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ON THE SIMULATION OF LIGHTNING AND FLASH FLOOD PRODUCING THUNDERSTORMS IN THE NORTHEASTERN BANGLADESH

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ABSTRACT

This study is an attempt to simulate the tropospheric conditions associated with lightning and thunderstorms, which occurred during 28-30 March 2017 over northeastern Bangladesh using WRF model. At Sylhet, rainfall amounts of 119 mm and 134 mm are found to occur on 29 March and 31 March 2017 respectively. The continuous very heavy rainfall has been responsible for the devastating flash flood in Sunamganj and adjoining areas in 2017. The study shows that forecasting of lightning and flash flood producing thunderstorms is possible by analyzing different meteorological parameters simulated by WRF Model. The simulated parameters are rainfall, sea level pressure, geopotential height (m), Convective Available Potential Energy (CAPE), winds at various tropospheric levels, cloud water mixing ratio and ice water mixing ratio, vorticity and x, y, z wind components. A low pressure area and strong circulations are found to develop 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. Interaction of northwesterly flows of winds at 500 hPa level and southerly flow coming from the Bay of Bengal is found to produce 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 lightning and flash flood producing thunderstorms. The thunderstorms become more marked due to the presence of westerly jet stream of 40 ms^{-1} over Bangladesh and India. The persisting characteristics of the circulation over West Bengal and Bangladesh, the micro-circulation, the intense geopotential low at 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. On 29 March 2017, cloud water mixing ratio is found to range from 160 to 1100 mgm^{-3} and ice water mixing ratio from 27 to 100 mgm^{-3} at different locations. The maximum cloud water mixing ratio values are 1100 and 1000 mgm^{-3}at Cherrapunji and Sylhet respectively, where torrential rain has occurred. 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.

Key words: *Thunderstorms; lightning; flash flood; cloud water mixing ratio; ice water mixing ratio.*

1. INTRODUCTION

Bangladesh is 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, squalls and rain/showers. The thunderstorms, also known as nor'westers or locally Kalbaishakhi, which occur during the pre-monsoon season, are very destructive in terms of lightning, 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 frequently, makes severe acoustic sounds and kill people. From 2011 to May 2017, about 1,174 people were reported to be killed by lightning in Bangladesh (Anik, 2017). This indicates that the prediction of thunderstorm in this region as well in the country is very important.

There are few studies are available which emphasize the total life cycles of Nor'wester events over Bangladesh and neighborhood region. In a study, Karmakar and Alam (2006) analyzed various stability indices and attempted to get threshold values of them. As per their study 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

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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. Many parts of India e.g. eastern Madhya Pradesh, Bihar, West Bengal regions are extremely unstable with respect to negative values of SI, LI, DPI, DII and EI (Karmakar and Alam, 2006). The atmospheric conditions are significantly favorable with a cyclonic circulation extended up to 3 to 4 km. The CT, VT, SWI, KI and TT values were found maximum over the mentioned area. In another study, Karmakar and Alam (2011) had introduced several modified indices which trigger Nor'westers over the region. As per the study, MCT≥ 20°C, MVT≥26°C, MTT ≥ 46°C, MSWI ≥300, MKI ≥ 40°C and MEI < -6 joules/gm were the critical values to generate thunderstorms and related phenomena over Bangladesh. The study also revealed that 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 Jgm^{-1} for severe nor'westers of tornadic intensity to occur in Bangladesh. The study indicated maximum instability persisted over the area of surface low pressure mainly over Bihar, West Bengal and adjoining Bangladesh region.

Karmakar and Quadir (2014a) found that the mixing ratio at 0000 UTC at Dhaka on the dates of occurrence of local severe storms ranges from 16.13 to 22.41 g kg^{-1} at 1000 hPa, showing a considerable amount of moisture near the surface with a tendency to increase at 1000 hPa. More 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. Karmakar and Quadir (2014b), in another study, found 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 reveals that it decreases with height, becoming minimum at the mid-troposphere, indicating conditional instability in the troposphere, which is conducive for the occurrence of local severe storms. The equivalent potential temperature then increases significantly beyond 500 hPa. An important and pioneer attempt is the study of Doppler Weather Radar (DWR) data assimilation for squalls events of Bangladesh undertaken by Das *et al.* (2015a) in which they showed how important DWR is for nowcasting and extraordinary importance of archival of DWR data. The DWR data is found to be useful for better research on the life cycle of Nor'wester events. In the study, DWR data assimilated numerical output precisely predicted squalls events and the meteorological surface variables along with the observational values of stability indices are compared with and without data assimilation values. The assimilation results showed a significant improvement within the three cases out of four. A recent devastating tornado event at Brahmanbaria is simulated with very precise resolution of WRF model by Das *et al.* (2015b) and outputs are analyzed every minute basis. In this study, storm relative environmental helicity and bulk Richardson number shear values are diagnosed from simulation and found 1774 and 457.3 m^2 s^{-2}. The vertical velocity values are found to range in between -28 to 58 ms^{-1}.

