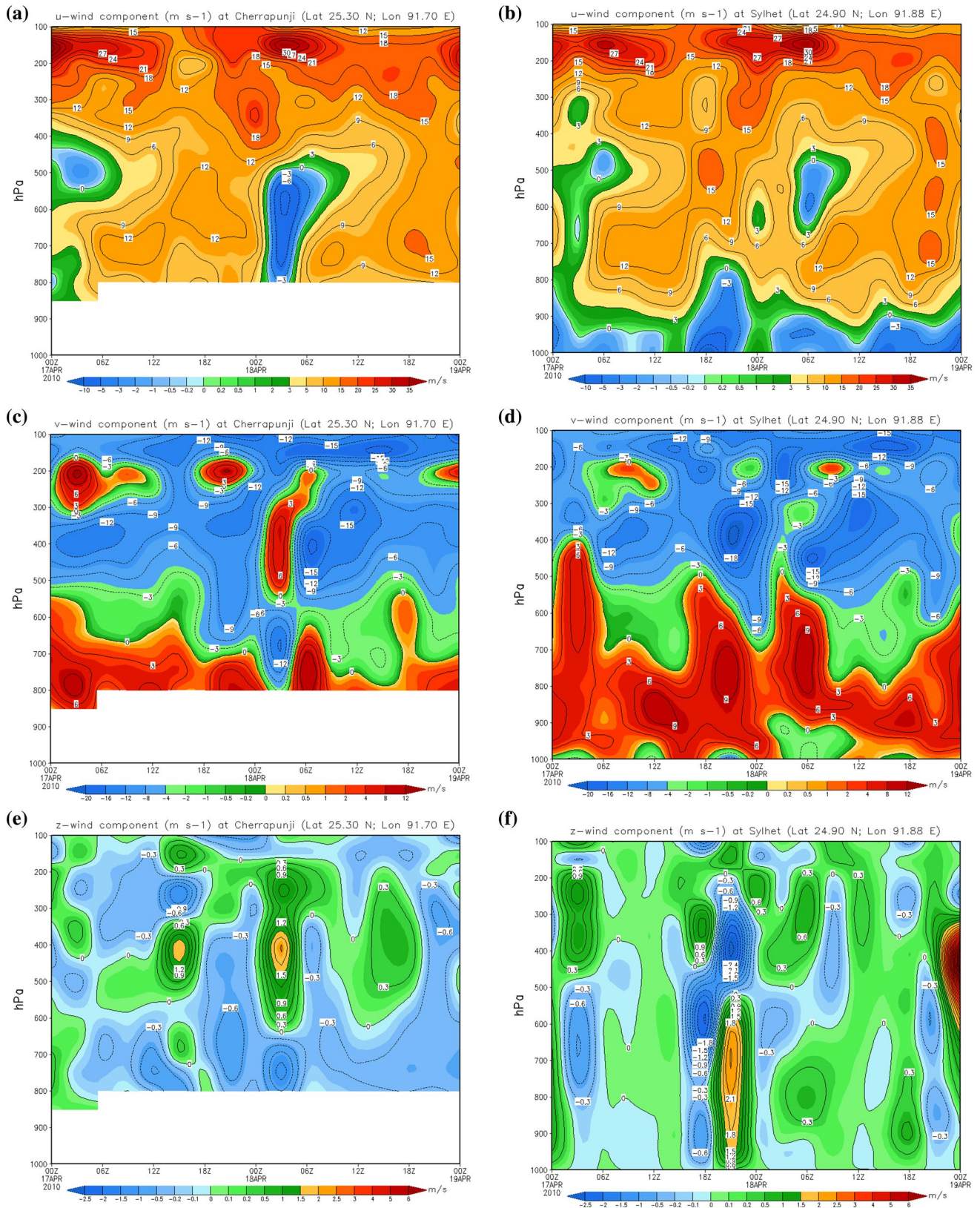
Fig. 9 Vertical x-cross section of simulated **a**, **b** zonal wind (u-component), **c**, **d** meridional wind (v-component) and **e**, **f** vertical velocity (z-component) of Cherrapunji (left panel) and Sylhet (right panel). The white empty space in the left panels are due to the elevation of Cherrapunji

