# Flash Flood Producing Thunderstorms and Associated Lightning Potential in the North-eastern Bangladesh: A Case Study

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***ABSTRACT***

*An attempt has been made to simulate the different atmospheric conditions associated with the severe thunderstorms and lightning, which occurred during 28-30 March 2017 over northeastern Bangladesh using WRF model. The continuous very heavy rainfall associated with the thunderstorms has been responsible for the devastating flash flood in Sunamganj and adjoining areas in 2017. The study reveals that by analyzing different atmospheric parameters simulated by WRF Model, it is possible to forecast severe thunderstorms which produce flash flood and lightning in the northeastern part of Bangladesh. In this study parameters such as rainfall, sea level pressure, geopotential height (m), CAPE, winds at various tropospheric levels, cloud water mixing ratio and ice water mixing ratio, vorticity and x, y, z wind components have been simulated. There have developed a low pressure area and strong circulations over West Bengal and adjoining Bangladesh with extended troughs towards northeast, having strong flows of southwesterly to south-southeasterly winds distinctly visible at low level over the Bay of Bengal and Bangladesh. There has been an interaction of northwesterly flows of winds at 500 hPa level and southerly flow coming from the Bay of Bengal producing sufficient instability in the troposphere to develop severe thunderstorms which when moved over northeast Bangladesh/Meghalaya have become stronger due to orographic influence, thereby become flash flood producing thunderstorms with lightning potential. Due to the presence of westerly jet stream of 40 ms-1 over Bangladesh and India, the thunderstorms become more marked. The study reveals that persisting characteristics of the wind circulation over West Bengal and Bangladesh, the micro-circulation and the intense geopotential low at 850 hPa along with its eastward extension have been responsible for continuous heavy to very heavy rainfall over Sylhet and Meghalayan region and producing wide-spread intense flash floods over there. On 29 March 2017, cloud water mixing ratio is found to range between 160 and1100 mgm-3 and ice water mixing ratio ranges from 27 to 100 mgm-3 at different locations. At Cherrapunji and Sylhet, the cloud water mixing ratio values are 1100 and 1000 mgm-3 respectively. The values of cloud water mixing ratio are maximum at Cherrapunji and Sylhet where torrential rain has occurred. At Mymensingh, Netrokona, Nikli, Sunamganj, Srimangal and Moulavibazar, the cloud water mixing ratio values are less. The high values of cloud water mixing ratio and ice water mixing ratio in the upper troposphere over northeastern Bangladesh and adjoining areas indicates significant convection in the troposphere and have been responsible for moderate to severe lightning. The distribution of CAPE has also shown increasing higher values, indicating moderate to severe lightning potential.*

***Keywords:*** *Thunderstorms, Lightning Potential, Flash Flood, Circulation and Geopotential.*

## 1. Introduction

Because of the unique geographical conditions with the Bay of Bengal in the south, the Himalayan ranges in the north and large continental areas in the west and the east, Bangladesh has become the playground of thunderstorms during the pre-monsoon (March-May) and monsoon (June-September) seasons. These thunderstorms are associated with lightning, thunder, hails, gusty winds, hails, squalls and rain/showers. In Bangladesh and adjoining Indian states, these thunderstorms are known as nor'westers or locally Kalbaishakhi, and are very destructive in terms of lightning potential, gusty winds/squalls, hails of different sizes and sometimes heavy showers in Bangladesh. They cause significant damage to crops (especially boro crops), trees, blow off kacha houses/tin sheds, kills human being and domestic animals. When they occur over the northeastern region of the country, flash floods occur, which damage crops, houses and paralyze the livelihoods of the people of the region. During the recent years, the lightning and thunders are found to occur frequently, making severe acoustic sounds and killing people. From 2011 to May 2017, about 1,174 people were reported to be killed by lightning in Bangladesh (Anik, 2017). Therefore, the prediction of thunderstorm Bangladesh and adjoining areas is very important.

A number of diagnostic studies on the formation of thunderstorms along with associated tropospheric conditions have been made over Bangladesh and India by different scientists of this region. An earlier study first of its kind over north-eastern region using thermodynamic indices was made by Mukhopadhyay et al. (2003). Different stability indices in relation to the occurrence of nor'westers have been studied by Karmakar and Alam (2006) for finding out the critical values of different instability indices favorable for the formation of thunderstorms and severe thunderstorms in Bangladesh. This study reveals that the critical values of Showalter Stability Index (SI), Lifted Index (LI), Dew-point Index (DPI), Dry Instability Index (DII), Cross Total Index (CTI), Vertical Total Index (VTI), Total Totals Index (TT), Energy Index (EI), SWEAT Index (SWI) and K-Index (KI) at 0000 UTC over Dhaka may be taken as + 3°C, 0°C, -3°C, 0°C, ≥16°C, ≥24°C, ≥ 40°C, -6 Joule/gm, >200 and >34°C respectively for the thunderstorms to occur in Bangladesh. The maximum negative values of SI, LI, DPI, DII and EI are found to lie over the eastern Madhya Pradesh, Bihar, West Bengal and adjoining Bangladesh indicating the highly unstable area. The negative areas of these indices in combination with the low pressure area over Bihar, West Bengal and adjoining Odisha and Bangladesh and the cyclonic circulation up to 3-4 km or above are favorable for the occurrence of thunderstorms in Bangladesh. The study has shown that the maximum values of CT, VT, SWI, KI and TT are found to exist over eastern Madhya Pradesh, Bihar, West Bengal and adjoining Bangladesh indicating the highly unstable area. The thunderstorms are found to occur at the northeastern or eastern end of the area of maximum instability. Another study has been made by them on the modified different stability indices in relation to the occurrence of severe thunderstorms / nor'westers in order to finding out the critical values of different modified indices favouring the formation of thunderstorms in Bangladesh (Karmakar and Alam, 2011). The critical values of different modified instability indices at 0000 UTC over Dhaka are: MCT ≥20°C, MVT ≥26°C, MTT ≥ 46°C, MSWI > 300, MKI ≥ 40°C and MEI < -6 joules/gm respectively for the nor'westers to occur in Bangladesh. The study of the modified stability indices has revealed that maximum instability lies over the area of surface low pressure especially over Bihar, West Bengal and adjoining Bangladesh at 0000 UTC on the dates of occurrence of nor'westers. For severe nor'westers of tornadic intensity, the critical values of different modified instability indices at 0000 UTC over Dhaka are: MCT ≥ 20° C, MVT ≥ 28° C, MTT ≥ 50° C, MSWI ≥500, MKI ≥ 42° C and MEI < -8 joules/gm respectively for the nor'westers to occur in Bangladesh.

In a study made by Karmakar and Quadir (2014a), it is found that the mixing ratio at 0000 UTC at Dhaka on the dates of occurrence of local severe storms ranges from 16.13 g $kg^{-1}$ to 22.41g $kg^{-1}$ at 1000hPa, showing a considerable amount of moisture near the surface with a tendency to increase with time. Much moisture becomes available in the lower troposphere and/or upwards in the morning on the dates of occurrence of local severe storms as compared to that on the dates of non-occurrence. In another study made by Karmakar and Quadir (2014b), it is seen that the potential temperature over Dhaka increases with height, becoming maximum at the top of the troposphere. The vertical variation of equivalent potential temperature over Dhaka is seen to decrease with height, becoming minimum at the mid-troposphere, indicating conditional instability in the troposphere. This condition is conducive for the occurrence of local severe storms. Then it increases significantly beyond 500 hPa. In a study of radar data assimilation, Das et al. (2015a) has found that the quantitative data from Doppler Weather Radar (DWR) such as the radial winds and reflectivity are useful for improving the numerical prediction of weather events like squalls. Mesoscale convective systems are responsible for majority of the squalls and hail events and related natural hazards that occur over Bangladesh and surrounding region in pre-monsoon season. DWR observations (radial winds and reflectivity) of Bangladesh Meteorological Department are used in this study for simulating the squall events during May 2011 with a view to update the initial and boundary conditions through three-dimensional variational assimilation technique within the Advanced Research Weather Research and Forecasting model. The outputs such as sea-level pressure analyzed and compared with the observed parameters associated with squall events which occurred in the month of May 2011. Das et al. (2015b) have studied the tornado occurred at Brahmanbaria in Bangladesh in the afternoon of 22 March 2013 using the tropical rainfall measuring mission (TRMM) data, radar observations and model simulations. The maximum reflectivity and the vertical extent of the system have been recorded to be about 54.7 dBZ and 15 km, respectively, by the Doppler weather radar (DWR) at Agartala, India. The event has been simulated by using the WRF model at 3- and 1-km horizontal resolution nested domains based on six hourly final (FNL) re-analysis data and boundary conditions of National Centers for Environmental Prediction (NCEP). Results show that, while there are differences of 40 minutes before the observed time of the storm, the distance between observed and simulated locations of the storms is 0.5°. The maximum amount of vorticity transferred by directional shear in the storm updraft (helicity) due to convective motion simulated by the model is found to be 1774 $m^2 s^{-2}$, and the highest value of bulk Richardson number shear that defines the region in which low-level meso-cyclogenesis is more likely has been 457.3 $m^2 s^{-2}$, which is generally supposed to produce rotating storms according to the prescribed range. The highest vertical velocity simulated by the model is about -28 to 58 m $s^{-1}$. Singh et al. (2015) studied a severe thunderstorm, which affected Delhi and adjoining region between 1630 hrs IST and 1730 hrs IST of 30 May 2014. They used WRF model to simulate and investigate the severe thunderstorm. Sensitivity experiments are conducted to study the impact of using different grid resolution (9km and 3km) with terrain resolution 5 min (~10 km) and 1 min (~2 km) respectively and the same microphysics (MPs) and cumulus parameterization (CPs) schemes on the simulation of the system. The results demonstrate that the model simulates better structure and intensity of the thunderstorm at higher resolution domain. The system moved eastward and steered by a westerly trough. They found that the thunderstorm was accompanied by strong wind, lightning, thunder and squall causing destruction to the life and property. According to them, the simulation at 3 km resolution provides better distributions of convergence zone in the wind fields at lower level then compare to simulation at 9 km resolution. Recently Karmakar et al. (2017) made a study on numerical simulation of physical and dynamical characteristics associated with the severe thunderstorm on April 5, 2015 at Kushtia and Jhenaidah. They concluded that the simulated results provide a basis to study the physical and dynamical characteristics of the thunderstorm, which are generally not identified by the meteorological observations which are too sparse. The model has captured a micro-low over Kumarkhali and its neighborhood, which favored the occurrence of the severe thunderstorm. The model simulated rainfall is about 26 mm near the place of occurrence, which matches well with the area where the reflectivity of hydrometeor is maximum. The convective available potential energy is found to be 1600 J $kg^{-1}$ at 1730 UTC near the place of occurrence of the thunderstorm; this indicates high atmospheric instability over the thunderstorm location for the formation of the thunderstorm. The vertical velocity, convergence, cloud water mixing ratio and the ice water mixing ratio and their vertical extensions are found to be satisfactory and responsible for the occurrence of large hails associated with the thunderstorm. Lal (2014) studied the relation between size of cloud ice and lightning in the tropics. They showed that total lighting increases with increase in the cloud ice size and attains maximum at certain cloud ice size and then decreases with increase in cloud ice size. Maximum lightning occurred for the mean cloud ice size of around 23–25 $\mu$m over the continental region and mean cloud ice size of around 24–28 $\mu$m over the oceanic region.