Singh *et al.* (2015) had taken an attempt to study a severe thunderstorm, which affected the Delhi and the adjoining region between 1630 and 1730 hrs IST of 30 May 2014. They used the WRF model to simulate and investigate the severe thunderstorm. Sensitivity experiments were conducted to study the impact of using different horizontal grid resolution (9 km and 3 km) 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 research indicates that the model simulated 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 the study, the simulation at 3 km resolution provided better distributions of convergence zone in the wind fields at a lower level as compared to simulation at 9 km resolution. A study was made on the numerical simulation of physical and dynamical characteristics associated with the severe thunderstorm on April 5, 2015 at Kushtia and Jhenaidah (Karmakar *et al.,* 2017). This study provides a basis to investigate the physical and dynamical characteristics of the thunderstorm, which are generally not identified by the meteorological observations, which are too sparse. The model had captured a micro-low over Kumarkhali and its neighborhood, which favored the occurrence of the severe thunderstorm. The model simulated rainfall was about 26 mm near the place of occurrence, which was found to match well with the area where the reflectivity of hydrometeor was maximum. The convective available potential energy (CAPE) was found to be 1600 J kg^{-1} at 1730 UTC near the place of occurrence of the thunderstorm; this indicated 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 were found to be satisfactory and responsible for the occurrence of large hails associated with the thunderstorm. Lal (2014) analyzed the relation between size of cloud ice and lightning in the tropics. They showed that total lighting increases with an increase in the cloud ice size and attains a maximum at certain cloud ice size and then decreases with an increase in cloud ice size. Maximum lightning occurred for the mean cloud ice size of around 23–25 μm over the continental region and mean cloud ice size of around 24–28 μm over the oceanic region. The study of Bradshaw (2016) demonstrates the spatial relationship between lightning and CAPE. Thunderstorm formation depends on environmental stability and the existence of electrification mechanisms. The evaluation of the relation between CAPE and lightning leads meaningful insight into thunderstorm formation and electrification, providing an understanding that can enhance severe weather forecasting products. Because CAPE is thought of being related to convection, since it is a measure 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 that CAPE values between 1000 and 2500 J kg^{-1} are competent 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.

1.1 Climatological distribution of the frequency of thunderstorm event in Bangladesh

The spatial distributions of mean monthly frequency of thunderstorms event have been analyzed for each month of the pre-monsoon season during 1980-2016. The distribution patterns of mean frequency thunderstorm event for March, April and May are similar to each other. The area of maximum frequency thunderstorm event 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 thunderstorm events occur over the region (Figure 1). The distribution patterns also show that the mean frequency of thunderstorm events is minimum over northwestern and extreme southeastern parts of the country. It has been found that this seasonal frequency is less by 1-8 thunderstorm events 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.

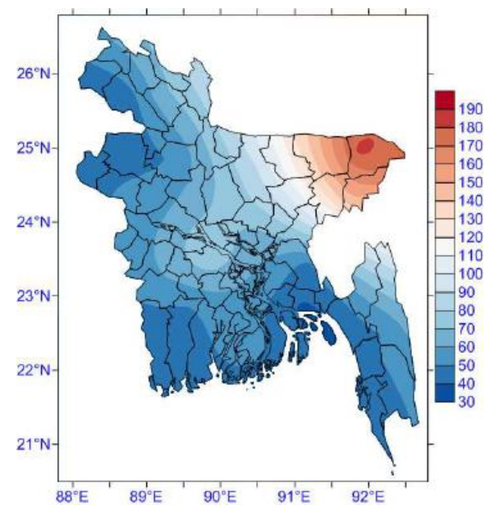


Figure1: Spatial distribution of mean frequency of seasonal thunderstorm events in the pre-monsoon season over Bangladesh during 1980-2016

1.2 Objectives of the study

The objectives of the present research are to simulate the atmospheric conditions favorable for the formation of flash flood producing thunderstorms and associated lightning over the northeastern Bangladesh by using WRF model.

2. DATA AND METHODOLOGY

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 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 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 thunderstorm events 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. 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.

Table1: WRF Model configurations

Model Features	Configurations
Horizontal Resolution	9 km
Vertical Levels	40
Topography	U.S. Geological Survey (USGS)
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
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) ; SW (Dudhia, 1989)
Gravity Wave Drag	No
Land Surface Processes	Unified NOAH Land Surface Model

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

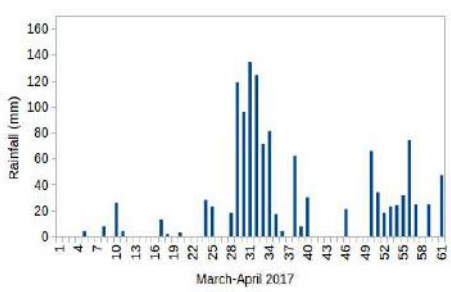


Figure 2a: Daily rainfall at Sylhet in March-April 2017

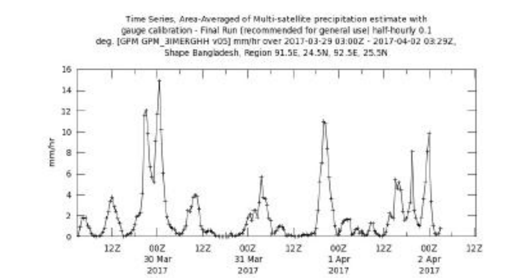


Figure 2b: Daily rainfall near Sylhet and adjoining area in March-April 2017

3.2 Instability indices during 29-31 March 2017

Different instabilities of the troposphere over Dhaka, Kolkata and Agartala at 0000 and 1200 UTC during 29-31 March 2017 are computed and furnished in Table 2. The table shows that most of the indices indicated stable conditions except LI, SWI and CAPE. Showalter Index showed stability of the troposphere moderate to absolute. The SWEAT index>200 indicated the instability at Dhaka and Agartala 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.