The time-pressure cross section of z-component of wind (vertical velocity) over Cherrapunji is shown in Fig. 9e and Sylhet are shown in Fig. 9f. The time-pressure cross section of z-component of wind over Cherrapunji indicates updraft (positive vertical velocity) from 0000 UTC of 17 April to 1900 UTC of 18 April 2010. The updraft is more prominent at during 1200–1800 UTC of 17 April and 0000–0600 UTC of 18 April 2010. The maximum updraft is 1–2 ms^{-1} above about 500 hPa to 350 hPa at 1500 UTC of 17 April and 0300 UTC of 18 April 2010, which indicate the strengthening of the convective storm. The downdraft (negative vertical velocity) is prominent at 2100 UTC of 17 April, 0300 UTC and 2100 UTC of 18 April 2010. The maximum downdraft varies from 0.5 to 1 ms^{-1} and indicates weakening of the convective system for a while in the layer of 830 hPa to 500 hPa from 1900 UTC of 17 April to 0500 UTC of 18 April 2010 and in the layer 320–220 hPa during 1500 UTC of 17 April and 2100 UTC of 18 April 2010.

The time-pressure cross section of z-component of wind over Sylhet indicates updraft (positive vertical velocity) from 0000 UTC of 17 April to 0000 UTC of 19 April 2010 throughout the troposphere. The maximum updraft over Sylhet at 0300 and 2100 UTC of 17 April is 1 to 2 ms^{-1} indicating more significant convection at that time. The downdraft is only at 1700 to 2300 UTC of 17 April 2010 near the level 700 hPa to 270 hPa which shows a weakening of the convective phenomena.

4 Conclusions

Based on the study, the following conclusions can be drawn-

- The model simulated results provide a basis to study the microphysical and dynamical characteristics of the flash flood producing rainstorms, which are not generally available from data of meteorological stations.
- The large-scale processes are found to be the significantly favorable conditions for producing rain-bearing convective storm over the steep topography of the Meghalaya region. This study reveals that the WRF model is able to simulate precipitation and associated parameters well. However, there is a spatial shift of model-simulated cloud and precipitation compared to the actual observations and TRMM derived precipitation.
- DWR derived reflectivity and radial wind provide an indication of the meso-convective event. The parallel bow-shaped convective lines had an elongated length of approximately 350 km. CTT analysis indicates the meso-convective systems with huge convection exaggerated horizontally and vertically over the mountainous highland.

- The WRF model with a 3-km resolution has simulated the formation of the convective storm, and the initiation of the storm, squall line and cloud cluster nearly at the time of occurrence. The model has captured the rainfall distribution reasonably although the total rainfall amount is underestimated compared to the observations.
- The WSM6 scheme as microphysics schemes, the Kain–Fritsch with the Noah land surface model as cumulus parameterization scheme, and the planetary boundary layer scheme as the YSU PBL scheme have produced the best results for heavy rainfall prediction over this region. The model has well captured the rain and reflectivity of hydrometeor close to the place of occurrence of the event.
- The value of reflectivity is found to be more than 52 dBZ both in the model result and observation at Moulvibazar DWR, indicating severe convection and heavy precipitation.
- The low-level wind field shows that there is a southwesterly flow from the Bay of Bengal towards the northeast Bangladesh, which later converges over the north-northeast region of Bangladesh. The strong southwesterly flow helps to transport a high amount of moisture from the Bay of Bengal across the south, the southeast region of Bangladesh and neighboring areas.
- The strong low-level convergence has carried the moisture up to 200 hPa level and accordingly high relative humidity is extended up to this level. The north and northeast regions of Bangladesh are characterized by strong vertical wind shear, high relative vorticity, low-level convergence, and upper-level divergence during the thunderstorms under study.
- The model has underestimated in capturing the strength of the flash flood in general due to the weakness in producing heavy precipitation. The 48-hour simulated rainfall is about 152 mm for outer domain-1, 195 mm for inner domain-2 and 209 mm for the innermost domain-3 but actual rainfall is 222.6 mm as observed by BMD rain gauge at Sylhet in Bangladesh. Model domain-3 underestimated precipitation by only 5.9%.
- The vertical cross-section of humidity, cloud water and cloud ice mixing ratios, reflectivity and the vertical cross section of u-, v- and z-components of wind have been significant for producing storm events. Time-pressure cross section of humidity shows the peak of the highest RH reaching up to 300 hPa level.
- The maximum cloud water mixing ratio is 700 mg m^{-3} at 900 hPa level over Srimangal and ice water mixing ratio is 200 mgm^{-3} at 300 hPa to 200 hPa level over Sunamganj and Cherrapunji.
- The maximum values of x-wind component are found -11 and 39 ms^{-1}, y-wind component $-$ 21 and 12.5 ms^{-1} and z-wind component $-$ 2.8 and 6.8 ms^{-1} at Cherrapunji and

Sylhet respectively indicate strengthening and weakening of flash flood producing the convective system. For the future study, the inclusion of Data Assimilation would be helpful to improve the heavy rainfall forecast over this region.