Bradshaw (2016) studied the spatial relationship between lightning and CAPE. Thunderstorm formation depends on environmental stability and the existence of electrification mechanisms. The evaluation of the relationship between CAPE and lightning lends meaningful insight into thunderstorm formation and electrification, providing an understanding that can enhance severe weather forecasting products. Generally, it is thought that CAPE values between 1000 and 2500 $Jkg^{-1}$ are adequate to support moderate convection, values between 2500-4000 J $kg^{-1}$ are adequate to support strong convection, and values greater than 4000 J $kg^{-1}$ indicate a potential for extreme convection (Wallace and Hobbs 2006). Because CAPE is thought to relate to convection, due to it being a measure 9 of the potential for instability in the environment, and because thunderstorm electrification mechanisms depend on convection for charge separation, there is a potential relationship between CAPE and lightning globally. Wallace and Hobbs (2006) mentioned CAPE values between 1000 and 2500 J $kg^{-1}$ are adequate to support moderate convection, values between 2500-4000 are adequate to support strong convection, and values greater than 4000 indicate a potential for extreme convection.

The spatial distributions of mean monthly thunderstorms have been analyzed for each month of the pre-monsoon season during 1980-2016. The distribution patterns of mean thunderstorm frequency for March, April and May are similar to each other. The area of maximum thunderstorm frequency is over Sylhet region extending southwestward up to Dhaka region having an elongated area extended southward up to Barisal-Khepupara region. Seasonally, about 170-182 thunderstorms occur over the region (Figure 1). The distribution patterns also show that the mean thunderstorm frequencies are minimum over northwestern and extreme southeastern parts of the country. It has been found that this seasonal frequency is less by 1-8 thunderstorms as compared to that during the period 1980-2008 (Karmakar and Quadir, 2014a) except a few places, indicating that the thunderstorm frequency has decreased in the recent time.

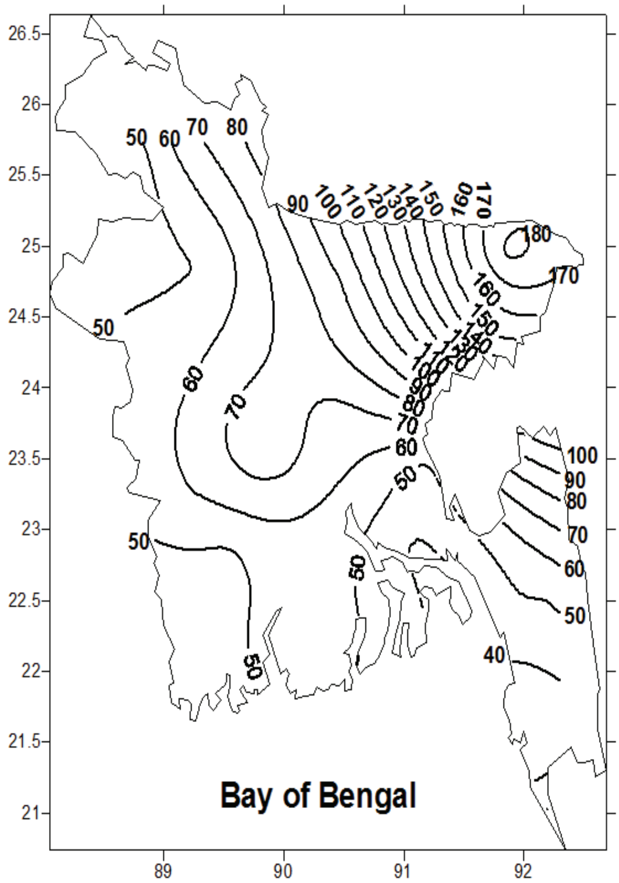



**Figure 1: Spatial distribution of mean seasonal thunderstorm frequency during the pre-monsoon season over Bangladesh during 1980-2016.**

The objectives of the present research are to simulate the atmospheric conditions favorable for the formation of thunderstorms, producing flash flood and associated lightning potential over the northeastern Bangladesh by using WRF model. The lightning Potential Index (LPI) has also been simulated by using WRF model for the period 29-30 March 2017 and their spatial distribution has been studied.

## 2. Data and Model Used

Daily rainfall data for the months of March through May of 2017 at Sylhet are collected from Bangladesh Meteorological Department (BMD) and used for the analysis of rainfall amount responsible for flash flood. Global precipitation measurement (GPM) data on rainfall during March-April 2017 is also used to compare the recorded rainfall. The rawinsonde data of Kolkata, Dhaka and Agartala for the period 29-31 March 2017 are collected from

**Table 1. WRF Model configurations.**

| **Model Features** | **Configurations** |
|---|---|
| Horizontal Resolution | 9 km |
| Vertical Levels | 40 |
| Topography | U.S. Geological Survey (*USGS*) |
| Dynamics | |
| Time Integration | Semi Implicit |
| Time Steps | 50 s |
| Vertical Differencing | Arakawa's Energy Conserving Scheme |
| Time Filtering | Robert's Method |
| Horizontal Diffusion | 2ndorder over Quasi-pressure, surface, scale selective |
| Physics | |
| Convection | Kain-Fritsch (new Eta) scheme(Kain 2004) |
| PBL | Yonsei University Scheme (*YSU*) |
| Cloud Microphysics | WRF Single-Moment 6-Class (WSM6) (Hong and Lim 2006) |
| Surface Layer | Monin-Obukhov |
| Radiation | LW Rapid Radiative Transfer Model (RRTM)<br>SW (Dudhia, 1989) |
| Gravity Wave Drag | No |
| Land Surface Processes | Unified NOAH L and Surface Model |

the University of Wyoming and are used for the computation of instability of the troposphere. In the present study, 1.0° × 1.0° gridded NCEP FNL (Final) Operational Global Analysis and Global Forecast System (GFS) data are used as initial and Lateral Boundary Conditions (LBC) for the domain. FNL product is from the Global Data Assimilation System (GDAS), which continuously collects observational data from the Global Telecommunications System (GTS), and other sources, for many analyses. The FNLs are made with the same model which NCEP uses in the Global Forecast System (GFS), but the FNLs are prepared about an hour or so after the GFS is initialized. The FNLs are delayed, so that more observational data can be incorporated. WRF model has been used for simulation of the severe thunderstorms which produced flash floods in northeastern part of Bangladesh.

The Advanced Research Weather Research and Forecasting model (ARW), version 3.7.1 (Skamarock et al*.,* 2008), which is a three-dimensional, fully compressible, non-hydrostatic model. The vertical coordinate is a terrain-following hydrostatic pressure coordinate and the model uses the Runge–Kutta third-order integration scheme. A domain with 9 km horizontal spatial resolution was configured, which is reasonable in capturing the mesoscale cloud clusters. Main features of the model employed for this study are summarized in Table 1. The WRF model was run for 72 hours since 28 March 2017 for the flash flood producing thunderstorms and lightning on 29 and 30 March 2017. The thunderstorms and lightning on 29 and 30 March 2017 occurred over northeastern parts of Bangladesh and adjoining northeast of India.

## 3. Results and Discussion

### 3.1 Temporal variation of rainfall at Sylhet in March-April of 2017

Figure 2a represents the graphical temporal variation of past 24hrs rainfall at 0000UTC on each day in March-April 2017. There was more than one peak with rainfall greater than 100 mm, especially in 2017 when rainfall of 119 mm and 134 mm are found to occur in past 24 hrs recorded at 0000 UTC on 29 March and 31 March along with 96 mm on

30 March, 124 mm on 1 April and 81 mm on 2 April 2017. Figure 2b gives the temporal variation of rainfall (mm/hr) near Sylhet and adjoining area obtained from GPM data. This figure also shows similar peak rainfall of about 15 mm/hr at 0000 UTC on 31 March 2017. Though this rainfall was much more than the recorded ones, both the peak rainfall occurred in the early morning of 31 March.