Table 2: Different instability indices at different stations during 29-31 March 2017

Stations	Dates	SI	LI	SWI	KI	CTI	VTI	TTI	CAPE
Dhaka	29 March 2017; 00Z	3.51	-1.52	211.61	33.4	16.9	22.9	39.8	1419.65
	12Z	2.83	1.35	244.79	27.8	17.6	20.9	38.5	563.8
	30 March 2017; 00Z	4.34	-0.83	225.58	25.5	13.7	25.7	39.4	1210.24
	12Z	6.82	-2.65	182.00	23.9	9.9	25.9	35.8	1936.59
	31 March 2017; 00Z	5.06	-0.93	177.21	20.9	12.3	26.3	38.6	1172.09
	12Z	-1.15	-3.53	435.72	19.9	21.5	22.3	43.8	2560.79
Kolkata	29 March 2017; 00Z	2.56	-2.95	193.8	22.7	15.3	27.3	42.6	1765.64
	12Z	2.71	-4.38	202.8	30.9	15.5	25.5	41	3379.17
	30 March 2017; 00Z	9.45	-1.05	101.6	15.7	3.9	27.9	31.8	1557.57
	12Z	4.28	-4.44	193.8	25.3	11.9	27.9	39.8	3701.84
	31 March 2017; 00Z	6.58	-1.49	130.21	18.3	9.7	26.7	36.4	1754.96
	12Z	3.9	14.53	153.81	28.9	12.5	12.5	41	0
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 thunderstorm events during 28-30 March 2017

3.3.1 Distribution of model simulated rainfall

The rainfall simulated by WRF model during 28-30 March 2017 and the distribution of rainfall during 29-30 March is shown in Figure 3 for example. Three hourly evolutions of rainfall show rainfall starting over Meghalaya plateau region at 0300 to 0600 UTC on 28 March 2017. It continues up to 0000 UTC on next day (Figure 3). The rainfall is more prominent on 29 to 30 March 2017 over the Meghalaya region as well as in the northeast 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 overpassed 64 to 128 mm at 1500, 1800 and 2100 UTC. The rainfall is distinct and heavy during 1500 UTC of on 29 March to 0000 UTC of 30 March 2017. This hefty amount of rainfall within a short duration has created flash flood havoc over the northeast region of Bangladesh.

3.3.2 Distribution of model simulated sea level pressure

The distribution of model simulated sea level pressure (SLP) over Bangladesh and adjoining area during 28-29 March 2017 has been analyzed and some results are given in Figure 4. From the analysis, 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 with its trough extended towards northeast. The SLP has changes in magnitude at different times, but the distribution has a strong trough extended towards northeast. This trough has been responsible for the development of severe thunderstorms in the northeast. SLP ranges are 1009 to 1012 hPa at 0000 UTC and 1007 to 1010 hPa at 1200 UTC over Bangladesh on 28 March 2017. For the next day at 0000 UTC, the value ranges from 1008 to 1011 hPa and at 1200 UTC the range is 1005 to 1010 hPa over Bangladesh (Figure 4). The northeastward extended trough is found to become more prominent with the progress of time.

3.3.3 Distribution of model simulated winds at different levels

From the analysis of wind filed at 10m level, it is found that a circulation is developed over West Bengal and adjoining Bangladesh at 1200 UTC on 28 March 2017 (Figure not shown) with a trough extended to northeast. Strong flow of southwesterly to south-southeasterly wind is distinctly visible over the Bay of Bengal and Bangladesh persisting up to 29 March 2017. This flow of winds brings a lot of moisture from the Bay of Bengal, converging over the low level circulation. On the following day at 1200 UTC, strong circulation is found over western Bangladesh with its trough extended to northeast over Sylhet and Meghalaya region (Figure 4).

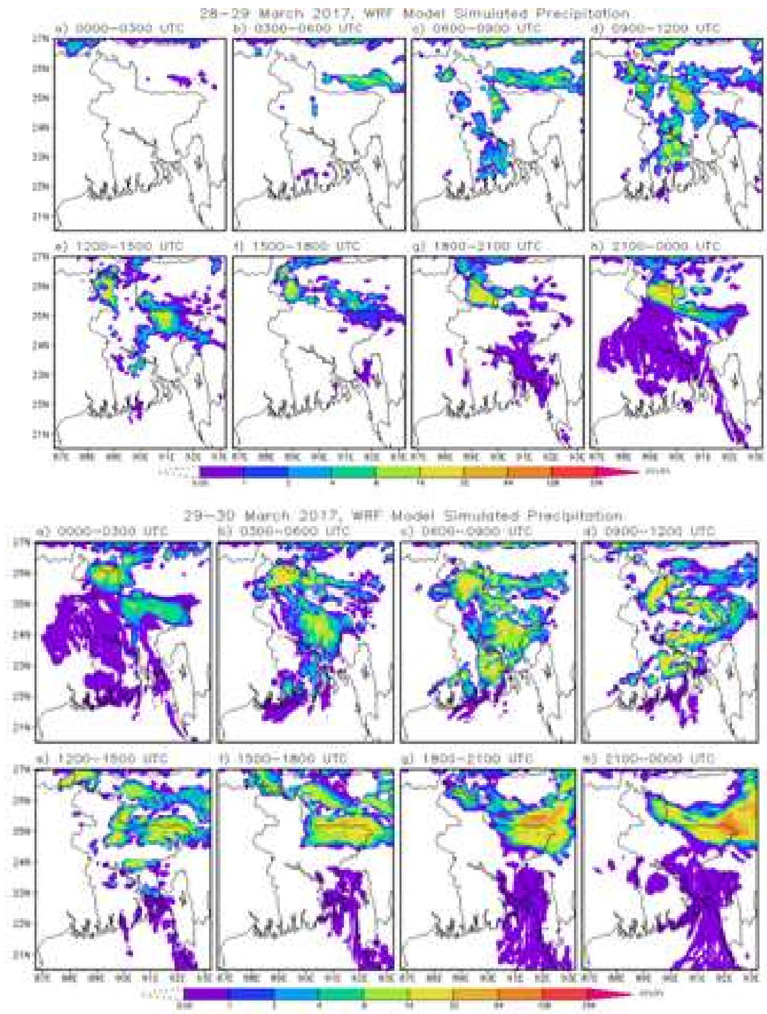


Figure 3: Distribution of simulated 3 hourly accumulated rainfall over Bangladesh during 0000 UTC 28 March to 0000 UTC 30 March 2017