References

Abhilash S, Das S, Kalsi SR, Das Gupta M, Mohankumar K, George JP, Banerjee SK, Thampi SB, Pradhan D (2007) Impact of Doppler radar wind in simulating the intensity and propagation of rainbands associated with mesoscale convective complexes using MM5-3DVAR system. Pure Appl Geophys 164(8–9):1491–1509. https://doi.org/10.1007/978-3-7643-8493-7_4

Basher Md, Stiller-Reeve M, Islam AS, Scott B (2017) Assessing extreme rainfall trends over the northeast regions of Bangladesh. Theoret Appl Climatol 1–12:2017. https://doi.org/10.1007/s00704-017-2285-4

CEGIS (2012) Master plan of the haor area, Bangladesh Haor and Wetland Development Board (BHWDB), summary report, vol II. Ministry of Water Resources, Government of Peoples Republic of Bangladesh

Chatterjee P, Pradhan D, De UK (2008) Simulation of hailstorm event using mesoscale model MM5 with modified cloud microphysics scheme. Ann Geophys 26:3545–3555

Chaudhuri C, Tripathi S, Srivastava R, Misra A (2015) Observation- and numerical-analysis-based dynamics of the Uttarkashi cloudburst. Ann Geophys 33:671–686. https://doi.org/10.5194/angeo-33-671-2015

Dalal S, Lohar D, Sarkar S, Sadhukhan I, Debnath GC (2012) Organizational modes of squall-type mesoscale convective systems during premonsoon season over eastern India. Atmos Res 106:120–138

Das Mohan K, Debsarma SK (2012) Cyclone Aila Moisture Effects on Heavy Rain and Flooding in Bangladesh, Bhutan, NE-India and Nepal. International Conference on Ensemble Methods in Geophysical Sciences, 12–16 November 2012. Toulouse, France. https://www.meteo.fr/cic/meetings/2012/ensemble.conference/

Das MK, Chowdhury MA, Das S (2015a) Sensitivity study with physical parameterization schemes for simulation of mesoscale convective systems associated with squall events. Int J Earth Atmos Sci 2(2):20–36

Das MK, Das S, Chowdhury AM, Karmakar S (2015b) Simulation of Tornado over Brahmanbaria on 22 March 2013 using Doppler Weather Radar and WRF Model. Geomat Nat Hazards Risk 7(5):1577–1599. https://doi.org/10.1080/19475705.2015.1115432

Das MK, Chowdhury MA, Das S, Debsarma SK, Karmakar S (2015c) Assimilation of Doppler weather radar data and their impacts on the simulation of squall events during pre-monsoon season. Nat Hazards 77(2):901–931. https://doi.org/10.1007/s11069-015-1634-9

Das MK, Saiful IAKM, Khan Md, Uddin J, Samarendra K (2017) Numerical simulation of flash-flood-producing heavy rainfall of 16 April 2016 in NE regions of Bangladesh. Vayu Mandal 43(2):97–108

Das S, Ashrit R, Moncrieff MW (2006) Simulation of a Himalayan Cloudburst event. J Earth Syst Sci 115(3):299–313

Das S, Ashrit R, Iyengar GR, Saji Mohandas M, Gupta D, George JP, Rajagopal EN, Dutta SK (2008) Skills of different mesoscale models over Indian region during monsoon season: Forecast errors. J Earth Syst Sci 117:603–620

Das S (2010) Climatology of thunderstorms over the SAARC region. SMRC report no. 35, p 66

Das S, Mohanty UC, Tyagi A, Sikka DR, Joseph PV, Rathore LS, Habib A, Baidya SK, Sonam K, Sarkar A (2014) The SAARC STORM: a coordinated field experiment on severe thunderstorm observations and regional modeling over the South Asian region. Bull Am Meteorol Soc 95:603–617