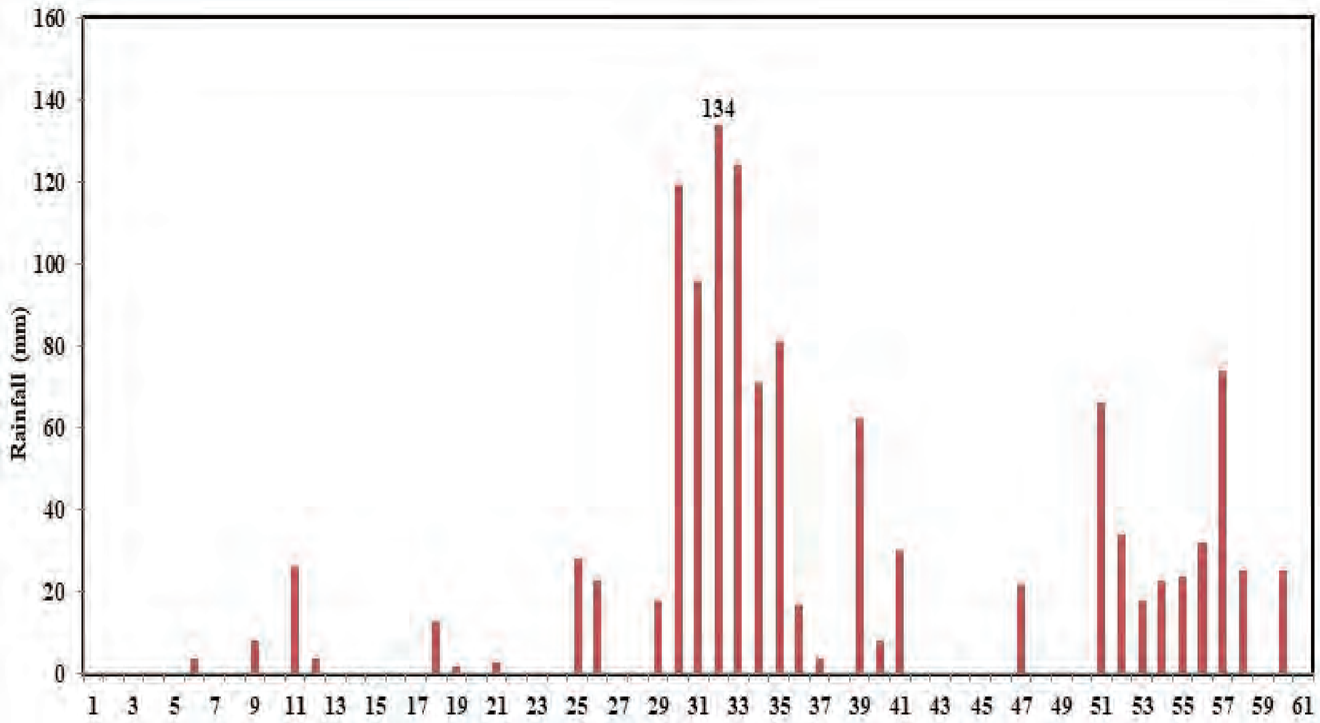



**Figure 2(a): Daily rainfall at Sylhet in March-April 2017.**

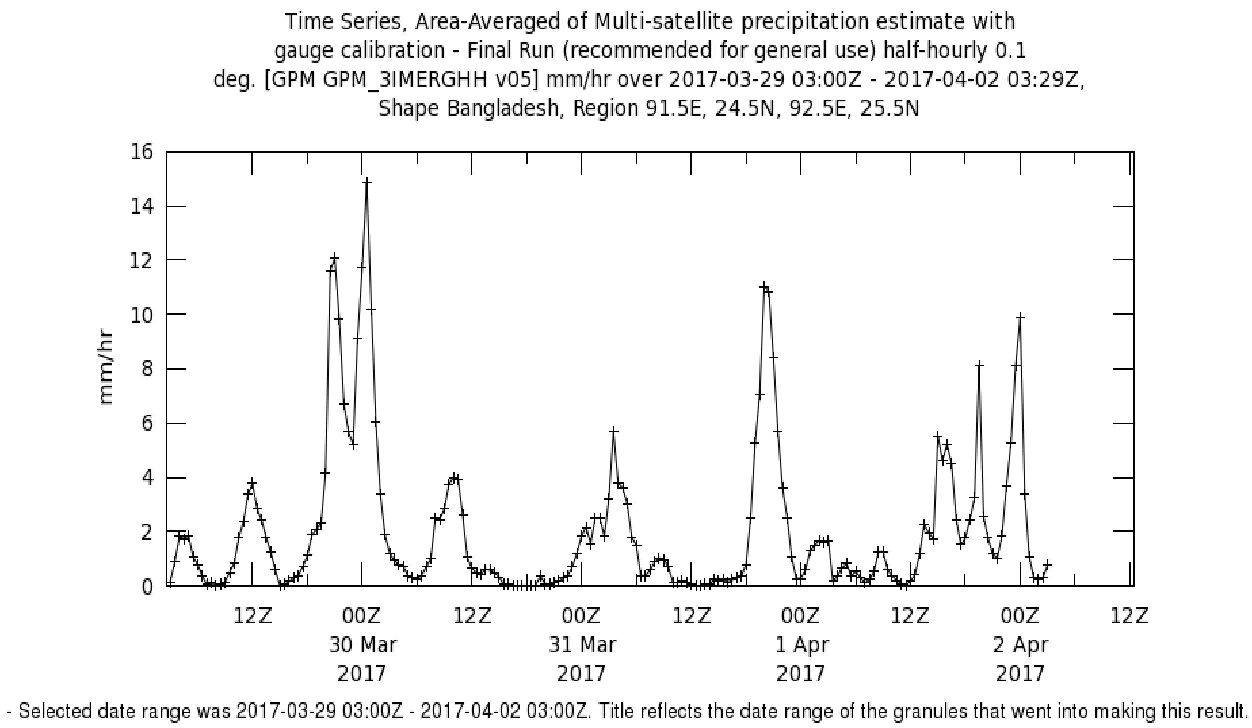



**Figure 2(b): Daily rainfall near Sylhet and adjoining area in March-April 2017.**

The continuous very heavy rainfall was responsible for the occurrence of devastating flash flood in Sunamganj and adjoining areas in 2017.

### 3.2 Instability indices during 29-31 March 2017

Different instabilities of the troposphere over Dhaka, Kolkata and Agartala at 0000 and 12 UTC during 29-31 March 2017 are computed. The results, given in Figures 3&4 for Dhaka and Kolkata, show that most of the indices indicated stable conditions except Lifted Index (LI), SWEAT Index (SWI) and CAPE. Showalter Index showed stability of the troposphere moderate to absolute. The SWEAT index>200 indicated the instability at Dhaka and Agartala (Table 2) for the thunderstorms to occur, instability being maximum (SWI=435.72) at 1200 UTC on 31 March 2017 at Dhaka. CAPE values indicated moderate to severe instability conducive for the occurrence of lightning and thunderstorms during the period. The erratic values of different instability indices suggest us to formulate new instability index for the thunderstorms and lightning to occur over the region.

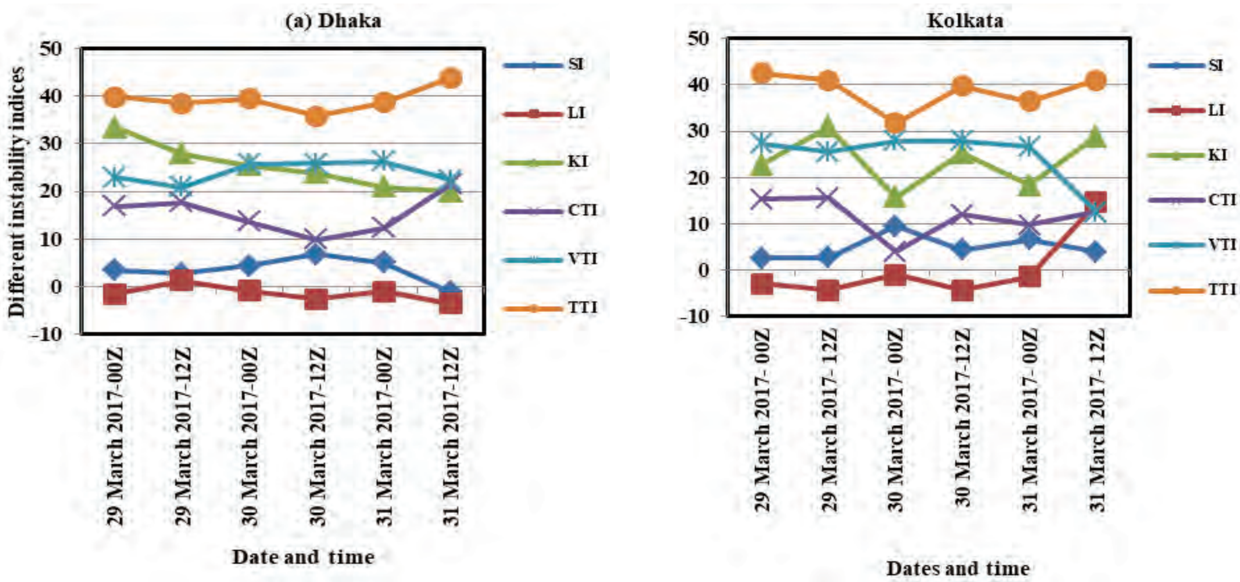



**Figure 3: Temporal variation of different instability indices at (a) Dhaka and (b) Kolkata.**

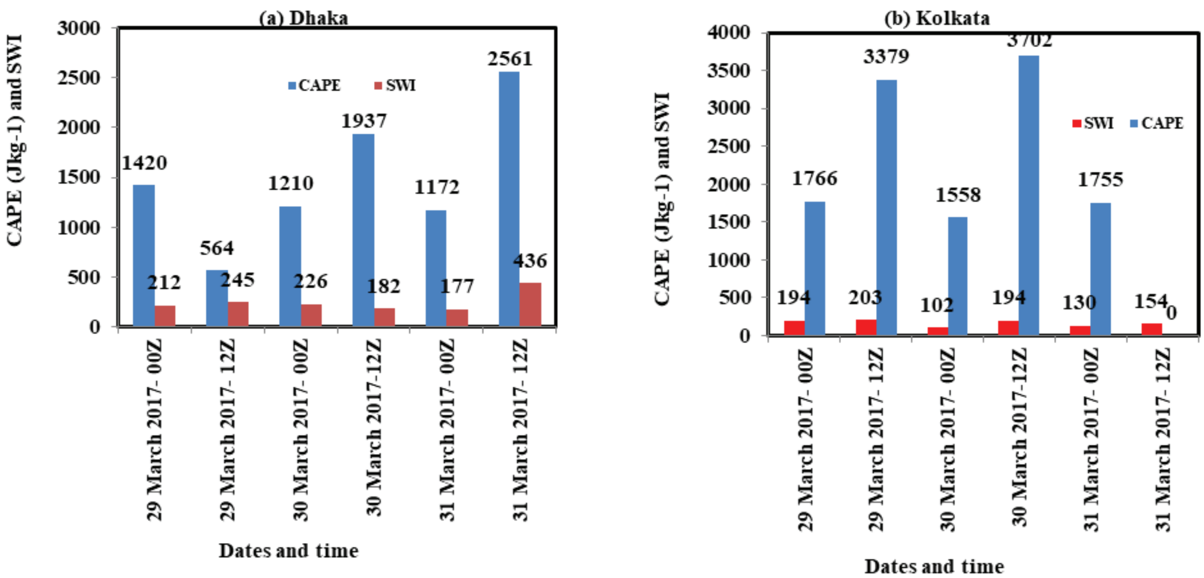



**Figure 4: Temporal variation of CAPE and SWI at (a) Dhaka and (b) Kolkata.**

**Table 2. Different instability indices at Agartala during 29-31 March 2017.**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Agartala | 29 March 2017; 00Z | 0.32 | -1.86 | 224.8 | 37.7 | 20.4 | 23.1 | 43.5 | 1538.08 |
| | 12Z | n | n | n | N | n | n | n | n |
| | 30 March 2017; 00Z | n | n | n | N | n | n | n | n |
| | 12Z | n | n | n | N | n | n | n | n |
| | 31 March 2017; 00Z | 2.64 | -2.55 | 216.79 | 30.3 | 15.9 | 25.9 | 41.8 | 1677.05 |

n=No data

## 3.3 Simulation of thunderstorms during 28-30 March 2017

### 3.3.1 Spatial distributed of simulated rainfall

The rainfall has been simulated by WRF model during 28-30 March 2017. Three hourly evolutions of rainfall during 29-30 March is shown in Figure 5 for example. Three hourly evolutions of rainfall show that the rainfall has started over Meghalaya plateau region at 0300 to 0600 UTC on 28 March 2017. Rainfall is found to continue up to 0000 UTC of next day (Figure 5). The rainfall is more prominent on 29 to 30 March 2017 over the Meghalaya region as well as in the northeastern part of Bangladesh. The first day rain is found to exceed 32 to 64 mm rainfall at 0900, 1200, 1800 and 2100 UTC and next day the rain has over passed 64 to 128 mm at 1500, 1800 and 2100 UTC. The rainfall is distinct and very heavy with amount of 256 mm during 1500 UTC of 29 March to 0000 UTC of 30 March 2017 over northeastern Bangladesh and adjoining Meghalaya, indicating that the heavy rainfall has occurred in the morning on 30 March2017. This hefty amount of rainfall within a short duration has created flash flood havoc over the northeast region of Bangladesh.