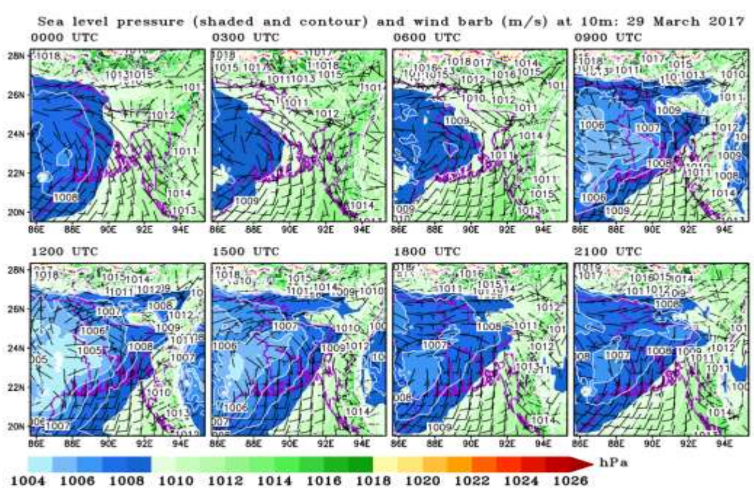


Figure 4: Distribution of model simulated sea level pressure and wind flow 10m over Bangladesh and adjoining area on 29 March 2017

The circulation over West Bengal and adjoining Bangladesh is more prominent at 850 hPa from 0000 UTC on 28 March with an extended trough towards the northeast. The analysis of geopotential height indicates a prominent low over the circulation and has become more intense from 0900 UTC on 28 March 2017 with a value of 1490 gpm and the strong trough is extended towards Sylhet and adjoining Meghalaya (Figure not shown). On 29 March 2017, the circulation persists, becoming more prominent from 0600 UTC and the whole country and adjoining north-northeastern Meghalayan area beyond has become under the grip of low geopotential height (1460 gpm) with an extended strong trough throughout the whole day (Figure 5). At 1500 UTC on 29 March 2017, a micro circulation has formed over the Sylhet region and continued up to 30 March (Figure not shown).

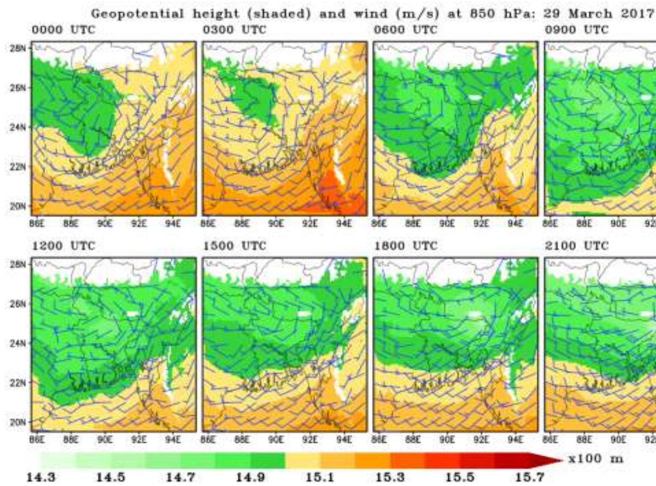


Figure 5: Distribution of model simulated wind circulation and geopotential height in meter (gpm) at 850 hPa on 29 March 2017

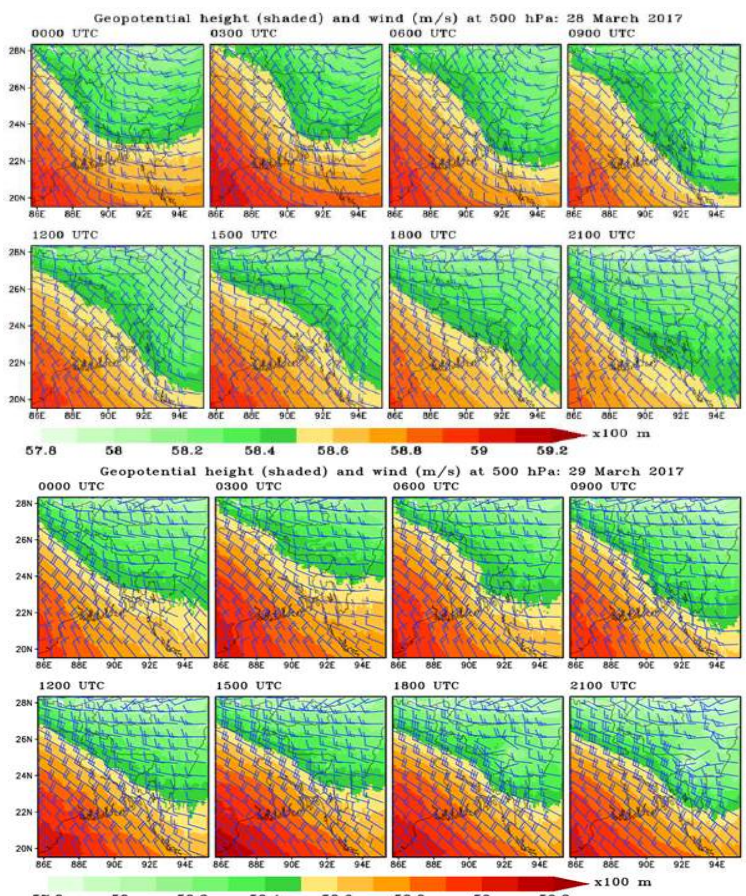


Figure 6: Distribution of model simulated winds and geopotential height (m) at 500 hPa level over on 28-29 March 2017