Das S, Sarkar A, Das MK, Rahman MM, Islam MN (2015d) Composite characteristics of Nor'westers based on observations and simulations. J Atmos Res 158–159:158–178. https://doi.org/10.1016/j.atmosres.2015.02.00

Deb SK, Srivastava TP, Kishtawal CM (2008) The WRF model performance for the simulation of heavy precipitating events over Ahmedabad during August 2006. J. Earth Syst. Sci. 117:589–602

Dimri VP (2013) Uttarakhand has early warning communication in 1894! Curr Sci 105(2):152

Dimri AP, Niyogi D, Barros AP, Ridley J, Mohanty UC, Yasunari T, Sikka DR (2015) Western DISTURBANCE: A REVIEW. Rev Geophys. https://doi.org/10.1002/2014RG000460

Dimri AP, Chevuturi A, Niyogi D, Thayyen RJ, Ray K, Tripathi SN, Pandey AK, Mohanty UC (2016a) Cloudbursts in Indian Himalayas: A review. Earth. https://doi.org/10.1016/j.earscirev.2017.03.006

Dimri AP, Thayyen RJ, Kibler K, Stanton A, Jain SK, Tullos D, Singh VP (2016b) A review of atmospheric and land surface processes with emphasis on flood generation in the Southern Himalayan rivers. Sci Total Environ 556:98–115

Dimri AP, Chevuturi A, Niyogi D, Thayyen RJ, Ray K, Tripathi SN, Pandey AK, Mohanty UC (2017) Cloudbursts in Indian Himalayas: a review. Earth Sci Rev. https://doi.org/10.1016/j.earscirev.2017.03.006

Dube A, Ashrit R, Ashish A, Sharma K, Iyengar G, Rajagopal E, Basu S (2014) Forecasting the heavy rainfall during Himalayan flooding—June 2013. Weather Clim Extrem 4:22–34

Dudhia J (1989) Numerical study of convection observed during the Winter Monsoon Experiment using a mesoscale two-dimensional model. J Atmos Sci 46:3077–3107

Hasan MA, Islam AS (2018) Evaluation of microphysics and cumulus schemes of WRF for forecasting of heavy monsoon rainfall over the Southeastern Hilly Region of Bangladesh. Pure Appl Geophys:1–30

Huffman G (2016) TRMM (TMPA-RT) Near real-time precipitation L3 3 hour 0.25 degree × 0.25 degree V7, Greenbelt, MD, Goddard Earth Sciences Data and Information Services Center (GES DISC), available at: https://disc.gsfc.nasa.gov/datacollection/TRMM_3B42RT_7.html **(last access: 2 November 2017)**

Hong S-Y, Lim J-OJ (2006) The WRF single-moment 6-class microphysics scheme (WSM6). J Korean Meteorol Soc 42:129–151

Holton J (1994) An introduction to dynamic meteorology, 4th edn. Elsevier Academic Press, Amsterdam, p 290

Houze RA Jr. (1975) Squall lines observed in the vicinity of the researcher during phase III of GATE. In: Proceedings, 16th Radar Meteorology Conference. American Meteorological Society, Houston , pp 206–209

Houze RA Jr (1997) Stratiform rainfall in regions of convection: a meteorological paradox? Bull Am Meteor Soc 78:2179–2196

Houze RA Jr (2004) Mesoscale convective systems. Rev Geophys 42:43. https://doi.org/10.1029/2004RG000150

Houze RA Jr, Rasmussen KL, Medina S, Brodzik SR, Romatschke U (2011) Anomalous atmospheric events leading to the Summer 2010 floods in Pakistan. Bull Am Meteor Soc 92:291–298

Houze RA Jr (2014) Cloud dynamics, 2nd edn. Elsevier/Academic Press, Oxford, p 432

Houze RA Jr., Rasmussen KL, McMurdie L, Chaplin MM, Kumar A (2017) Synoptic and mesoscale aspects of the June 2013 flooding in Uttarakhand, India. Mon Weather Rev **(in revision)**

IMD (India Meteorological Department) (1944) Nor'wester of Bengal. IMD technical note no. 10

Islam MN, Hayashi T, Terao T, Uyeda H, Kikuchi K (2005) Characteristics of rainfall systems analyzed from radar data over Bangladesh. J Nat Disaster Sci 27(1):17–23

