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SIMULATION OF SEVERE THUNDERSTORMS IN CONJUGATION OF WESTERLY AND EASTERLY ON 31 MARCH 2019 IN BANGLADESH

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ABSTRACT

The diagnostic and prognostic studies of thunderstorms/squalls are very important to save live and loss of properties. The present study aims at diagnose the different tropospheric parameters, instability and synoptic conditions associated the severe thunderstorms with squalls, which occurred at different places in Bangladesh on 31 March 2019. For prognostic purposes, the severe thunderstorms occurred on 31 March 2019 have been numerically simulated. In this regard, the Weather Research and Forecasting (WRF) model is used to predict different atmospheric conditions associated with the severe storms. The study domain is selected for 9 km horizontal resolution, which almost covers the south Asian region. Numerical experiments have been conducted with the combination of WRF single-moment 6 class (WSM6) microphysics scheme with Yonsei University (YSU) PBL scheme in simulation of the squall events. Model simulated results are compared with the available observations. The observed values of CAPE at Kolkata both at 0000 and 1200 UTC were 2680.4 and 3039.9 J kg^{-1} respectively on 31 March 2019 and are found to be comparable with the simulated values. The area averaged actual rainfall for 24 hrs is found is 22.4 mm, which complies with the simulated rainfall of 20-25 mm for 24 hrs.

Keywords: *Thunderstorms; conjugation; westerly; easterly; instability; WRF.*

1. INTRODUCTION

In Bangladesh, pre-monsoon season (March-May) is the season of severe thunderstorms/squalls which are accompanied by lightning, gusty winds and thunder with moderately heavy to very heavy showers at times. The lightning and thunder associated with these severe storms kill a lot of people in the country and are increasing day by day. Not only that the frequency of thunderstorms has tendency to increase at most places in Bangladesh.

Thunderstorms are very common in Bangladesh and surrounding Indian States during the pre-monsoon, monsoon and post-monsoon seasons. Of these, the thunderstorms, which occur during the pre-monsoon season, are very severe with high gusty/squally winds, thunder, hails, lightning and heavy showers. The thunderstorms are known as Nor'westers or Kalbaishakhis in Bangladesh and adjoining states of India. Sometimes tornado cells are embedded in the mother thunderstorms and cause great devastation and loss of lives in the country (Hossain and Karmakar, 1998). Now-a-days, a number of people are being killed due to lightning mainly over the whole country. The thunderstorms, which occur over the northeastern part of Bangladesh and adjoining Meghalaya Plateau of India, cause flash floods almost every year in the northeastern part of the country, causing enormous loss of agricultural crops. The monthly frequency of thunderstorms increases from March to May in Bangladesh with maximum frequency in Sylhet region. About 170-183 thunderstorms occur over northeastern Bangladesh in the pre-monsoon season of 1980-2016 (Karmakar and Mannan, 2014). The distribution patterns also show that the mean thunderstorm frequencies are minimum over northwestern and extreme southeastern parts of the country. The areas where these nor'westers form are Chota Nagpur, Bihar, West Bengal, Sub-Himalayan West Bengal, Bangladesh and northeastern India, the reasons of which are the presence of greater instability, incursion of moisture from the Bay of Bengal in the lower levels extending to 3 km or more, convergence in the lower troposphere and presence of westerly trough and westerly jet stream in the upper troposphere (Bhattacharya, 1994; Karmakar, 2005; Karmakar and Alam, 2005, 2006a, 2006b, 2007; Litta *et al.,* 2012; Karmakar and Mannan, 2014; Karmakar *et al.* 2015; Karmakar and Das, 2020). Over northeast Bangladesh, the terrain and the environmental conditions are different at different places, so the behavior and strength of the severe thunderstorms are different at different places. The rainfall associated with these thunderstorms produce flash floods in this region. The lightning associated with thunderstorms kill a number of people and animals every year in Bangladesh. Number of lightning-related fatalities and injuries are being increased in Bangladesh (Holle *et al.,* 2018). According to Holle *et al.* (2018), the latest eight years have a

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fatality rate of 2.08 per million people per year and injury rate of 1.7. They mentioned that trend of many more casualties starting in 2010 has indeed continued. The decadal totals are as follows:1990-1999: 30 deaths and 22 injuries per year; 2000-2009: 106 deaths and 72 injuries per year, and 2010-2017: 260 deaths and 211 injuries per year. These show that frequency of death and annual thunderstorms are increasing now-a-days (Holle *et al.* 2018; Mannan *et al*., 2008). The trend of death toll in Bangladesh, taking the data of 1990-2016 from Dewan et al, 2017 and the data of 2011-2019 from the statement of Ministry of Disasters and Relief in Protham Alo dated 13 October 2021, is drawn and shown in Figure 1. It is found the rate of increase of death due to thunderstorm and lightning is 10.45 persons per year during the period 2010-2019 (Figure 1). The rate and the values of R^2 are significantly high. Karmakar and Das (2020) made a study on the simulation of lightning and flash flood producing thunderstorms in the northeastern Bangladesh and the results are found to be encouraging for the forecasting of lightning and flash flood in the northeastern part of the country. Most of the people are killed in day time while working in the open paddy/crop fields. The northeastern part of Bangladesh is the most vulnerable for thunderstorms and lightning where about 180 thunderstorms may occur during the pre-monsoon season (Karmakar and Das, 2020).

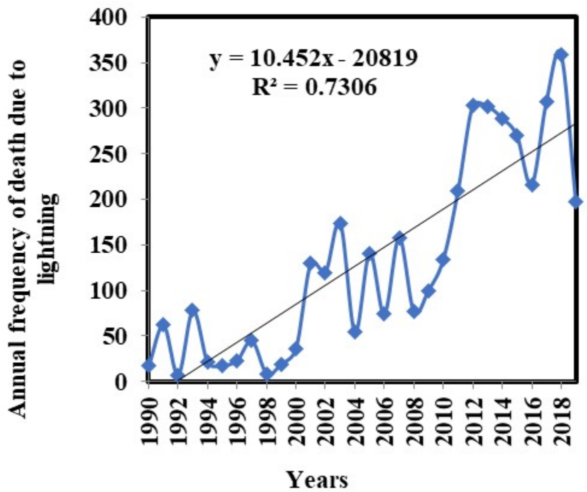


Figure 1: Annual death toll due to thunderstorms in Bangladesh during 1990-2019 (based on Dewan *et al*, 2017 and Statement of Ministry of disaster in Protham Alo, 13 October 2021

Figure 2: A tree uprooted by a sudden storm partially crushes a car near Ramna Park, adjacent to Hotel InterContinental, in Dhaka in the evening on March 31, 2019 (Md Manik/Dhaka Tribune: Total 6 persons killed in Dhaka City)