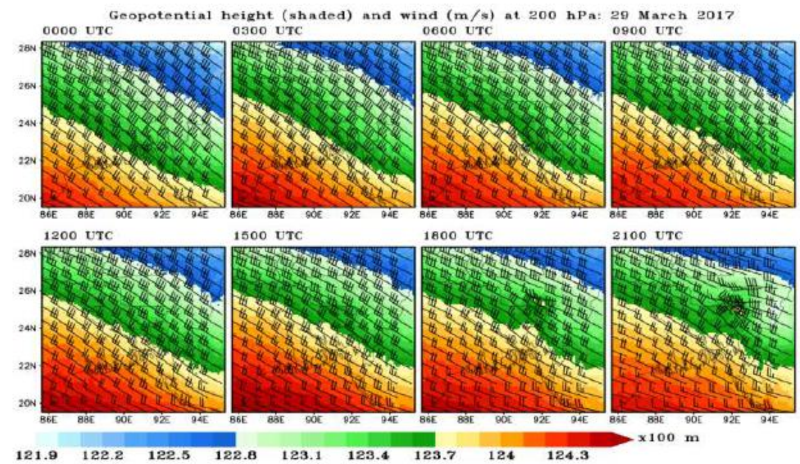


Figure 7: Distribution of model simulated winds and geopotential height (m) at 200 hPa level on 29 March 2017

The circulation begins to weaken slightly from 1500 UTC on 30 March 2017. 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 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.

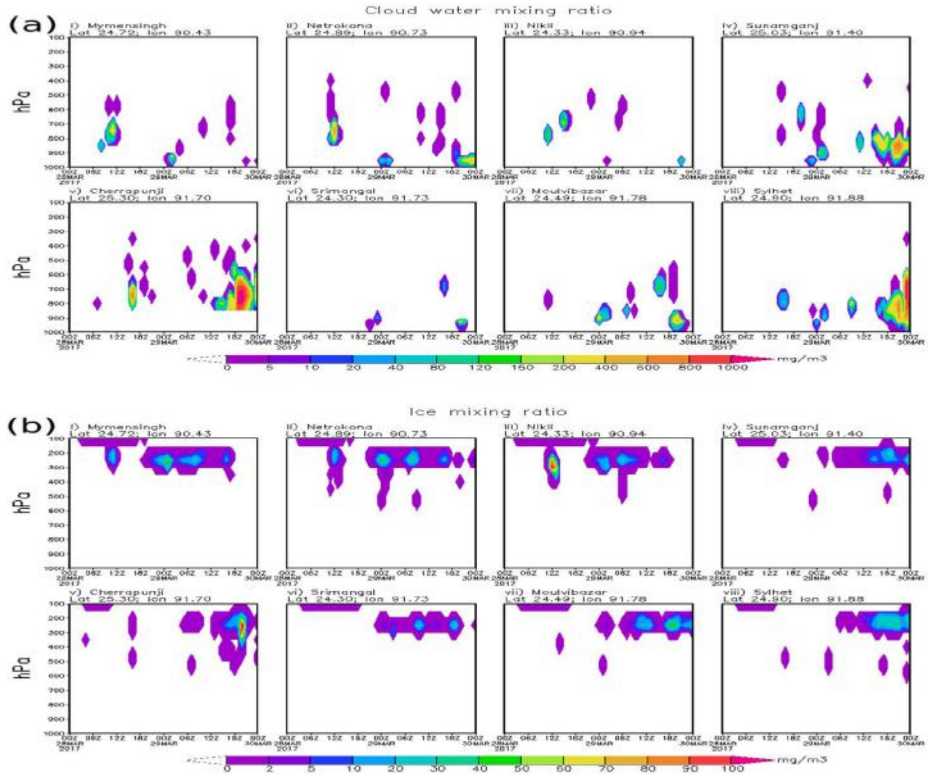
At 500 hPa level, there is a strong northwesterly flow of wind over India and Bangladesh with westerly winds over the Sylhet and Meghalaya regions (Figure 6). A strong westerly trough of circulation along with a strong trough of geopotential height is found to exist at 500 hPa over northeast Bangladesh and adjoining areas. The southerly flow coming from the Bay of Bengal at the lower level (Figure 5) is warm and moist whereas the northwesterly wind coming through India is relatively cold and dry. These two types of wind flows produced sufficient instability in the troposphere to develop severe thunderstorms which when have moved over northeast/Meghalaya have become stronger due to orographic influence, thereby cause flash flood producing thunderstorms and associated lightings. These thunderstorms have become more marked due to the presence of westerly jet stream of 40-45 ms^{-1} at 200 hPa level (Figure 7), which gives persistence characteristics of westerly jet streams over Bangladesh and India. The system has been found to continue up to 30 March with weakening at the end period.

3.3.4 Distribution of model simulated cloud water and ice water mixing ratio

The model simulated cloud water and ice water mixing ratios are given in Figures 8(a-b). 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}. At Mymensingh, Netrokona, Nikli, Sunamganj, Cherrapunji, Srimangal, Moulavibazar and Sylhet the maximum cloud water mixing ratio values are found to be 300, 600, 160, 650, 1100, 180, 400 and 1000 mgm^{-3} respectively (Figure 8a) and the maximum ice mixing ratio values are 50, 40, 100, 33, 100, 27, 45 and 33 mg m^{-3} respectively (Figure 8b). The values of cloud water mixing ratio is 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 indicates significant convections as well as lightning during the period over there. The cloud hydrometeor shows maximum values >1000 mg m^{-3} over Cherrapunji at 1800 UTC on 29 March and over Sylhet at 0000 UTC on 30 March 2017. Similarly, the ice water mixing ratio shows maximum values of >100mg m^{-3}over Cherrapunji 1t 1800 UTC on 29 March and over Nikli region at 1200 UTC on 28 March 2017.