Islam MN, Uyeda H (2008) Vertical variations of rain intensity in different rainy periods in and around Bangladesh derived from TRMM observations. Int J Climatol 28:273–279

Kain JS (2004) The Kain–Fritsch convective parameterization: an update. J Appl Meteor 43:170–181

Karmakar S, Alam MM (2005) On the sensible heat energy, latent heat energy and potential energy of the troposphere over Dhaka before the occurrence of Nor'westers in Bangladesh during the pre-monsoon season. Mausam 56:671–680

Khan MJU, Islam AS, Das MK, Mohammed K, Bala SK, Islam GMT (2019) Observed trends in climate extremes over Bangladesh from 1981 to 2010. Clim Res 77(1):45–61

Kumar A, Dudhia J, Rotunno R, Niyogi D, Mohanty UC (2008) Analysis of the 26 July 2005 heavy rain event over Mumbai, India using the Weather Research and Forecasting (WRF) model. Q J R Meteorol Soc 134:1897–1910

Kumar A, Houze RA Jr, Rasmussen KL, Peters-Lidard C (2014) Simulation of a flash flooding storm at the steep edge of the Himalayas. J Hydrometeorol 15:212–228

Lazri M, Ameur S, Brucker JM, Testud J, Hamadache B, Hameg S, Ouallouche F, Mohia Y (2013) Identification of raining clouds using a method based on optical and microphysical cloud properties from Meteosat second generation daytime and nighttime data. Appl Water Sci 3(1):1–11

Mourad L, Ameur S (2013) Jean Michel Brucker, Jacques Testud, Bachir Hamadache, Slimane Hameg, Fethi Ouallouche and Yacine Mohi, 2013. Identification of raining clouds using a method based on opticaland microphysical cloud properties from Meteosat second generation daytime and nighttime data, Appl Water Sci 3:1–11. https://doi.org/10.1007/s13201-013-0079

Litta AJ, Mohanty UC, Das S, Idicula SM (2012) Numerical simulation of severe local storms over east India using WRF–NMM mesoscale model. Atmos Res 116:161–184. https://doi.org/10.1016/j.atmosres.2012.04.015

Medina S, Houze RA, Kumar A, Niyogi D (2010) Summer monsoon convection in the Himalayan region: terrain and land cover effects. Q J R Meteorol Soc 136:593–616. https://doi.org/10.1002/qj.601

Mohammed K, Islam AS, Islam GMT, Bala SK, Alferi L, Khan MJU, Das MK (2017) Extreme flows and water availability of the Brahmaputra River under 1.5 °C and 2 °C global warming scenarios. Clim Change. https://doi.org/10.1007/s10584-017-2073-2

Mohanty UC, Routray A, Krishna KO, Prasad SK (2012) A study on simulation of heavy rainfall events over Indian region with ARW-3DVAR modeling system. Pure Appl Geophys 169:381–399

Murata F, Terao T, Kiguchi M, Fukushima A, Takahashi K, Hayashi T, Arjumand H, Bhuiyan MSH, Choudhury SA (2011) Daytime thermodynamic and airflow structures over northeast Bangladesh during the pre-monsoon season: a case study on 25 April 2010. J Meteorol Soc Jpn 89A:167–179

NCEP (National Centers for Environmental Prediction) (2000) National Weather Service/NOAA/U.S. Department of Commerce, updated daily, NCEP FNL Operational Model Global Tropospheric Analyses, continuing from July 1999. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6M043C6 (**Last access: 2 Nove**)

Nowreen S, Murshed SB, Islam AKMS, Bhaskaran B, Hasan MA (2014) Changes of rainfall extremes around the haor basin areas of Bangladesh using multi-member ensemble RCM. Theor Appl Climatol 119:363–377

Otkin Jason A, Greenwald Thomas J (2008) Comparison of WRF model-simulated and MODIS-derived cloud data. Mon Weather Rev 136(6):1957–1970

Pradhan D, Sinha V (2005) Thunderstorm genesis over Kolkata—a case study. Vatavaran 29(1):20–27

Rajeevan M, Kesarkar A, Thampi SB, Rao TN, Radhakrishna B, Rajasekhar M (2010) Sensitivity of WRF cloud microphysics to simulations of a severe thunderstorm event over Southeast India. Ann Geophys 28:603–619. https://doi.org/10.5194/angeo-28-603-2010