These facts indicate the necessity of accurate forecasting of thunderstorms in Bangladesh. A number of studies have been made by different scientists on the forecasting of thunderstorms in Bangladesh (Chowdhury and Karmakar, 1986; Chowdhury *et al*., 1991; Hossain and Karmakar, 1998; Karmakar, 2001; Karmakar, 2005; Karmakar and Alam, 2005, 2005a, 2006, 2006a, 2006b, 2007, 2007, 2011, 2011a, 2017; Mannan and Karmakar, 2006; Mannan *et al.*, 2008; Karmakar and Mannan, 2014; Karmakar and Quadir, 2014, 2014a; Karmakar *et al*., 2015; Das *et al.* 2015, 2015a; Karmakar and Alam, 2015; Karmakar and Imam, 2016; Karmakar *et al*., 2016, 2017; Das *et al*., 2017; Mannan *et al*., 2017; Karmakar and Das, 2017; Das *et al*., 2017; Karmakar and Quadir, 2017; Das *et al*., 2019; Karmakar and Das, 2020; Mohan *et al*., 2020). Even then it seems that the number of studies is not saturated; more studies are required to investigate to determine the characteristics of thunderstorms in Bangladesh. Johnson and Mapes (2001) studied the mesoscale processes and severe convective weather. In the study, they listed mesoscale preconditioning processes for severe weather such as Boundary layer processes, Terrain effects, Surface effects, Differential effects, Convergence lines and Moisture lines. These mechanisms serve to gradually destabilize the environment and modify the wind shear profile, thereby setting the stage for severe weather in most instances. However, some of these processes may actually trigger convection, if the destabilization occurs rapidly enough and thus blurring the distinction between preconditioning and triggering.

The present study is undertaken to investigate the different tropospheric conditions associated with the severe thunderstorms which formed in the conjugated atmosphere of easterly and westerly over Nepal, India and Bangladesh with great devastations.

- The scope of this study is to improve the prediction of thunderstorms and associated lightning over Bangladesh with sufficient lead time.
- For this, numerical simulation of the severe weather events, which produce heavy precipitation and lightning along with gusty wind, is important to predict the precise time, location and intensity of the

upcoming hazard & disaster so that advance warning with sufficient lead time can be issued to the people and preventive measures can be taken.

The objectives of the present study are:

- To find the places of occurrence of severe thunderstorms on 31 March 2019 and damages.
- To study the synoptic conditions and satellite images associated with the severe thunderstorms on 31 March 2019.
- To investigate the atmospheric conditions favorable for the thunderstorms 31 March 2019.
- To simulate instability indices, rainfall, CAPE, and other parameters associated with the thunderstorms on 31 March 2020 using NWP model.

2. DATA USED AND METHODOLOGY

- 3-hourly rainfall data for the months of March and April of 2019 at different stations were collected from Bangladesh Meteorological Department (BMD) and used for the analysis of rainfall amount conditions during the severe thunderstorm on 31 March 2019.
- Synoptic charts at 0000 and 1200 UTC on 31 March 2019 of BMD were used.
- Satellite images at every 3 hours of 31 March 2019 collected from BMD.
- The radiosonde data of Kolkata, Guahati and Agartala (Dhaka_missing) at 0000 and 1200 UTC on 30-31 March 2019 were collected from the University of Wyoming and were used for the computation of instability of the troposphere.
- For WRF Model, 0.25° × 0.25° gridded NCEP GFS Operational Global Analysis and Global Forecast System (GFS) data has been used as initial and Lateral Boundary Conditions (LBC) for the domain.

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	2nd order 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), SW-(Dudhia 1989)
Gravity Wave Drag	No
Land Surface Processes	Unified NOAH Land Surface Model

Table 2: Specifications of global objective analysis: Global Model (GSM)

Forecast Domain	Global
Grid size/Number Grids	0.1875 deg/1829 (equator)-6 deg./60 (Closest to the poleLX960 (TL959)
Verticl levels/Top	60/0,1hPa
Forecast Range (Initial time)	84 hours (updated with 6-hr intervals). 216 hours (updated with 12-hr intervals)
Analysis	4D-Var

3. RESULTS AND DISCUSSION

3.1 Places of thunderstorms and damage

On 31 March 2019, 28 people were killed by a tornado in Nepal (https://abcnews.go.com/International/wireStory/rainstorm-hits-south-nepal-pm-25-dead-hundreds-62081498) and 6 people were killed in Dhaka only (Disaster Forum, Dhaka Tribune, 8 September 2019). The places of thunderstorms, which occurred in Bangladesh on 31 March, 2019 are given in Table 3. The high wind speed associated with the thunderstorms damaged and uprooted many trees in the country. The damage caused by the thunderstorms at Dhaka city is given in Figure 2.

3.2 Analysis of Synoptic conditions

Investigations of synoptic charts collected from BMD indicate that (Figure 3) a series of low pressure systems formed over Uttar Pradesh, Eastern Madhya Pradesh, West Bengal and Odissa with trough extended to Bangladesh on 31 March 2019 at 0000 UTC. These are favorable for the formation of thunderstorms. A number of low pressure cells were found over Foot hills of the Himalayas, India and Bangladesh with steep pressure gradients over Bangladesh and the North Bay of Bengal at 1200 UTC on 31 March 2019. Conjugation of westerly low-pressure systems took place with easterly low pressure over (i) Eastern Madhya Pradesh and West Bengal at 0000 UTC, (ii) Nepal and Bangladesh at 1200 UTC and (iii) West Bengal and Odisha at 1200 UTC. A part of the low pressure over eastern Nepal descended from north towards south and conjugated with the easterly low-pressure system moving over Odisha towards northeast and the conjugation occurred over north Bangladesh. This low-pressure system generated a tornado over Nepal on 31 March 2019. All these conjugated low-pressure systems were found to move east/south-eastwards.

Table 3: Severe Thunderstorms at different places in Bangladesh on 31 March 2019

Date	Station	Squall/Gusty wind	Wind Speed	Direction	Time (UTC)
31.03.19	Sylhet	Squall	30 kts/56 kph	NNW'ly	1008-1012
31.03.19	PBO Dhaka	Squall	**40 kts/74 kph**	SW'ly	**1222**
31.03.19	Rajshahi	Squall	22 kts/41 kph	SW'ly	0920-0950
31.03.19	Faridpur	Squall	26 kts/48 kph	NW'ly	0900-0930
31.03.19	Cumilla	Squall	25 kts/46 kph	NE'ly	1230-1300
31.03.19	Chandpur	Squall	25 kts/46 kph	S'ly	1300-1330
31.03.19	PBO Dhaka	Gusty wind	24 kts/44 kph	SW'ly	1700
31.03.19	Chattagram	Squall	34 kts/63 kph	SW'ly	1530-1600
31.03.19	Cox'sBazer	Squall	**45 kts/83 kph**	NE'ly	**1600-1630**
31.03.19	Sylhet	Squall	30 kts/56 kph	NNW'ly	1008-1012
31.03.19	Khulna	Squall	34 kts/63 kph	NW'ly	1800-1830
31.03.19	Sayedpur	Squall	30 kts/56 kph	NW'ly	1930-2000
31.03.19	Rangpur	Squall	**40kts/74 kph**	NE'ly	**1900-1930**
31.03.19	PBO Dhaka	Squall	27 kts/50 kph	NW'ly	2335
31.03.19	Koyra	Squall	30 kts/56 kph	N'ly	2100-2130