3.3.5 Distribution of model simulated vorticity

The distribution of vorticity at 850 hPa level over Bangladesh and adjoining area has been simulated at 0000 UTC of 28 March 2017 and is found to be 12×10^{-5} s^{-1}, which gradually increases at 1200 UTC when it is 60×10^{-5} s^{-1}. The next day the vorticity is found 80×10^{-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 has severe characteristics (Figure 9).



Figures 8: Time-pressure cross-section of (a) cloud and (b) ice water mixing ratio of 28 and 29 March 2017

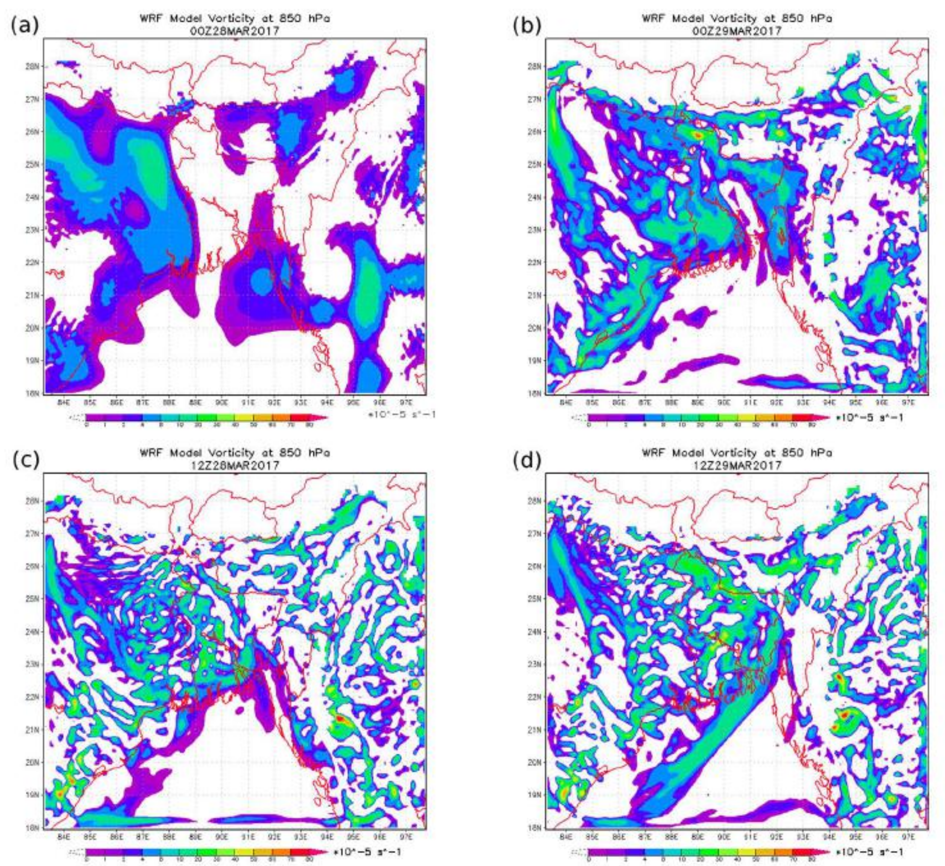
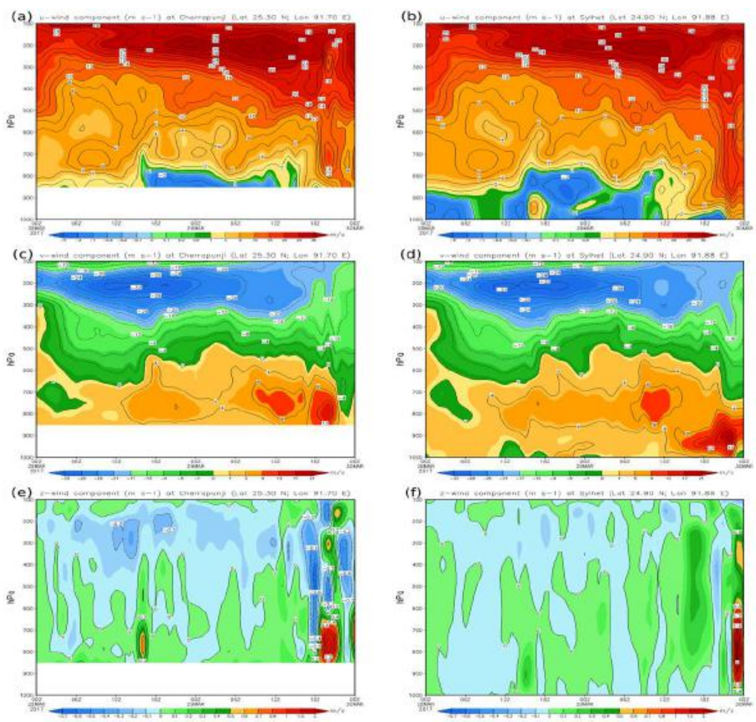


Figure 9: Distribution of vorticity at 850 hPa on 28 and 29 March 2017

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

Vertical time pressure cross sections of the zonal, meridional and vertical components of wind over Cherrapunji and Sylhet are shown in Figures 10(a-f). Figures 10(a, b) shows 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. At Sylhet, there is easterly wind in the lower troposphere. The zonal wind became 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 [Figures 10(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 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.