### 3.3.2 Spatial distribution of model simulated sea level pressure

The sea level pressure (SLP) has been simulated over Bangladesh and adjoining area for the period 28-29 March 2017, the distribution of SLP on 29 March 2017 being shown in Figure 6. From the analysis of SLP, it is found that a low pressure is developed over West Bengal with a pressure of about 1009 hPa at 0000 UTC on 28 March having its trough extended towards northeast Bangladesh. The SLP has changes in magnitude at different times, but the distribution has a strong trough extended towards northeast. Because of the presence of this trough, severe thunderstorms have developed in the northeast region including Meghalaya plateau. SLP ranges from 1009 to 1012 hPa at 0000 UTC and 1007 to 1010 hPa at 1200 UTC over Bangladesh on 28 March 2017. On the next day at 0000 UTC, the value is found to range from 1008 to 1011 hPa and at 1200 UTC the range is 1005 to 1010 hPa over Bangladesh (Figure 6). With the progress of the time, the trough, being narrow, has been found to be more prominent over the northeastern Bangladesh.

### 3.3.3 Spatial distribution of model simulated winds at different levels

The analysis of wind field at 10 m level has indicated that a circulation is developed at 10m level over West Bengal and adjoining Bangladesh at 1200 UTC on 28 March 2017 (not shown in Fig. for brevity) having a trough extended towards northeast. Strong southwesterly to south-southeasterly flow of wind is distinctly visible over the Bay of Bengal and Bangladesh, persisting up to 29 March 2017. This flow of winds is responsible for bringing a lot of moisture from the Bay of Bengal, converging over the low level circulation. Strong circulation is also found on the following day at 1200 UTC, over western Bangladesh with its trough extended towards northeast over Sylhet and Meghalaya region.

The circulation and the distribution of geopotential at 925, 850, 500 and 200 hPa levels have been prepared and studied; the circulation and geopotential distribution at 925 hPa are shown in Figure 7. It is found that strong circulations exist both at 925 and 850 hPa (not shown in figure) levels over West Bengal and adjoining Bangladesh, the winds being observed to flow from the Bay of Bengal and converge over West Bengal and adjoining Bangladesh with a trough extended towards northest.

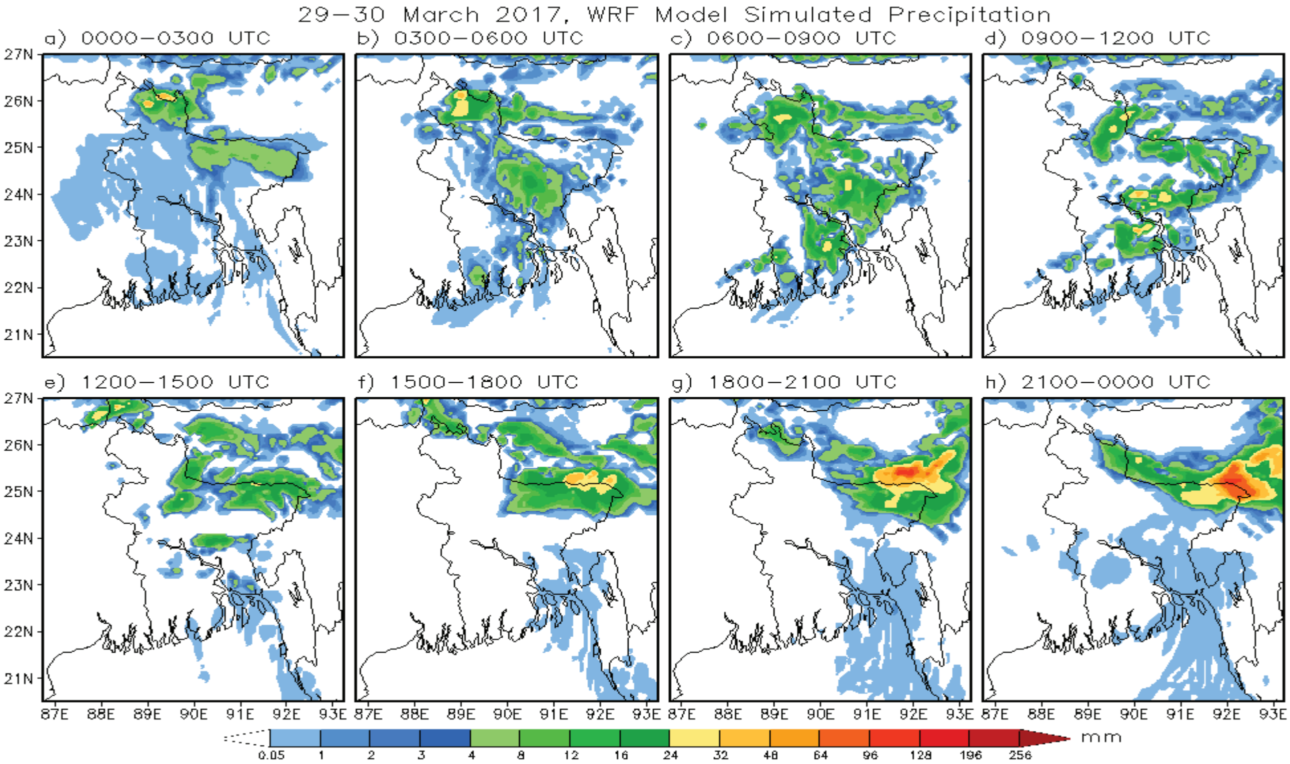



**Figure 5: Spatial distribution of simulated 3 hourly accumulated rainfalls over Bangladesh during 28-30 March 2017.**

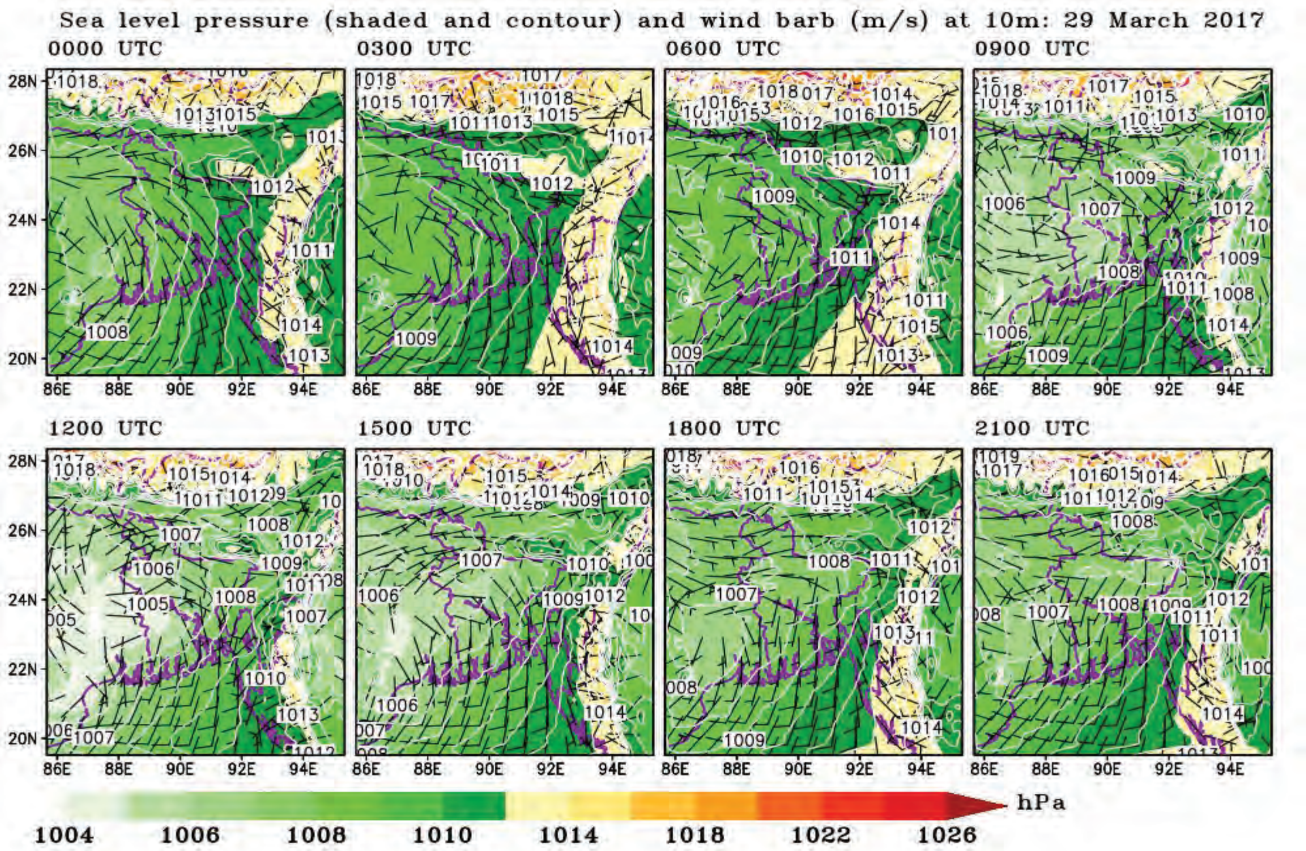



**Figure 6: Spatial distribution of model simulated sea level pressure and wind flow 10m over Bangladesh and adjoining area on 29 March 2017.**