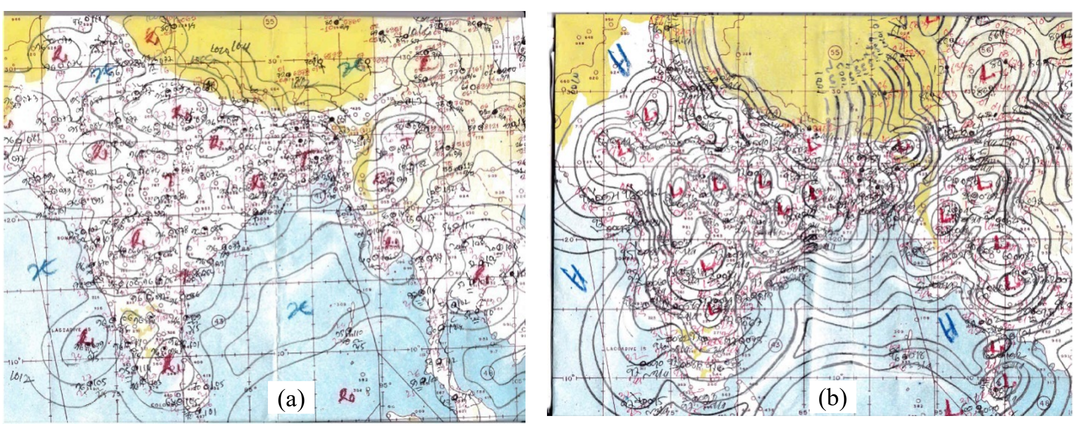


Figure 3: Synoptic conditions (a) 0000 UTC on 31 March 2019 and (b) 1200 UTC on 31 March 2019 (Source: BMD)

3.3 Analysis of Satellite imageries

A part of the cell over Nepal descended from north towards south and combined with the conjugated ones moving northeast ward from Odissa and West Bengal over Bangladesh. The systems in satellite images (Figure 4) were in agreement with the Synoptic charts at 0000 and 1200 UTC (Figure 3). Several conjugations of westerly and easterly are found to occur over India, Nepal and Bangladesh and these conjugations helped the systems to become strong systems over the region. As a result, severe thunderstorms occurred at different places with gusty winds and lightning. One westerly moving over northern India towards east-northeast was found to combine with another westerly moving over eastern Nepal towards east/southeast ward and the system was intensified to a significant cloud mass causing tornado effects over Nepal and devastated a large area. This system was found to descend southward over north Bangladesh and combined with the cells moving northeast ward over Odisha-West Bengal and a number of thunderstorms occurred over Bangladesh. An easterly flow moving over Odisha was found to combine with a westerly flow moving over eastern Madhya Pradesh and West Bengal near western Bangladesh to form an intense system, which again conjugated with the system descending from Nepal over northern Bangladesh and became a very large bright mass of cb-cloud (Figures 4d, e); besides small bright Cb cells were also found to enter/form in-situ in Bangladesh. As a result, a number of thunderstorms occurred over the country. The animation of the satellite showed interesting and unique conjugations of Cb- cells of westerly and easterly several times over India, Bangladesh and Nepal.

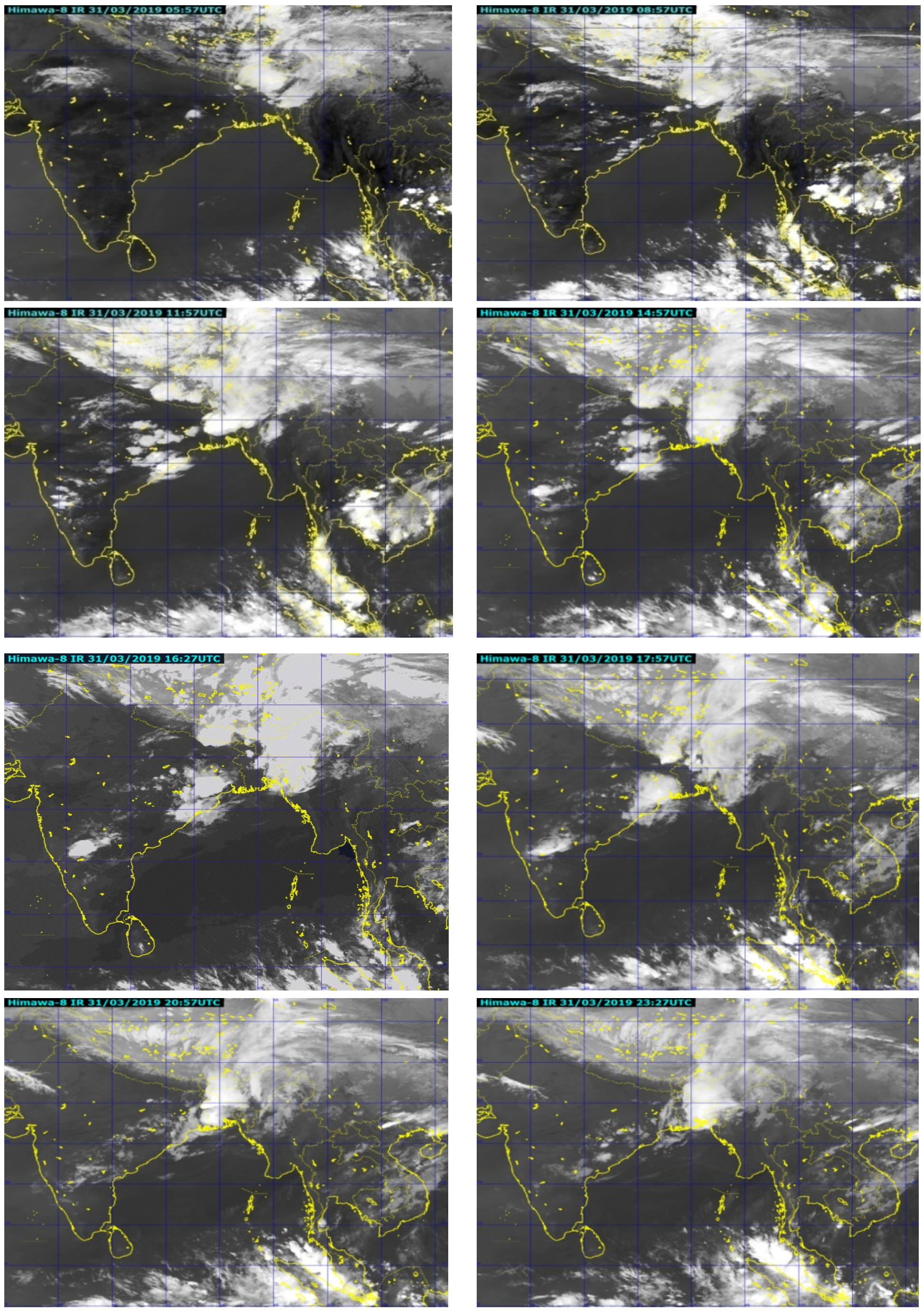


Figure 4: Satellite cloud conditions with conjugation atmosphere of westerly and easterly

3.4 Analysis of Radar imagery

Radar echo at Dhaka was not available, but that in Moulavibazar in the northeast Bangladesh was available as shown in Figure 5. The figure shows that a squall line already was passing Chittagong Hill Tracts and another one was over Meghalaya Plateau at 8:33:42 UTC. The other thunderstorms occurred after this Radar observation as given in Table 1.