Rama Rao YV, Hatwar HR, Salah AK, Sudhakar Y (2007) An experiment using the high resolution eta and WRF models to forecast heavy precipitation over India. Pure Appl Geophys 164:1593–1615

Rasmussen KL, Houze RA Jr (2012) A flash flooding storm at the steep edge of high terrain: disaster in the Himalayas. Bull Amer Meteor Soc 93:1713–1724

Routray A, Mohanty UC, Das AK, Sam NV (2005) Study of heavy rainfall event over the west-coast of India using analysis nudging in MM5 during ARMEX-I. Mausam 56(1):107–120

Routray A, Mohanty UC, Niyogi D, Rizvi SRH, Osuri KK (2010) Simulation of heavy rainfall events over Indian Monsoon Region using WRF-3DVAR data assimilation system. Meteorol Atmos Phys 106:107–125

Roy B, Islam AS, Islam GMT, Bhattacharya B, Ali MH, Khan AS, Hossain MS, Sarker JC, Khan MU (2019) Determining flash flood danger level at gauge stations of the North East Haor regions of Bangladesh. J Hydrol Eng 24(4):05019004

Roy SKB, Prasad K (2001) Some characteristics of limited area model precipitation forecast of Indian monsoon and evaluation of associated flow features. Meteool Atmos Phys 76:223–236

Samarendra K, Quadir DA, Das MK (2017) Numerical simulation of physical and dynamical characteristics associated with the severe thunderstorm on 5 April 2015 at Kushtia and Jhenaidah. Nat Hazards 86(3):1127–1146. https://doi.org/10.1007/s11069-016-2733-y

Sikka DR, Rao PS (2008) The use and performance of mesoscale models over the Indian region for two high-impact events. Nat Hazards 44:353–372

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Duda MG, Huang XY, Wang W, Powers JG (2008) A description of the advanced research WRF version 3. NCAR Tech. Note NCAR/TN-475+STR, p 113. https://doi.org/10.5065/D68S4MVH

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Liu Z, Berner J, Wang W, Powers JG, Duda MG, Barker DM, Huang XY (2019) A description of the advanced research WRF version 4. NCAR Tech. Note NCAR/TN-556+STR, p 145. https://doi.org/10.5065/1dfh-6p97

Sun J, Crook NA (1997) Dynamical and microphysical retrieval from Doppler radar observations using a cloud model and its adjoint,

part I: model development and simulated data experiments. J Atmos Sci 54:1642–1661

Tyagi B, Krishna VN, Satyanarayana ANV (2011) Skill of thermodynamic indices for forecasting premonsoon thunderstorms over Kolkata during STORM pilot phase 2006–2008. Nat Hazards 56:681–698. https://doi.org/10.1007/s11069-010-9582-x

Tyagi B, Satyanarayana ANV, Vissa NK (2013) Thermodynamical structure of atmosphere during premonsoon thunderstorm season over Kharagpur as revealed by STORM data. Pure Appl Geophys 170:675–687. https://doi.org/10.1007/s00024-012-0566-5

Vaid BH (2013) Numerical simulations and analysis of June 16, 2010 Heavy Rainfall Event over Singapore Using the WRFV3 Model. Int J Atmos Sci 2013:8. https://doi.org/10.1155/2013/825395

Virts KS, Houze RA Jr (2016) Seasonal and intraseasonal variability of mesoscale convective systems over the South Asian monsoon region. J Atmos Sci 73:4753–4774. https://doi.org/10.1175/JAS-D-16-0022.1

Webster PJ, Jian J, Hopson TM, Hoyos CD, Agudelo P, Chang H-R, Curry JA, Grossman RL, Palmer TN, Subbiah AR (2010) Extended-range probabilistic forecasts of Ganges and Brahmaputra floods in Bangladesh. Bull Am Meteor Soc 91(11):1493–1514

Yatagai A, Kamiguchi K, Arakawa O, Hamada A, Yasutomi N, Kitoh A (2012a) APHRODITE: constructing a long-term daily gridded precipitation dataset for asia based on a dense network of rain gauges. Bull Am Meteor Soc 93(9):1401–1415

Yatagai A, Nakamura H, Miyasaka T, Okumiya K (2012b) meteorological conditions related to the august 2010 flood event in Ladakh, in the West Himalayas. Geophys Res Abs 14:12856