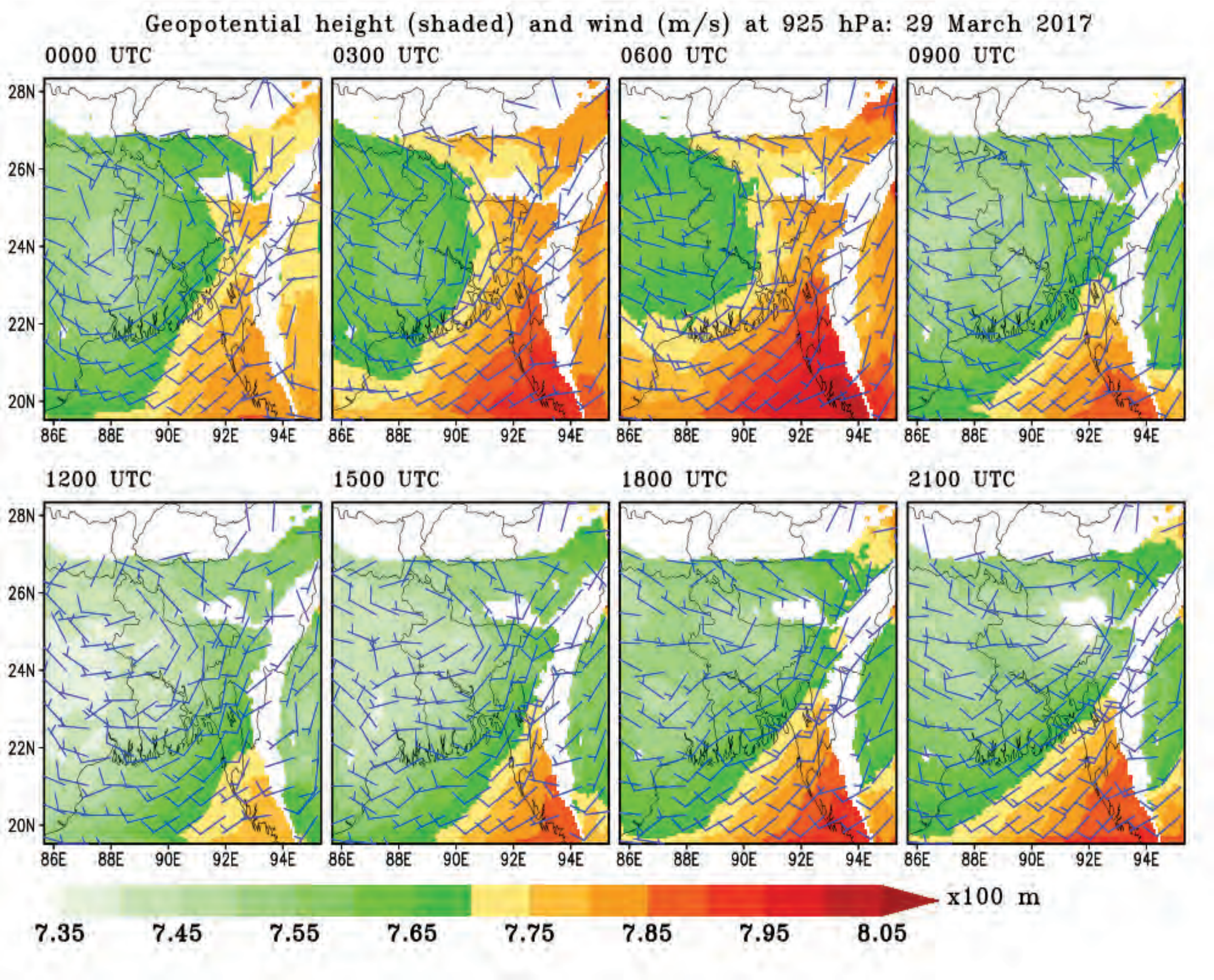



**Figure 7: Spatial distribution of model simulated wind circulation and geopotential height in meter (gpm) at 925 hPa on 29 March 2017.**

The circulation over West Bengal and adjoining Bangladesh is found more prominent at 925 hPa and 850 hPa from 0000 UTC on 29 March, having an extended through towards the northeast. The distribution of geopotential height indicates a prominent low over the circulation area and has become more intense from 0900 UTC on 29 March 2017 with a values of about 740 and 1490 gpm at 925 and 850 hPa levels and the strong trough is extended towards Sylhet and adjoining Meghalaya (figure not shown). The circulation persists and has become more prominent from 1200 UTC with a subsequent shifting towards northeast. The whole country and adjoining north-northeastern Meghalayan area beyond has become under the grip of low geopotential heights having 735 gpm and 1460 gpm at 925 and 850 hPa respectively with an extended strong trough throughout the day (Figure 7). At 1500 UTC on 29 March 2017, a micro circulation has formed over the Sylhet region and continued up to 30 March. From 1500 UTC on 30 March 2017 the circulation begins to weaken slightly. The circulation over West Bengal is found to shift eastward too. The persisting characteristics of the circulation over West Bengal and Bangladesh, the micro-circulation, the intense geopotential low at 925 and 850 hPa, and their eastward extension have been responsible for continuous heavy to very heavy rainfall over Sylhet and Meghalayan region, causing wide-spread intense flash floods over there.

At 500 hPa level, there is a strong northwesterly flow of wind over India and Bangladesh over the Sylhet and Meghalaya regions on 28 March 2017, the wind becoming westerly over Meghalaya from 1500 UTC on 28 March (Figure 8). A strong

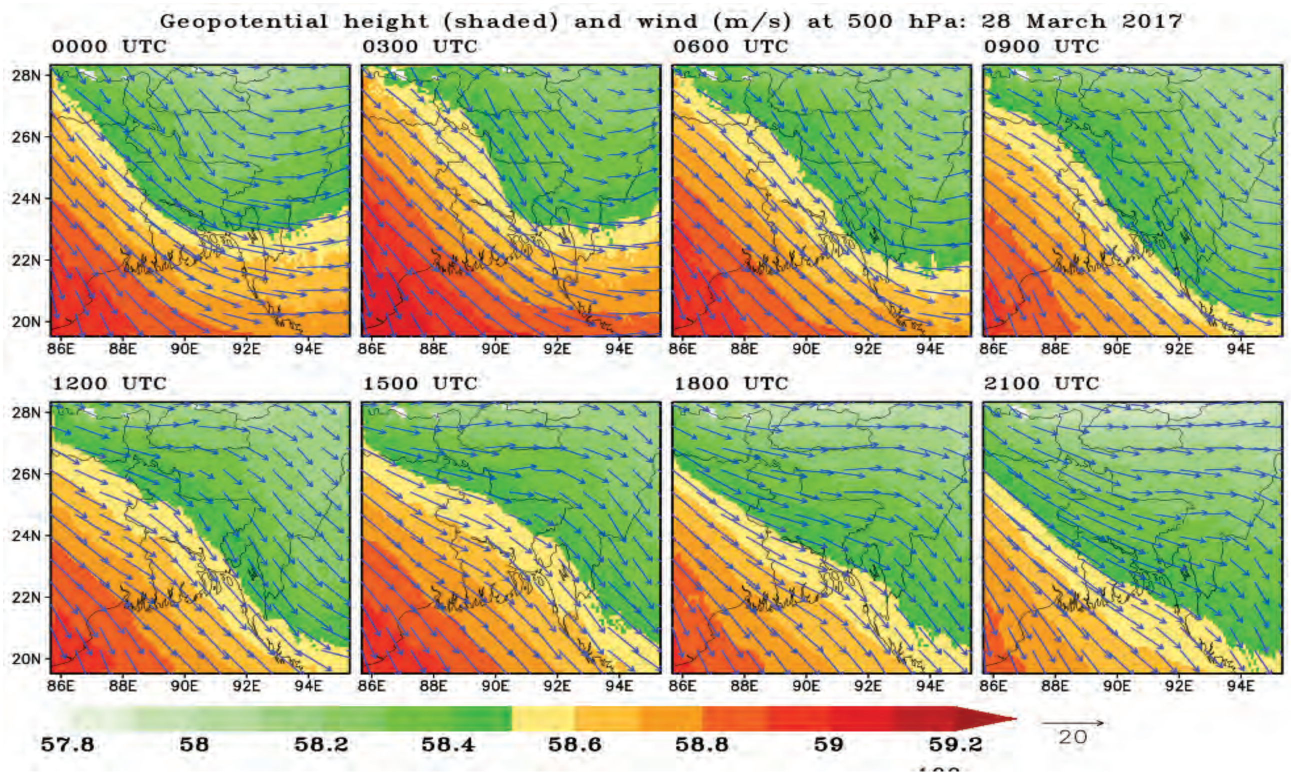



**Figure 8: Spatial distribution of model simulated winds and geopotential height (m) at 500 hPa level over on 28 March 2017.**

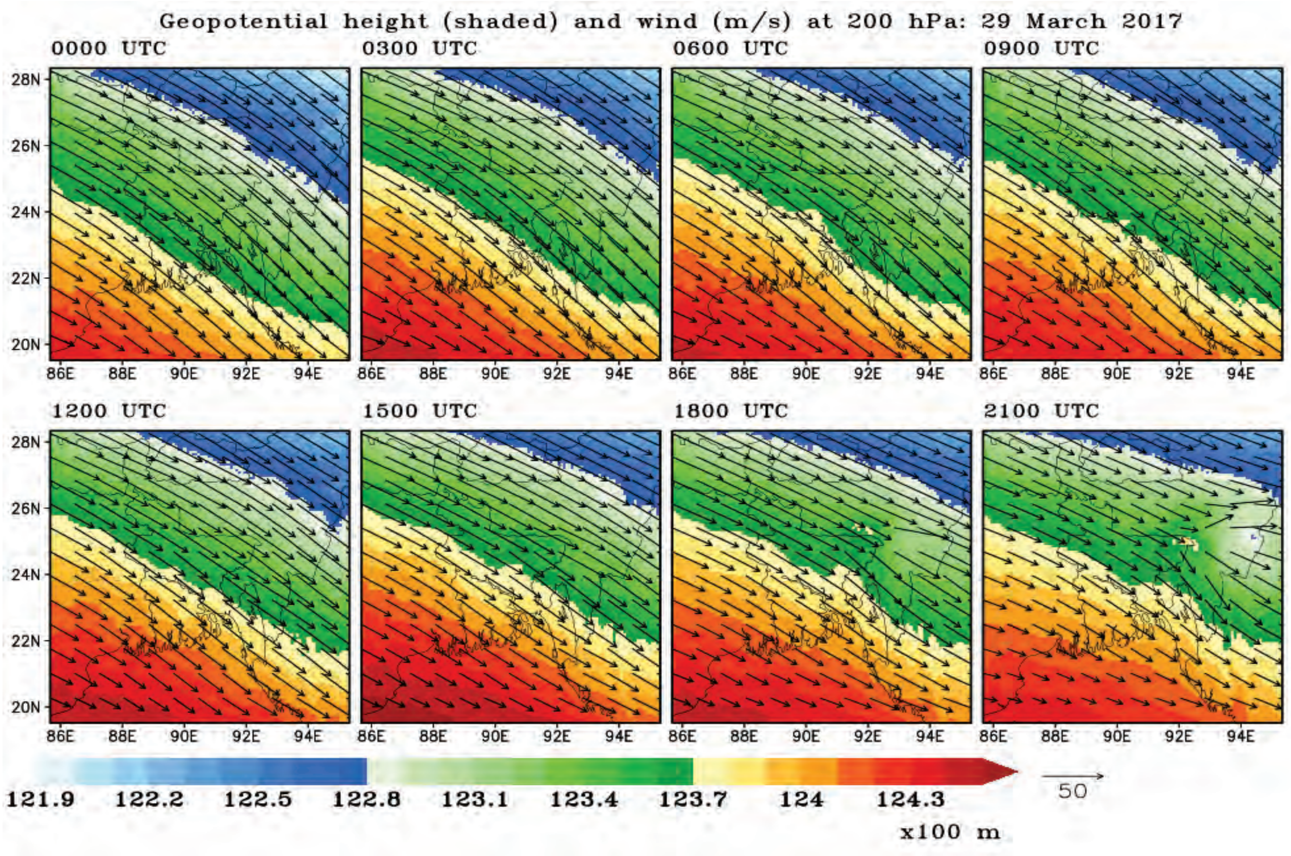
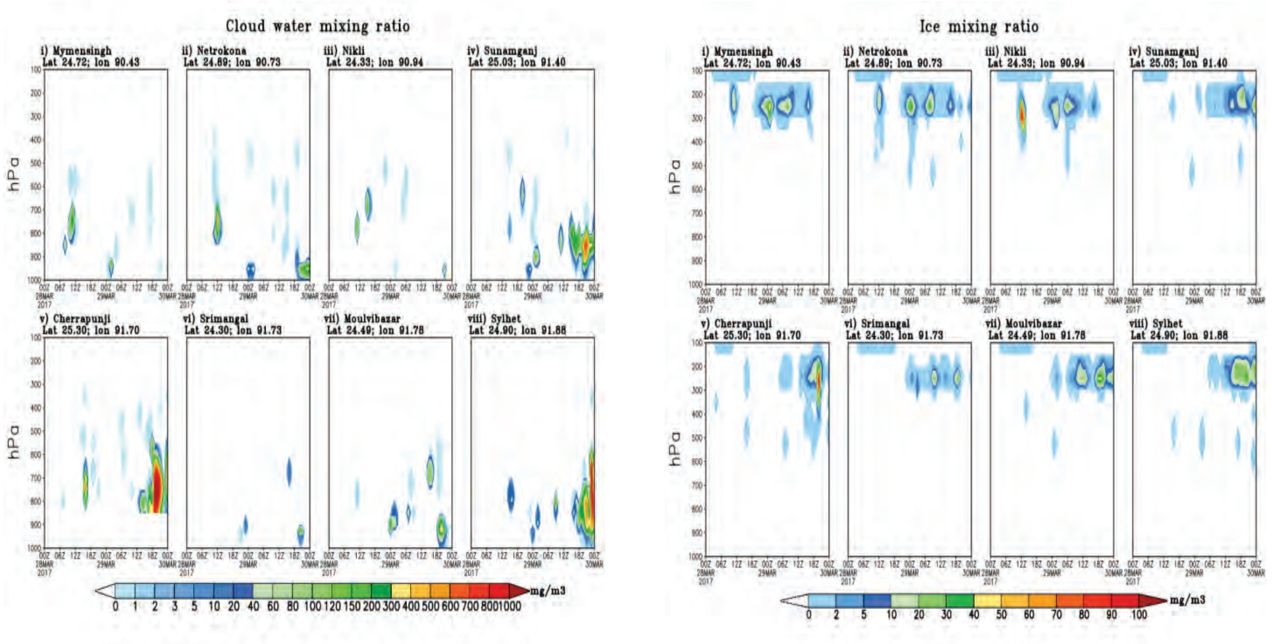