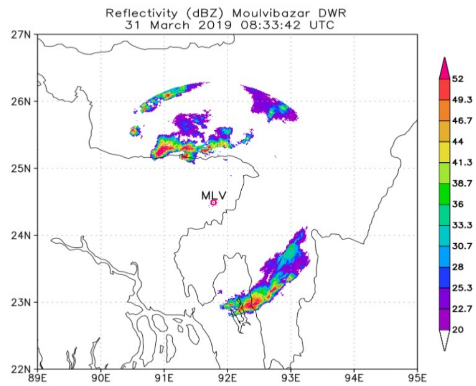


Figure 5: Radar image at 0833 UTC on 31 March 2019 at Moulavibazar

3.5 Observed Instability Indices of the troposphere on 29-31 March 2019

No thunderstorm can be formed in the stable atmosphere; it forms when there is sufficient instability in the atmosphere. The critical values of Showalter Stability Index (SI), Lifted Index (LI), Cross Total Index (CT), Vertical Total Index (VT), Total Totals Index (TT), SWEAT Index (SWI) and K-Index (KI) at 0000 UTC over Dhaka are ≤ + 3°C, ≤0°C, ≥ 16°C, ≥ 24°C, ≥ 40°C, >200 and >34°C respectively for the nor 'westers to occur in Bangladesh (Karmakar and Alam 2006). In the present study, the Instability indices such as SI, LI, CTI, VTI, TTI, CAPE, KI, SWEATI were investigated at Kolkata, Guahati and Agartala using Rawinsonde data (Table 4). Of these indices, Li, TTI, CAPE and SWEATI were found to be favorable at Kolkata and Guahati. From the analysis, it is found that satiability of the troposphere changed to unstable with the progress of time at Kolkata. CAPE at Kolkata was appreciably higher at 0000 and 1200 UTC on 31 March 2019. The values of CAPE at Kolkata both at 0000 and 1200 UTC were 2680.4 and 3039.9 J/Kg respectively on 31 March 2019 and were favorable for the formation severe thunderstorms.

Table 4: Different Instability indices

Stations and time	**LI**			SWEAT		
	29-03-2019	30-03-2019	31-03-2019	29-03-2019	30-03-2019	31-03-2019
Kolkata_00Z	-2.77	-3.74	-6.85	104.98	151.21	182.78
Kolkata_12Z	-2.97	-6.5	-9.4	174.21	230.79	124.62
Agartala_00Z	0.73	2.98	0.92	181.2	166.1	160.4
Guahati_00Z	4.59	1.28	-1.53	156.99	157.58	171
Guahati_12Z	1.9	1.42	*	161.39	189.01	*
Stations and time	**TTI**			**CAPE**		
	29-03-2019	30-03-2019	31-03-2019	29-03-2019	30-03-2019	31-03-2019
Kolkata_00Z	38.4	43.6	49.2	1554.3	1868.1	2680.4
Kolkata_12Z	43	49.8	48	1918.8	2552.2	3039.9
Agartala_00Z	40.4	41.2	45.2	220.21	59.99	81.37
Guahati_00Z	38.8	41.6	48.7	0	296.76	552.48
Guahati_12Z	38.8	45.8	*	326.97	94.05	*

3.6 Observed Precipitable Water Content on 29-31 March 2019

Atmospheric moisture plays a very important role in the formation of thunderstorms. The precipitable water is the depth of water in a column of the atmosphere and is obtained by integrating the available moisture in the atmosphere. The precipitable water content is found to be maximum over the places where local severe storms occur in Bangladesh (Karmakar and Quadir, 2014). In the case of present study, the precipitable water content of the troposphere as computed from the rawinsonde data has the tendency to increase either on 30 March or on

31 March 2019 as compared to that on 29 March 2019. Maximum precipitable water was 46.93 mm at Guahati and 42.59 at Agartala at 0000 UTC on 31 March 2019 (Table 5). During the period, there were no rawinsonde observations at Dhaka.

Table 5: Precipitable water content (mm) of the troposphere

Stations	Time in UTC	29-03-2019	30-03-2019	31-03-2019
Kolkata	0000	31.93	36.76	36.32
Kolkata	1200	38.29	42.65	34.84
Agartala	0000	28.72	37.23	42.59
Guahati	0000	25.84	40.71	46.93
Guahati	1200	36.56	39.74	*

3.7 Observed 3-hourly Rainfall Conditions on 31 March 2019

The thunderstorms, which occurred over Bangladesh due to the confluence of westerly and easterly, were associated with rainfall at different places of the country. 3 hrly rainfall on 31 March 2019 at different stations of BMD are given in Table 6 and the temporal variations at Dhaka, Sylhet and Srimangal are shown in Figure 6. The Table and the figures show that the maximum rainfall occurred during the period 1500-2100 UTC on this day. 3 hrly rainfalls were 28.4 mm at 21 UTC at Satkhira, 24.2 mm at 15 UTC at Comilla**,** 22.4 mm at 15 UTC at Srimangal, 21 mm at 15 UTC at Chandpur and 16.8mm at 15 UTC at Dhaka.

Table 6: 3hrly rainfall on 31 March 2019 at different stations of Bangladesh

Time (UTC)	Dinajpur	Rangpur	Syedpur	Ishurdi	Bogura	Chuadanga	Jessore	Khulna	Satkhira	Dhaka	Srimangal	Sylhet
0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	2.2
6	0	0	0.2	0	0	0	0	0	0	0	5.2	1
9	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	5.5	0	0	0	0	0	0	0	10.8
15	0	0	0	0	0	5.4	0	0	0	16.8	22.4	6
18	0	0	0	0	0	0	0	0	0	1.2	1.8	0
21	16	30	16	0	15	0	18	6	28.4	0	0	1.6
Time	Faridpur	Madaripur	Barisal	Bhola	Chandpur	Chittagong	Teknaf	Comilla	Feni	Hatiya	Sandwip	Sitakunda
0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0
12	4.4	0	0	0	0	0	0	0	0	0	0	0
15	1.2	8.2	2.3	12.8	21	0	0	24.2	17	0	0	7
18	0	0	0	0	3	4	0	2.6	1	6	6.8	0
21	0	5	0	0	1	0	3	0	0	0	0	0

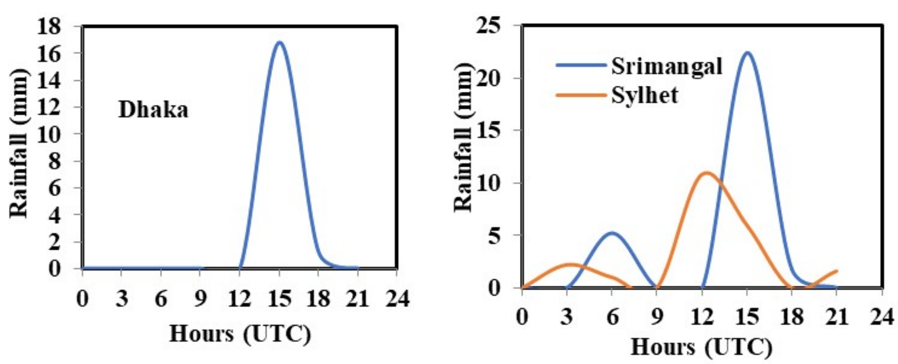


Figure 6: Temporal variation of 3-hrly rainfall over (a) Dhaka and (b) Srimangal and Sylhet.