Figures 10: Vertical-cross sections of x, y and z component of wind of 28 and 29 March 2017

3.3.7 Observed and model simulated CAPE

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). The 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 part of Bangladesh. But the three stations are far away in the south/southwest of the place of occurrence of thunderstorm events.

Table 3: CAPE and lightning risk (*http://weather.mailasail.com/Franks-Weather/Cape)*

CAPE Index	Lightning Risk
< 1000	Slight
1000 – 2500	Moderate
2500-3500	Very
> 3500	Extremely

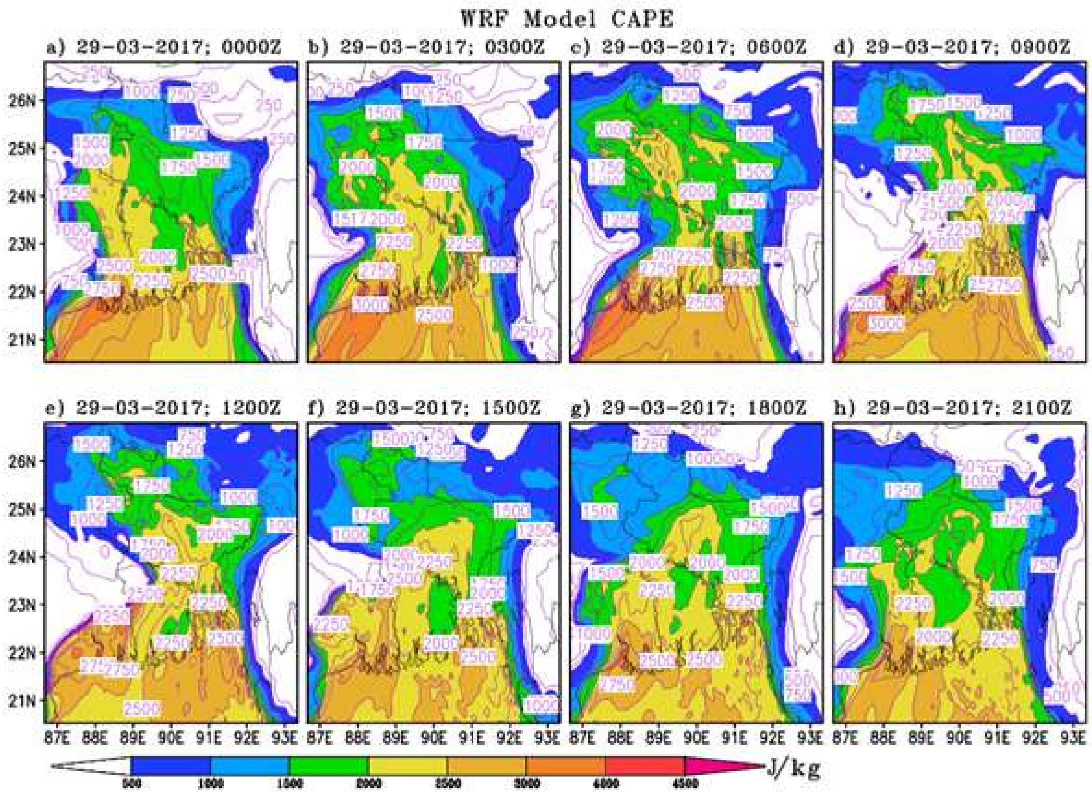


Figure 11: Distribution of model simulated CAPE over Bangladesh and adjoining area at synoptic hours on 29 March 2017

The WRF model has simulated CAPE at synoptic hours on 28 March 2018. 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 11) over northeastern Bangladesh.

Table 4: Observed CAPE computed from rawinsonde data

Stations	CAPE					
	29 March 2017		30 March 2017		31 March 2017	
	00 UTC	12 UTC	00 UTC	12 UTC	00 UTC	12 UTC
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	-

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 12(a) 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 1200 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 as shown in Figure 12(b, c).