**Figure 9: Spatial distribution of model simulated winds and geopotential height (m) at 200 hPa level on 29 March 2017.**




(a) (b)

**Figure 10 (a-b): Time-pressure cross-section of (a) cloud water mixing ratio and (b) ice water mixing ratio on 28 and 29 March 2017.**

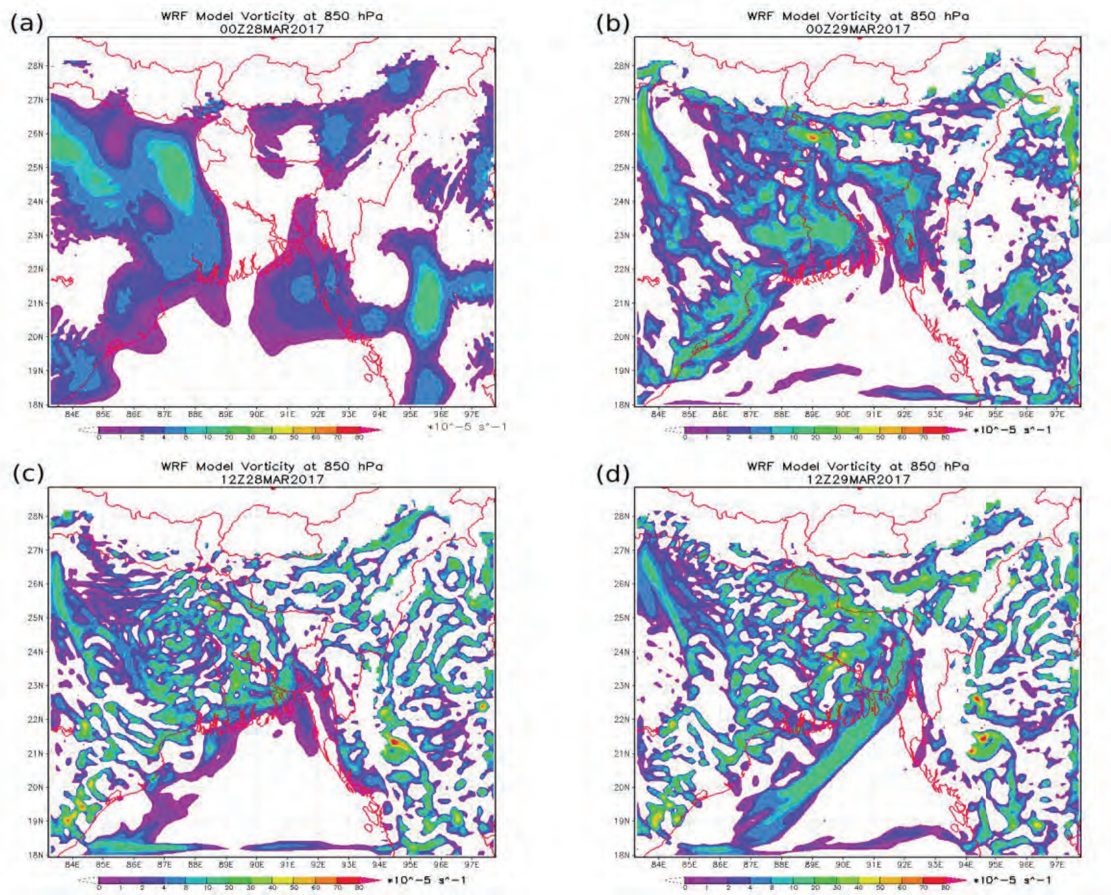



**Figure 11: Spatial distribution of vorticity at 850 hPa on 28 and 29 March 2017.**

westerly trough of circulation along with a strong trough of geopotential height is found to exist at 500 hPa over northeast Bangladesh and adjoining areas. The southerly flow coming from the Bay of Bengal is warm and moist whereas the northwesterly wind coming through India at 500 hPa is relatively cold and dry. These two types of wind flows, when conjugated, have produced sufficient instability in the troposphere for developing severe thunderstorms which when have moved over northeast/Meghalaya have become stronger due to orographic influence, thereby causing flash flood producing thunderstorms and associated lightings. The thunderstorms have become more marked due to the presence of persisting westerly jet streams of 40-45 $ms^{-1}$ at 200 hPa level (Figure 9) over Bangladesh and India. The system has been found to continue up to 30 March with weakening at the end period.

### 3.3.4 Spatial distribution of model simulated cloud water and ice water mixing ratio

The model simulated cloud water and ice water mixing ratios are given in Figure 10 (a-b). The figures clearly show that cloud-water mixing and ice-water mixing occur frequently over these areas because these areas are very potential for frequent thunderstorms or convections. The vertical cross section at different location shows cloud water mixing ratio ranges are 160 to 1100 mg $m^{-3}$ and ice water mixing ratio from 27 to 100 $mgm^{-3}$. The cloud water mixing ratio values are found to be 300, 600, 160, 650, 1100, 180, 400 and 1000 $mgm^{-3}$ (Fig. 10a) and ice water mixing ratio values are 50, 40, 100, 33, 100, 27, 45 and 33 mg $m^{-3}$ respectively (Fig. 10b) at Mymensingh, Netrokona, Nikli, Sunamganj, Cherrapunji, Srimangal, Moulavibazar and Sylhet respectively. The values of cloud water mixing ratio are maximum at Cherrapunji and Sylhet where torrential rain has occurred. Nikli and Cherrapunji have the maximum ice water mixing ratio. The higher cloud water mixing ratio and ice water mixing ratio over Nikli, Srimangal, Sylhet and Cherrapunji indicate significant convections as well as lightning potential during the period over there. It may be noted that the cloud-water mixing and ice-water mixing are found to occur almost all the hours, because rain and lighting are continuous during 28-31 March 2017 as can be seen from Figure 2a.

### 3.3.5 Spatial distribution of model simulated vorticity

The spatial distribution of vorticity at 850 hPa over Bangladesh and adjoining area has been simulated at 0000 UTC of 28 March 2017 and is found to be $12\times10^{-5}s^{-1}$, which gradually increases at 1200 UTC when it is $60\times10^{-5}$ $s^{-1}$. The next day the vorticity is found to be $80\times10^{-5}$ $s^{-1}$ at 0000 and 1200 UTC. This increase in vorticity on 29 March 2017 indicates that the lightning and flash flood producing thunderstorm have severe characteristics (Figure 11).

### 3.3.6 Time pressure cross sections of x, y and z components of wind

Figure 12(a-f) shows the vertical time pressure cross sections of the zonal, meridional and vertical components of wind over Cherrapunji and Sylhet The figures show that positive u-component of wind i.e. westerly wind both at Cherrapunji and Sylhet is dominant from about 850 hPa to the top of the troposphere having higher wind speed in the upper troposphere during 28-29 March 2017. There is easterly wind at Sylhet in the lower troposphere. The zonal wind has become more prominent with speed of +14 $ms^{-1}$ at Cherrapunji and +18 $ms^{-1}$ at Sylhet coming down to about 850 hPa at Cherrapunji and 950 hPa at Sylhet between 1800 UTC of 29 March and 0000 UTC of 30 March 2017. Westerly wind is about 30-32 $ms^{-1}$ at around 200 hPa level, indicating the presence of westerly jet stream.