3.8 Simulation of Meteorological Parameters of the Troposphere Associated with Severe Thunderstorms on 31 March 2019

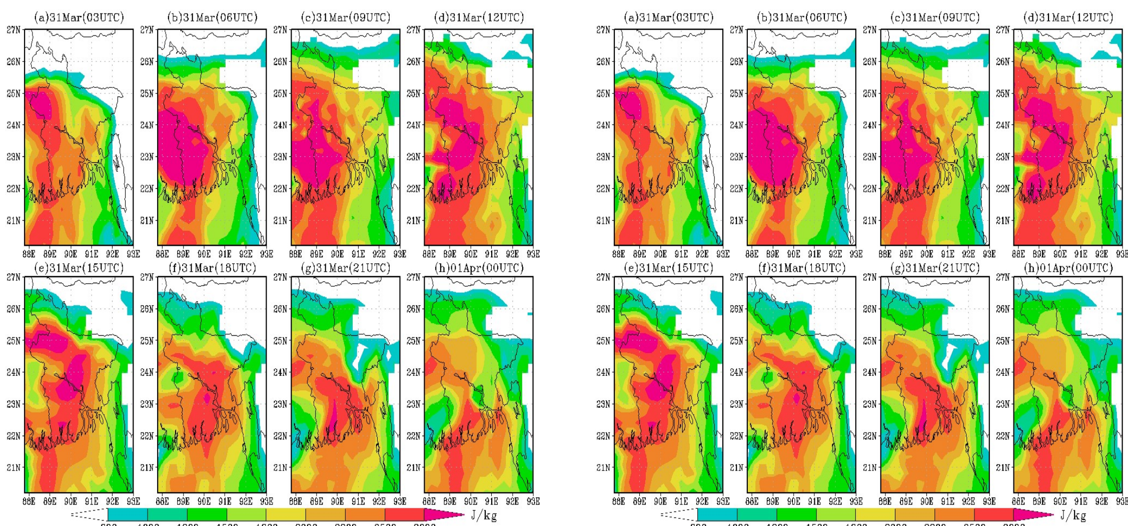
3.8.1 Simulated CAPE at different levels on 31 March 2019

If there is enough heating to produce convection, CAPE is a measure of the energy that can be realized. The greater the energy that is released during convection, the greater will be the charge separation and the more lightning is liable to occur. 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. Table 7 gives a rough guide of the likelihood of lightning when using CAPE (Franks Weather: file:///C:/Users/User/Desktop/CAPE-%20A%20Lightning%20Risk%20Index%20-%20Franks-Weather%20-%20The%20Weather%20Window.htm)

Table 7: Criteria of CAPE for Lightning Risk

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

CAPE has been simulated at 950, 925, 900 and 850 hPa and their spatial distributions over Bangladesh and adjoining areas are shown in Figures 7-8. CAPE is strong with more than 3000 J/Kg over large part of Bangladesh, West Bengal and North Bay of Bengal at 0300 UTC at 950 hPa level throughout the day (Figure 7a). At 925 hPa level, the area of CAPE>3000 J/kg is over western Bangladesh and 1200-2500 J/Kg elsewhere over the country (Figure 7b). The observed values of CAPE at Kolkata both at 0000 and 1200 UTC were 2680.4 and 3039.9 J kg^{-1} respectively on 31 March 2019 in Table 4 were comparable with the simulated values. Simulated CAPE is favorable for thunderstorms and lightning over the country. The value of CAPE indicates the severe risk of lightning potential over the country and adjoining area.



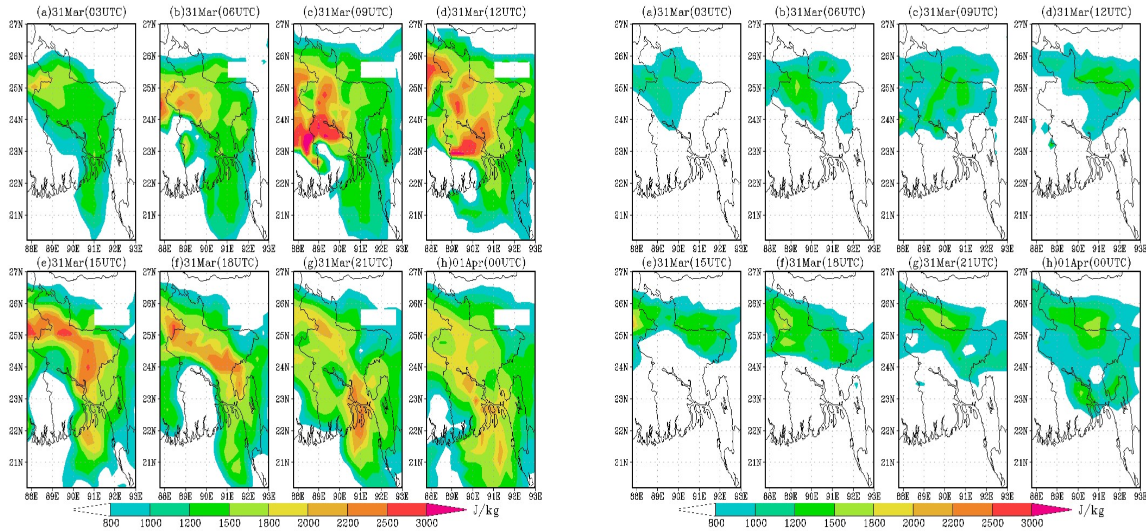
(a)950 hPa (b) 925 hPa

Figure 7: Simulated CAPE over Bangladesh at (a) 950 and (b) 925 on 31 March 2019

Figure 8a also shows that CAPE is strong with more than 3000 J/Kg over some parts of Bangladesh and north Bay of Bengal after 0300 UTC at 900 hPa level throughout the day. At 850 hPa level, the area of CAPE 1200-1500 J/Kg is over northern Bangladesh on 31 March 2019. CAPE above 850 hPa is weak meaning to say that CAPE is stronger in the lower troposphere during the formation of thunderstorms (Figure 8b).

3.8.2 Simulated Total Totals Index (TTI) on 31 March 2019

Total Totals Index (TTI) has been simulated and its distribution is given in Figure 9. It is found that the simulated TTI>55 over northern and central Bangladesh at 0300 UTC and TTI>50 elsewhere in the country except Chittagong Hill Tracts. The area of TTI>55 is reduced and become disintegrated subsequently up to 1500 UTC and again intensified and persisted up to 0000 UTC on 1 April 2019. The reduction of intensity may be due to rainfall occurrence. The TTI computed from RS data at Kolkata is 49.2 at 0000 UTC (Table 4). The simulated values are slightly over estimated as compared to computed TTI form rawinsonde data.