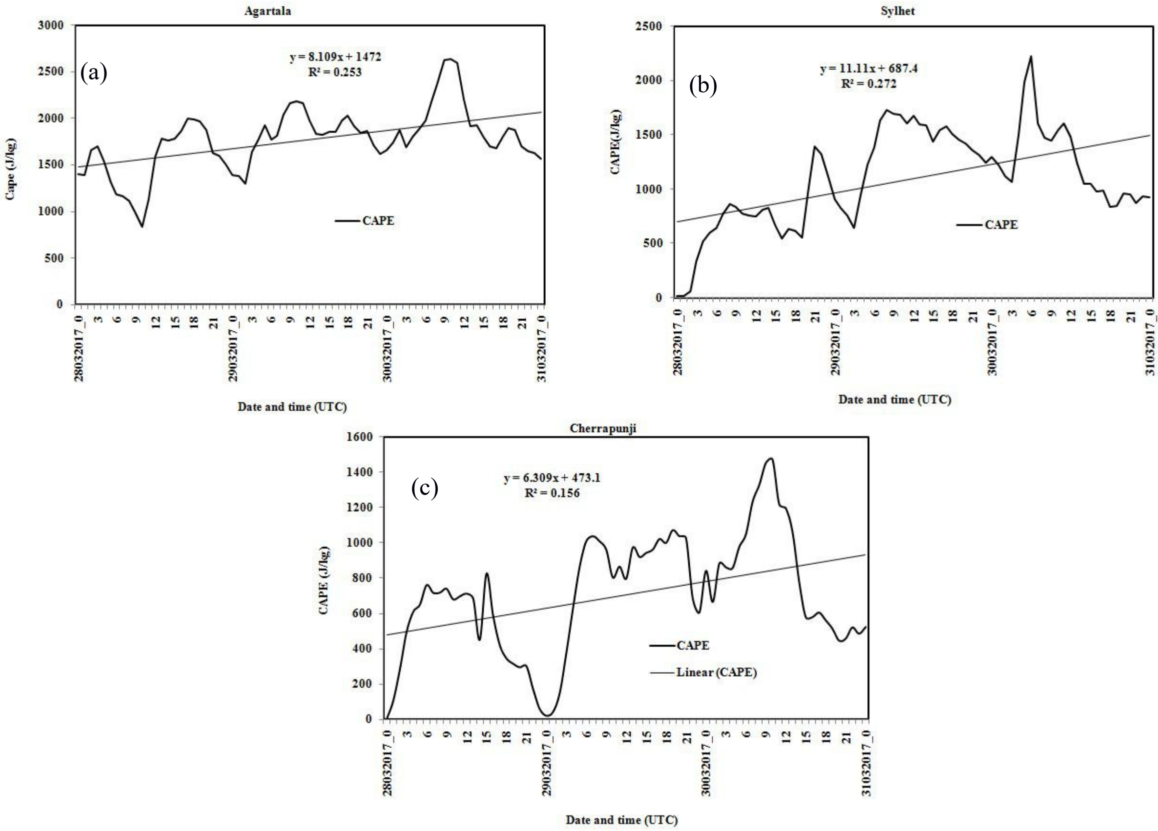


Figure 12: Hourly variation in CAPE at (a) Agartala, (b) Sylhet and (c) Cherrapunji during 28-31 March 2017

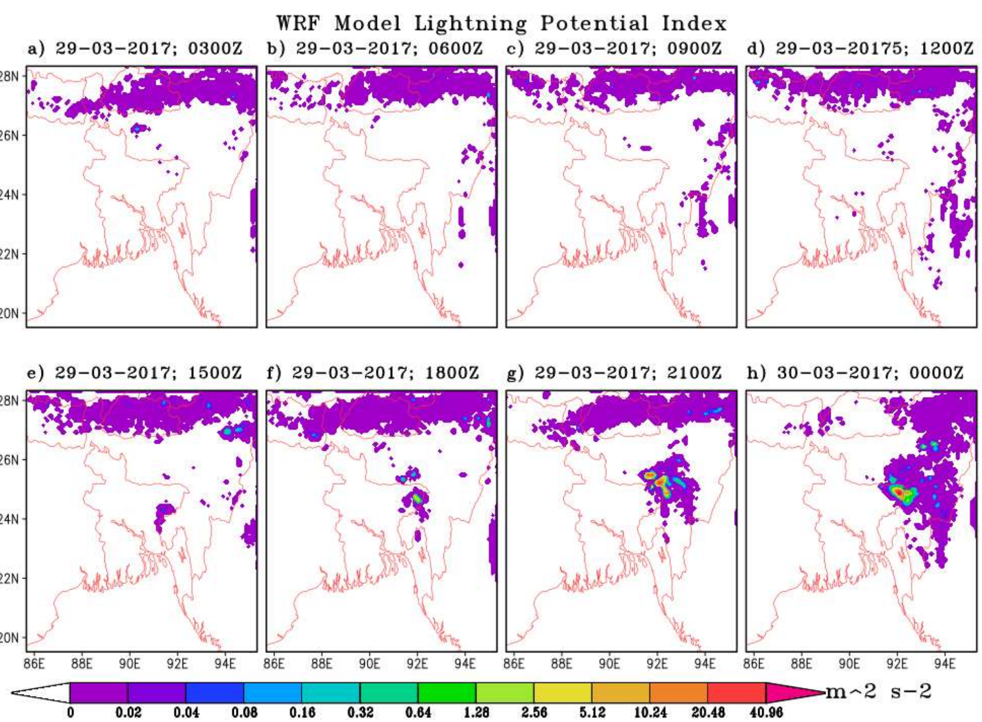


Figure 13: Lightning Potential Index (LPI) during 29-30 March 2017

3.4 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 28 March, there is slight LPI over the area north of Sylhet but slight over 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 28 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 13). This indicates 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:

- Heavy to very heavy rainfall occurred at Sylhet, which has been responsible for the occurrence of flash flood. The WRF model has captured the rainfall for the lightning and flash flood producing thunderstorm events. 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.
- The model has simulated a low pressure area over West Bengal with its trough extended to northeastward, giving a favorable condition for the formation of thunderstorm events. A circulation is developed at 10 m level over West Bengal and adjoining Bangladesh at 1200 UTC on 28 March 2017 with a trough extended to northeast. The circulation over West Bengal is found to shift eastward with time. 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.
- 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.
- 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. 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 thunderstorm events. These thunderstorms and lightning become more marked due to the presence of westerly jet stream of 40 ms^{-1} over Bangladesh and India.
- On 29 March 2017, cloud water mixing ratio ranges from 160 to 1100 mg m^{-3} and ice water mixing ratio from 27 to 100 mg m^{-3}. 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.
- 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.
- 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.
- Vorticity has been favorable for the occurrence of thunderstorm events on 29 March 2017. The vertical velocity has alternate positive and negative values vertically but with definite positive values during the latter part of the study period with maximum speed of 2.5 ms^{-1} at Cherrapunji. The vertical velocity is found to be conducive for the occurrence of thunderstorms and lightning.
- The most of the instability indices are not found favourable for the occurrence of thunderstorm events except LI, SWI and CAPE. LI, SWI and CAPE has indicated moderate to strong convection over

Bangladesh and surrounding Indian states. At Agartala, Sylhet and Cherrapunji, CAPE has continuous and sharp increasing trend at 8.109, 11.11 and 6.309 J kg^{-1} hr^{-1} respectively, which has been favourable for lightning. LPI is favourable for moderate to severe lightning.

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