The meridional wind component (v-component) is positive i.e. southerly in the lower troposphere at both Cherrapunji and Sylhet. The southerly wind is found to extend up to 600 hPa at Cherrapunji and beyond 600 hPa level at Sylhet (Figure 12 c, d). Above 600 hPa, the northerly wind (negative v-component) is dominant. The southerly wind has strengthened in the lower troposphere with speed of +5-12 m $s^{-1}$ at Cherrapunji and +8-16 m $s^{-1}$ at Sylhet from 1100 UTC of 29 March to 0000 UTC on 30 March 2017. This higher southerly wind indicates that the torrential rain has occurred at the night of

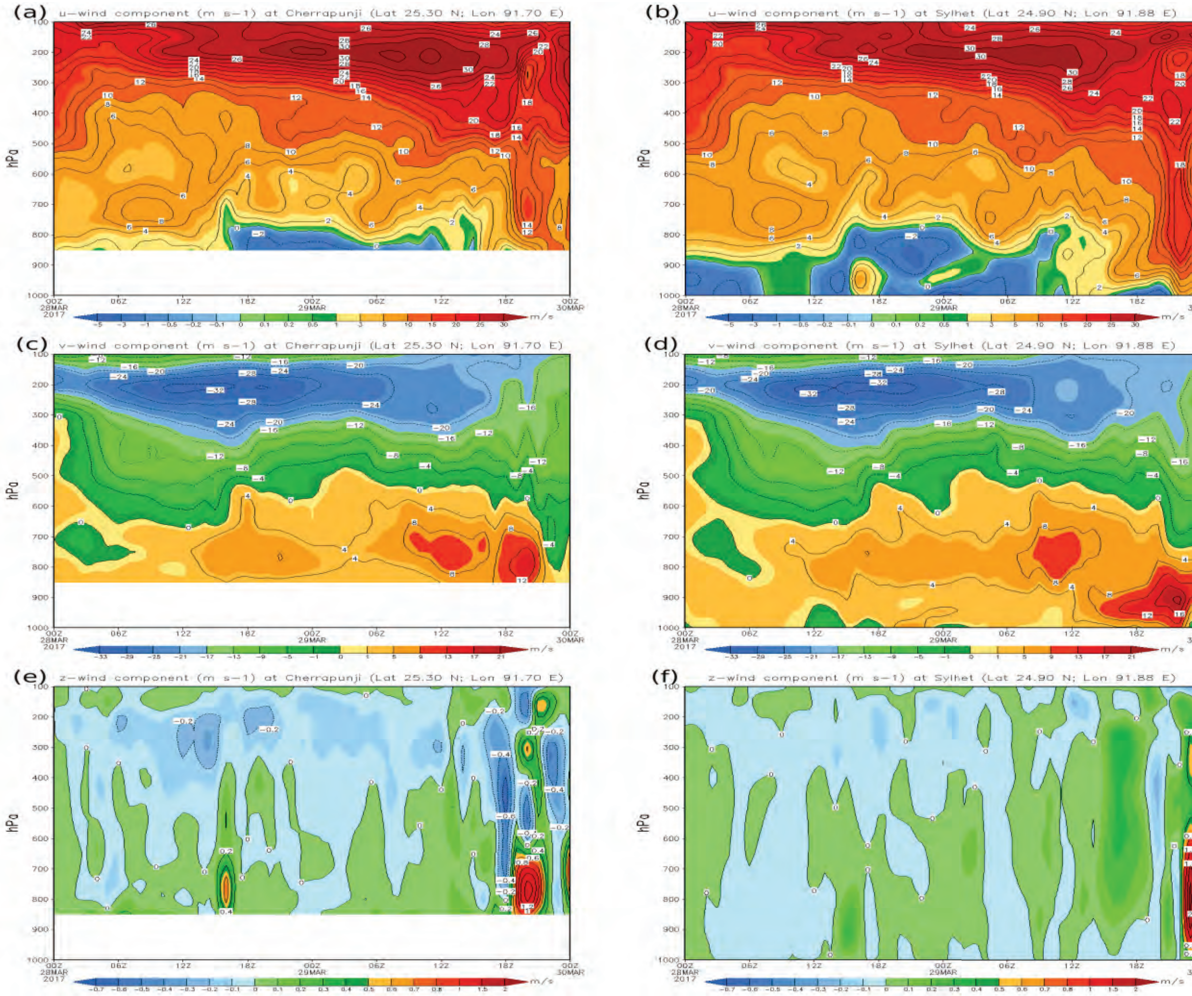



**Figure 12 (a to f): Vertical-cross sections of x, y and z components of wind of 28 and 29 March 2017.**

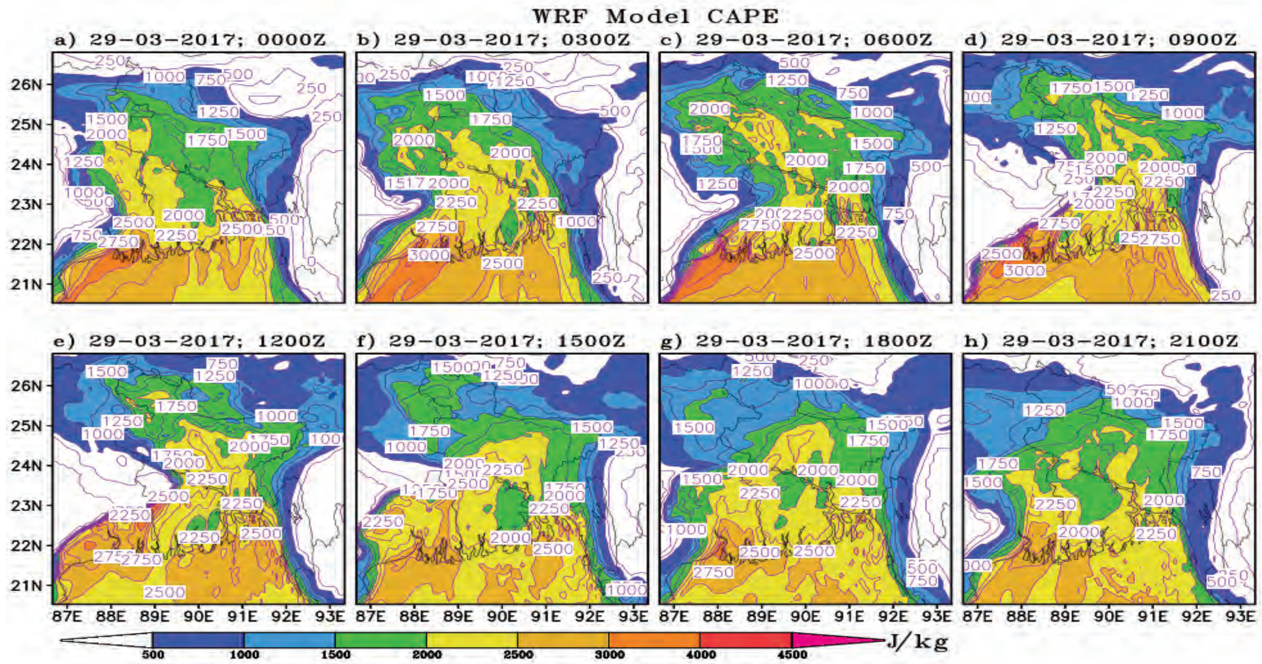



**Figure 13: Spatial distribution of model simulated CAPE over Bangladesh and adjoining area at synoptic hours on 29 March 2017.**

**Table 4. Observed CAPE computed from rawinsonde data.**

| Stations | CAPE | | | | | |
|---|---|---|---|---|---|---|
| | 29 March 2017 | | 30 March 2017 | | 31 March 2017 | |
| | 00Z | 12 Z | 00Z | 12 Z | 00Z | 12 Z |
| Dhaka | 1419.65 | 563.80 | 1210.24 | 1936.59 | 1172.09 | 2560.79 |
| Kolkata | 1765.64 | 3379.17 | 1557.57 | 3701.84 | 1754.96 | 00.00 |
| Agartala | 1538.08 | - | - | - | 1677.05 | - |

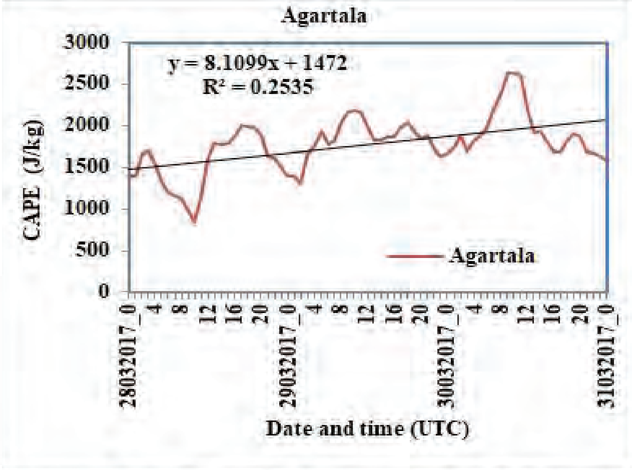



**Figure 14: Hourly variation in CAPE at Agartala during 28-31 March 2017.**

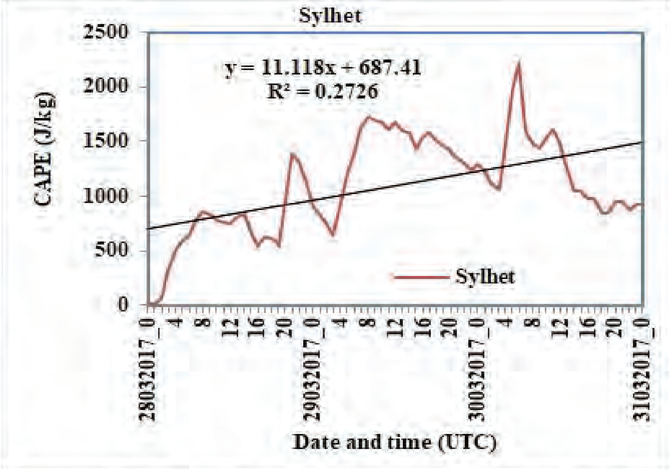



**Figure 15: Hourly variation in CAPE at Sylhet during 28-31 March 2017.**

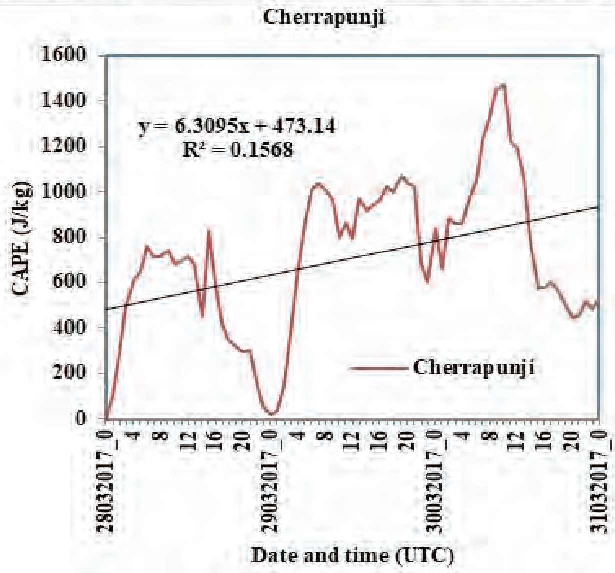



**Figure 16: Hourly variation in CAPE at Cherrapunji during 28-31 March 2017.**

29 March 2017. Maximum northerly wind speed of -32 $ms^{-1}$ is found at around 200 hPa level. The vertical component of wind (z-component) has positive and negative values alternatively but with definitely positive values of +1.2 $ms^{-1}$ or more from 850 hPa to about 650 hPa at Cherrapunji and from 950 hPa to 600 hPa at Sylhet after 1200 UTC on 29 March 2017.