(a) 900 hPa (b) 850 hPa

Figure 8: Simulated CAPE over Bangladesh at (a) 900 and (b) 850 hPa levels on 31 March 2019

3.8.3 Simulated SWEAT Index on 31 March 2019

The distribution of simulated SWEAT Index on 31 March 2019 is shown in Figure 10. It is found from the figure that the SWEAT Index was very prominent with a value of about 475 at 0300 UTC over northwestern Bangladesh and was found to shift eastward as the time progresses. Intensity of SWEAT index was found to decrease from 1500 UTC. Model simulated results were indicative for severe thunderstorms occurrence but was much higher than that computed from rawinsonde data. The maximum values of simulated SWEAT Index range from 475-500, which was prominent from 0300 UTC to 1200 UTC on 31 March 2019 over northwestern Bangladesh to northeastern Bangladesh and adjoining Meghalaya Plateau.

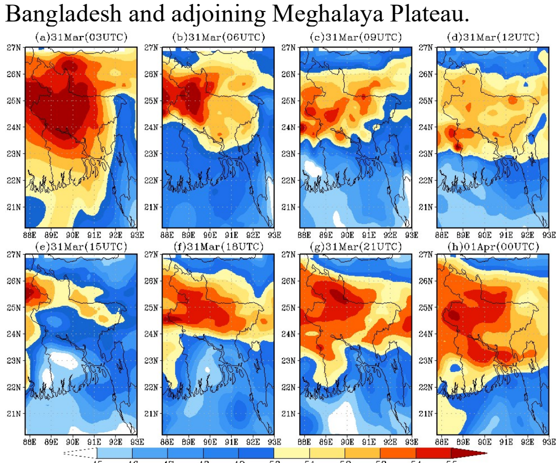


Figure 9: Simulated TTI over Bangladesh on 31 March 2019

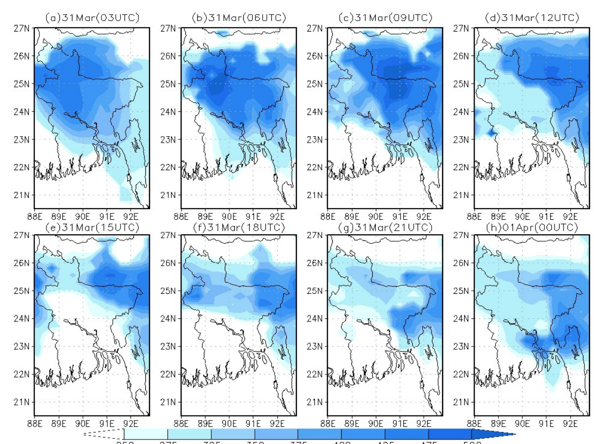


Figure 10: Distribution of simulated SWEAT Index on 31 March 2019

3.8.4 Simulated Precipitable Water (PPW) content on 31 March 201

The distribution of simulated precipitable water at different times on 31 March 2019 is shown in Figure 11. Simulated precipitable water content increases with the progress of the day over northern Bangladesh and spreads over the whole country except southwestern and southeastern parts of the country. The maximum precipitable water content was found to be 60-70mm. Rainfall was found to occur where PPW was higher i.e. in the northern and central Bangladesh.

3.8.5 Simulated wind and Vorticity at different levels on 31 March 2019

Wind and vorticity play important role in producing convective systems and are simulated at different levels. Their distributions are shown in Figures 12-14. Figure 13 shows that south/southwesterly wind is flowing from the Bay of Bengal, converging over West Bengal and adjoining Bangladesh with trough extended towards northeast throughout the day. The vorticity was positive and the value of (12-15)$\times 10^{-5}s^{-1}$ was found at the surface over northern part of the country. At 950 hPa level, the vorticity was more prominent over the northern part during 0300-0600 UTC and strong positive vorticity of about $20\times 10^{-5}s^{-1}$ was found near Dhaka and Faridpur at 0900 UTC slightly shifted eastward at 1200 UTC. This vorticity has been favorable for the formation of thunderstorms.

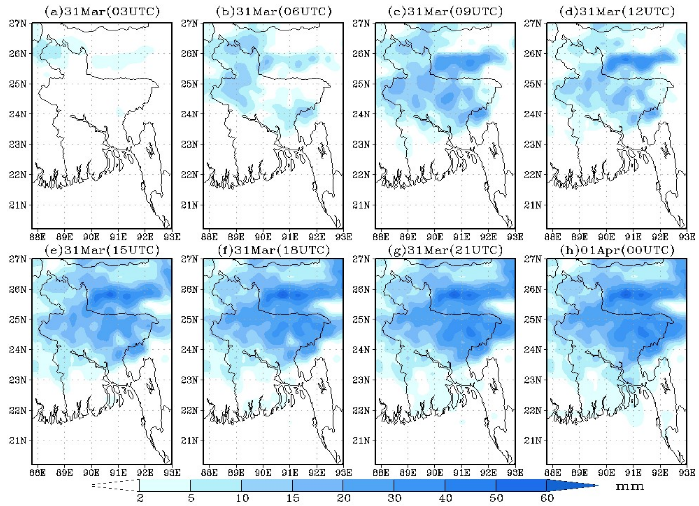


Figure 11: Distribution of simulated Precipitable Water (PPW) content on 31 March 2019

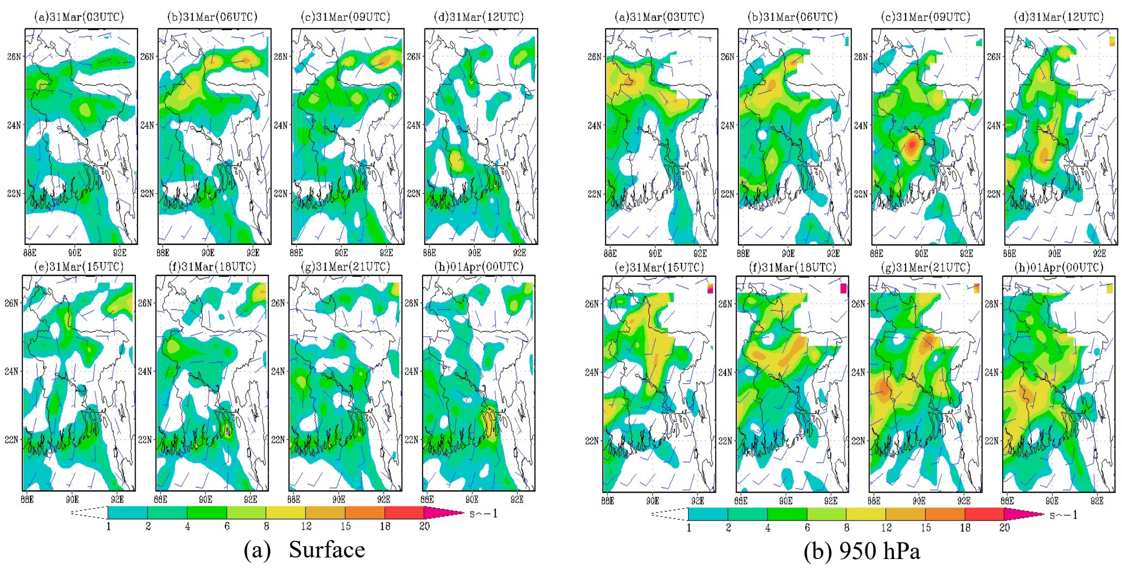
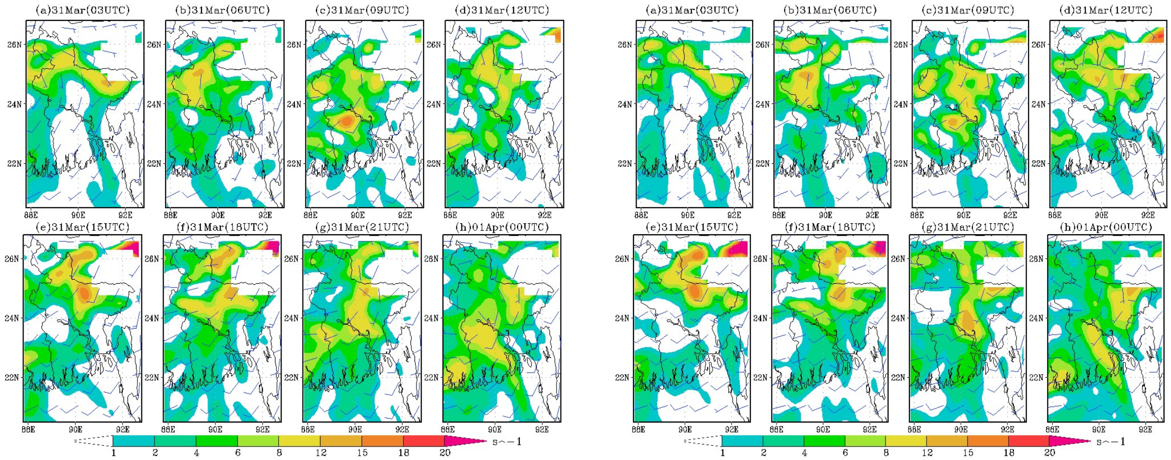