### 3.3.7 Comparison between observed and model simulated CAPE

Convective Available Potential Energy (CAPE) is a measure of the amount of energy available for convection. It is directly related to the maximum potential vertical speed within an updraft and its higher values indicate greater potential for severe weather. When the CAPE index is zero, the air will be stable and convection is not possible. For CAPE values up to about 1000, the probability of heavy showers increases. Large CAPE also promotes lightning activity (Craven and Brooks, 2004). Table 3 gives a rough guide of the likelihood of lightning in terms of CAPE. The values of CAPE obtained from rawinsonde data during the period 29-31 March 2017 are given in Table 4. The values of CAPE indicate that moderate to very lightning risk has been associated with thunderstorms which occurred during 29-31 March 2017 over northeastern Bangladesh. But the three stations are far away in the south/southwest of the place of occurrence of thunderstorms.

CAPE has been simulated by using WRF model at synoptic hours on 28 March 2017. It is found that the convective available potential energy varies from one synoptic hour to another but has increased in the north/northeastern Bangladesh and adjoining area with the progress of the day, the simulated maximum value being 1750 $Jkg^{-1}$ J/kg at 0600, 0900 and 1800 UTC over Mymensingh and further northeast and this value indicates moderate lightning risk over there. On 29 March 2017, the distribution pattern of CAPE is almost similar but the magnitude is found to be 1750-2000 $Jkg^{-1}$ at 1200 UTC (Figure 13) over northeastern Bangladesh. It may be mentioned that CAPE has been always much higher in southern Bangladesh and adjoining Bay of Bengal, which may be due to the presence of more moisture over there. Figure 14 gives the hourly trend in simulated CAPE at Agartala during 28-31 March 2017 and shows that the CAPE has a significant increasing trend from 0000 UTC of 28 March to 0000 UTC of 31 March. The rate of increase in CAPE is 8.109 $Jkg^{-1}$/hr, indicating increased convection and lightning risk. The maximum CAPE at Dhaka is around 2640.8 $Jkg^{-1}$at around 12 UTC on 30 March 2017. CAPE is also found to increase significantly at Sylhet and Cherrapunji during the period 0000 UTC on 28 March to 0000 UTC on 31 March 2017 and the rates of increase of CAPE are 11.11 and 6.039 J $kg^{-1}$ $hr^{-1}$ respectively (Figures 15&16).

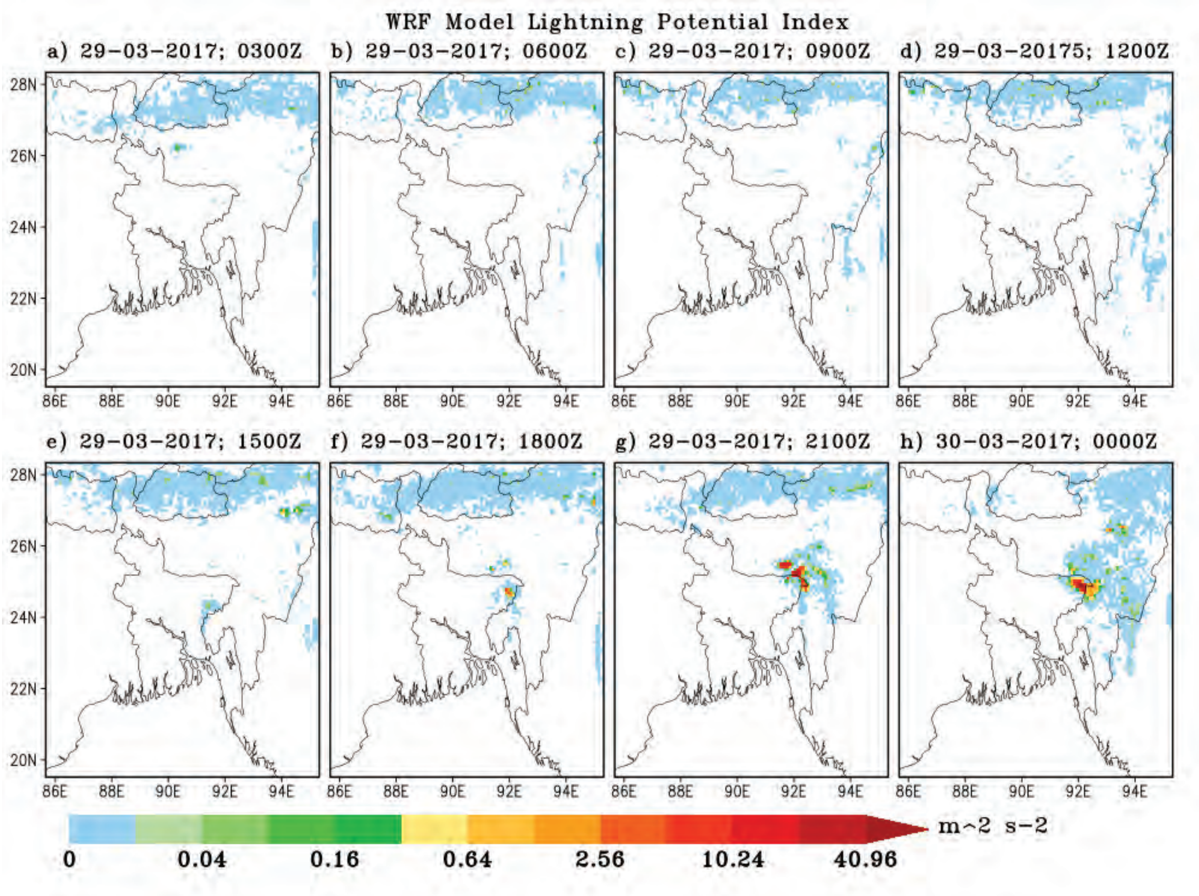



**Figure 17: Lightning Potential Index (LPI) during 29-30 March 2017.**

### 3.4 Spatial distribution of Lightning Potential Index (LPI) during 29-30 March 2017

The Lightning Potential Index (LPI) has been simulated for the period 0000 UTC of 29 March to 0000 UTC of 30 March. 2017. In the morning on 29 March 2017, there is slight LPI over the area north of Sylhet and Meghalaya with a value of 0.02 $m^2$ $s^{-2}$. LPI appeared over a relatively larger area covering Sylhet and Meghalaya at 1500 UTC on 29 March 2017 and has become more prominent

at 1800 UTC on 29 March to 0000UTC on 30 March 2017. The maximum LPI is about 40 $m^{-2}s^{-2}$ at 2100 UTC on 29 March 2019 (Figure 17). This indicates the existence of moderate to severe lightning conditions over the northeastern Bangladesh. LPI has been found to decrease from 1200 UTC on 31 March 2019.

## 4. Conclusions

On the basis of the present study, the following conclusions can be drawn:

(i) Heavy to very heavy rainfall at Sylhet due to thunderstorm, has been responsible for the occurrence of flash flood. The WRF model has captured the rainfall for the lightning and thunderstorms. Maximum rainfall is found to occur in the late night or early morning. The flash floods have occurred because of very heavy rainfall over Meghalaya Plateau and Sylhet region.

(ii) The WRF model has well simulated a low pressure area over West Bengal with its trough extended to northeastward, giving a favorable condition for the formation of thunderstorms. The persisting characteristics of the circulation over West Bengal and Bangladesh, the micro-circulation, the intense geopotential low at 850 hPa and upwards along with their eastward extension have been responsible for continuous heavy to very heavy rainfall over Sylhet and Meghalayan region, causing wide-spread intense flash floods over there.

(iii) A strong westerly trough of circulation along with a strong trough of geopotential is found to exist at 500 hPa over northeast Bangladesh and adjoining areas. At 500 hPa level, there has been a strong northwesterly flow of wind over India and Bangladesh with westerly winds over the Sylhet and Meghalaya regions.

(iv) The southerly flow coming from the Bay of Bengal is warm and moist whereas the northwesterly wind coming through India is relatively cold and dry. The mixing of these two types of winds have produced sufficient instability in the troposphere to develop moderate to severe lightning and thunderstorms, which when moved over northeast/Meghalaya become stronger due to orographic influence, thereby become flash flood producing thunderstorms. These thunderstorms and lightning become more marked due to the presence of westerly jet stream of 40 $ms^{-1}$ over Bangladesh and India.

(v) At Cherrapunji and Sylhet, the cloud water cloud water mixing ratio values are 1100 and 1000 mg $m^{-3}$ respectively. The values of cloud water mixing ratio are maximum at Cherrapunji and Sylhet where torrential rain has occurred. Sunamganj and Srimangal have the maximum ice water mixing ratio. At Mymensingh, Netrokona, Nikli, Sunamganj, Cherrapunji, Srimangal, Moulavibazar and Sylhet, the cloud water mixing ratio values are 130, 150, 140, 550, 1100, 22, 40 and 240 mg $m^{-3}$ respectively and ice water mixing ratio values are 160, 180, 110, 240, 220, 160, 220 and 200 mg $m^{-3}$ respectively during the study period.

(vi) The westerly wind both at Cherrapunji and Sylhet are found dominant from about 850 hPa to the top of the troposphere having higher wind speed in the upper troposphere during 28-29 March 2017. At Sylhet, there is easterly wind in the lower troposphere. The zonal wind becomes more prominent with speed of +14 $ms^{-1}$ at Cherrapunji and +18 $ms^{-1}$ at Sylhet coming down to about 850 hPa at Cherrapunji and 950 hPa at Sylhet between 1800 UTC of 29 March and 0000 UTC of 30 March 2017. Westerly wind is about 30-32 $ms^{-1}$ at around 200 hPa level, indicating the presence of westerly jet stream.

(vii) The southerly wind is found to extend up to 600 hPa at Cherrapunji and beyond 600 hPa level at Sylhet. The southerly wind has strengthened in the lower troposphere with speed of +5-12 $ms^{-1}$ at

Cherrapunji and +8-16 $ms^{-1}$ at Sylhet from 1100 UTC of 29 March to 0000 UTC on 30 March 2017. This higher southerly wind indicates that the torrential rain has occurred at the night of 29 March 2017.

(viii) Vorticity and vertical velocity is found to be conducive for the occurrence of thunderstorms and lightning.

(ix) The instability such as LI, SWEAT Index and CAPE. LI, SWEAT Index and CAPE have indicated moderate to strong convection over Bangladesh and surrounding Indian states. CAPE has continuous and sharp increasing trend at 8.109 J $kg^{-1}$ $hr^{-1}$, 11.11 J $kg^{-1}$ $hr^{-1}$ and 6.309 J $kg^{-1}$ $hr^{-1}$ at Agartala, Sylhet and Cherrapunji respectively, which has been favourable for lightning. LPI is favourable for moderate to severe lightning.

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