Figure 12: Distribution of simulated wind and vorticity at (a) surface and (b) 950 hPa on 31 March 2019

Figure 13 gives the distribution of wind and vorticity at 925 and 900 hPa levels on 31 March 2019. From the figure it is seen that south/southwesterly wind was flowing from the Bay of Bengal at 925 and 900 hPa, converging over West Bengal and adjoining Bangladesh with trough extended towards northeast throughout the day. The vorticity is positive and intense over northern part of Bangladesh and the higher values were spread over the country both at 925 and 900 hPa levels throughout the whole day. The values were of the order of (4-20) $\times 10^{-5}s^{-1}$ and the higher values of 20×10^{-5} s^{-1} were over Meghalaya region during 1200-1800 UTC. The higher positive values of vorticity were indicative of the favorable conditions for the formation of thunderstorms in Bangladesh.

Figure 14 shows the distribution of wind and vorticity at 850 hPa on 31 March 2019 over Bangladesh. South / southwesterly wind was flowing from the Bay of Bengal, converging over West Bengal and adjoining Bangladesh with trough extended towards northeast throughout the day. The vorticity was positive and the value of (15-20) $\times 10^{-5}s^{-1}$ was found at 850 hPa over northern /northeastern part of the country and over $20\times 10^{-5}s^{-1}$ over Meghalaya Plateau at 1200-1500 UTC on 31 March 2019.



(a) 925 hPa (b) 900 hPa

Figure 13: Distribution of simulated wind and vorticity at (a) 925 hPa and (b) 900 hPa on 31 March 2019

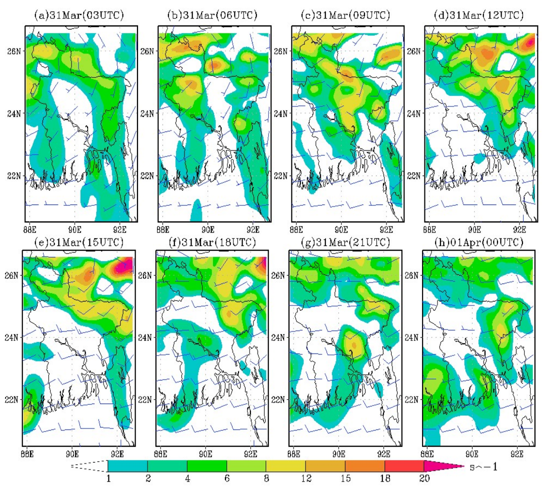


Figure 14: Distribution of simulated wind and vorticity at 850 hPa on 31 March 2019

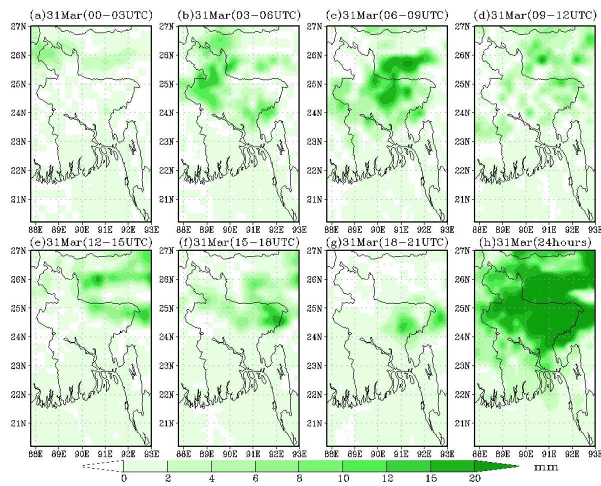


Figure 15: Distribution of simulated rainfall on 31 March 2019

3.8.6 Simulated 3hrly and 24 hrly rainfall on 31 March 2019

3 hrly and 24hrly rainfalls were simulated on 31 March 2019 over Bangladesh and their spatial distribution is given in Figure 15. Rainfall occurred slightly over extreme NW-Bangladesh during 0000-0300 UTC. Rainfall was found to increase during 0300-0600 and 0600-0800 UTC, spread over north-northeastern Bangladesh then it was reduced during subsequent hours. In 24 hours, 20-25 mm rainfall occurred over central-northern-northeastern part of the country and Meghalaya. At Dhaka and northeastern part of Bangladesh, rainfall of 24 hours is given below (Table 8). The area averaged actual rainfall for 24 hrs is found to comply with the simulated rainfall of 20-25 mm (Figure 15 h).

3.8.7 WRF Model simulated Large scale distribution of geopotential and circulation at different levels on 31 March 2019

Large scale distributions of geopotential height and wind circulation were simulated for 0000 and 1200 UTC at 950 hPa level and are shown in Figure 16 (a, b). Very strong low geopotential height and circulation were found at low level at 0000UTC on 31 March 2019 over India and Bangladesh with trough extended to eastern Bangladesh. Strong circulation of wind was found over eastern Uttar Pradesh, Bihar and adjoining Bangladesh at 0000 UTC and this was due to the strong southwesterly flow coming over the Bay of Bengal. The Low geopotential became more intense and spread over more areas over India, foot of the Himalaya, Bangladesh and Myanmar at 1200 UTC on 31 March 2019. The value of minimum geopotential was 440-460m at 950 hPa at 1200 UTC over northern and central India and western part of Bangladesh. This value of geopotential is comparable with the observed data as given in Table 9. The circulation was very prominent over northwestern

Bangladesh and adjoining India. These conditions of low geopotential and strong circulation were very favorable for the occurrence of severe thunderstorms (Karmakar and Das, 2020).

Table 8: Actual 24 hrs rainfall at some stations of BMD

Stations	24 hrs rainfall (mm)	Area averaged 24 hrs rainfall (mm)
Dhaka	18.0	
Comilla	26.8	22.4
Srimangal	29.4	
Sylhet	15.6	

Table 9: Observed geopotential height (m) at some stations near 950 hPa level

Stations	Stations Index	hPa	UTC	gpm
Kolkata	42809	951	1200	485
Agartala	42724	955	0000	474
Patna	42492	954	0000	472
Ahmedabad	42647	952	0000	503
Lucknow	42369	954		464

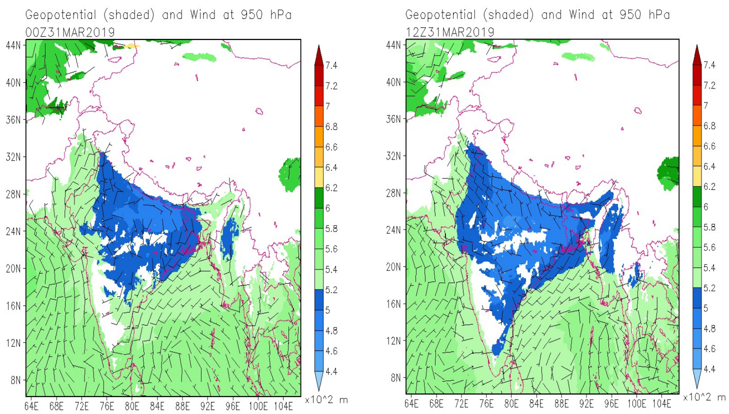


Figure 16: Distribution of simulated geopotential height at (a) 0000 UTC and (b) 1200 UTC at 950 hPa on 31 March 2019

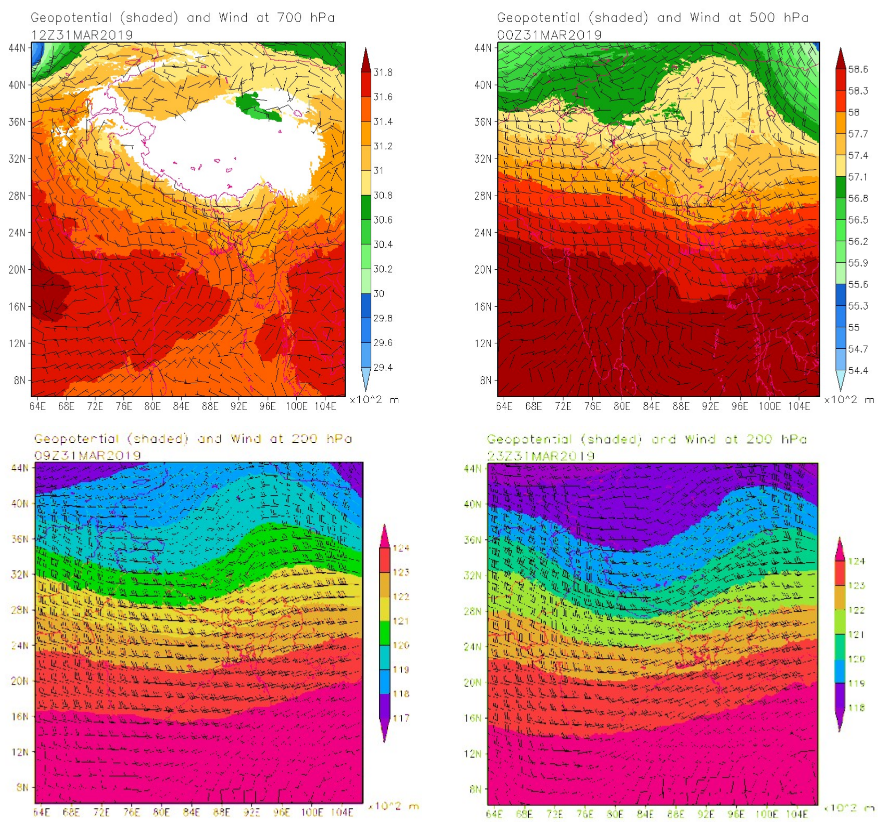


Figure 17: Large scale distribution of simulated geopotential height and circulation at (a) 1200 UTC of 700 hPa, (b) 0000 UTC of 500 hPa, (c) 0900 UTC of 200 hPa and (d) 2300 UTC of 200 hPa on 31 March 2019

At 700 hPa level strong circulation was found to persist over Bangladesh descending from the north, which was indicating that the thunderstorms that formed over Nepal and foothills of the Himalaya would descend towards Bangladesh. Strong high geopotential was found to penetrate southern India from the west (Figure 17a).

WRF Model simulated large scale distribution of geopotential and circulation at 500 hPa at 0000 UTC on 31 March 2019 is shown in Figure 17b. The trough of low geopotential height persisted over Bangladesh and adjoining area with strong west/northwesterly winds over northern India. These strong west/northwesterly winds were dry and relatively cold, which in conjugation with warm and moist southerly winds produced sufficient instability in the troposphere and favored the formation of severe thunderstorms (Karmakar and Das, 2020).

WRF Model Simulated Large scale distributions of geopotential and circulations at 200h Pa at 0900 and 2300 UTC on 31 March 2019 are shown in Figures 17(a-b). From the figures it is seen that strong trough of geopotential and westerly trough of strong wind flow existed over western Nepal extending S/SE ward towards Bangladesh. Strong westerly trough with jet stream wind speed of 35-40 ms^{-1} were found over northern India, Nepal and Bangladesh. This existence of westerly jet stream trough was favorable for severe thunderstorms (Ramaswamy,1956).

4 CONCLUSIONS

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

- On 31 March 2019, a series of low pressure systems formed over Uttar Pradesh, Eastern Madhya Pradesh, West Bengal and Odissa with trough extended to Bangladesh at 0000 UTC as well as a number of low pressure cells were found over the foothills of the Himalayas, India and Bangladesh with steep pressure gradients over Bangladesh and the North Bay of Bengal at 1200 UTC.
- Conjugation of westerly low-pressure systems with easterly low pressure took place over (i) Eastern Madhya Pradesh and West Bengal at 00 UTC, (ii) Nepal and Bangladesh at 1200 UTC and (iii) West Bengal and Odisha at 1200 UTC. A part of the low pressure over eastern Nepal descended from north towards south and conjugated with the easterly low-pressure system moving over Odisha towards northeast and the conjugation occurred over north Bangladesh. This low-pressure system generated a tornado over Nepal on 31 March 2019.
- The thunderstorms were severe formed by confluence of westerly and easterly converted into southwesterly flows over Odissa and West Bengal and another confluence of the southwesterly cells with the southward descending cells from Nepal.
- The observed synoptic conditions and instability were favorable for the formation of many cells of thunderstorms.
- The WRF model simulated CAPE and TTI were very indicative for the well-developed thunderstorms. At 925 hPa level, western Bangladesh has CAPE>3000 J/kg and CAPE of 1200-2500 J/Kg was elsewhere over the country. The CAPE values were very indicative of severe lightning over Bangladesh and adjoining area.
- All the simulated parameters and their distributions were favorable for the formation of thunderstorms.
- The WRF model simulated low level circulations and the westerly geopotential trough and upper level strong trough of westerly winds were very important decisive in case of 24 and 48 hrs forecast.

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