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SIMULATION OF DYNAMICAL FEATURES OF SQUALLS OVER BANGLADESH DURING THE PRE-MONSOON SEASON

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ABSTRACT

The pre-monsoon (March through May) thunderstorms produce surface wind squalls, lightning, thunder, hail-storms, heavy rain showers, flash flood, dust storms, and downbursts. Tornado cells are sometimes embedded in the mother thunder cloud. These mesoscale convective systems (MCSs) are locally called "Nor'westers" or "Kalbaishakhi" in Bengali. Improving the simulation of Nor'westers is important as such events routinely result in strong gusty wind, hails, rain, flash flood and significant loss of lives and properties over Bangladesh, east and northeastern Indian region and the neighborhood. Performance of the mesoscale models is sensitive to the quality of initial conditions. The present study deals with the improvement of numerical simulation of squall events during pre-monsoon season with improved initial condition through mesoscale numerical simulation. Weather Research and Forecasting (WRF) model along with Advanced Research WRF (ARW) dynamical core is used to improve the simulation of these intense events. Pre-monsoon squalls and tornado are studied by employing observations from satellite based estimates - Tropical Rainfall Measuring Mission (TRMM) and synoptic stations. Subsequently, an attempt is also made to simulate the storms using WRF model at 4 km horizontal resolution with 40 vertical levels. Attempts have been made to carry out detailed study on the observed characteristics of squalls using precipitation distributions obtained from ground based weather radar and precipitation retrieved from TRMM. Subsequently, the squalls have been simulated using the WRF model and their microphysical and dynamical characteristics are determined. The purpose of the study is to diagnose the physical and dynamical characteristics of squalls associated Nor'westers over Bangladesh.

Keywords: Squalls; Mesoscale; Nor'westers; WRF ARW.

INTRODUCTION

The squall is a Mesoscale Convective System (MCS). A MCS is defined as a cloud system that occurs in connection with an ensemble of thunderstorms and produces a contiguous precipitation area ~100 km in horizontal scale in at least one direction. MCSs can occur worldwide and year-round taking different sizes and shapes (Houze 2004, 2014). The largest systems can extend ~500 km in a horizontal direction and persist for ~20 hours. In general,

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these systems are too small to be captured by the routine upper-air sounding network, but too large to be represented by point observations. It is a significant problem to modelers since the systems require models with a domain of several hundred kilometers, yet fine enough resolution to simulate individual thunderstorm elements properly. MCSs also produce a broad range of severe convective weather events: squalls, gust, hail, tornadoes, lightning, and flooding (Houze, 1975, 1997; Houze *et al.*, 2017; Kumar *et al*., 2014, Rasmussen and Houze, 2012; Sikka and Rao, 2008; Virts and Houze, 2016).

Severe thunderstorms/ Squalls are the MCSs which frequently observed in Bangladesh during the pre-monsoon season. The Squalls develop mainly due to merging of cold and dry northwesterly winds aloft and southerly low level warm and moist winds coming from the Bay of Bengal (BoB) (Das, 2010; Das *et al.*, 2014, 2015a,b; Medina *et al.*, 2010). Strong heating of landmass during mid-day initiates convection over Chota Nagpur plateau (Jharkhand in India), which moves towards southeast (West Bengal and Bangladesh area) and gets intensified by mixing with the low level warm moist air mass from the BoB (Das, 2010; Yamane *et al.*, 2009 a, b). The southerly Low Level Jet (LLJ) from the BoB is very frequent during the pre-monsoon period due to the thermal low produced over land. The LLJ gets established in east of the thermal low (IMD, 1944; Koteswaram and Srinivassan, 1958; Srinivasan *et al*., 1973). The zone of wind discontinuity that forms due to these wind flow regime and the heat low acts as a triggering mechanism for the generation of local severe thunderstorms (Srinivasan *et al*., 1973; Science Plan, 2005). On many occasions, there is an outburst of squalls when a passing westerly trough at 500 hPa is superimposed over the LLJ. The thunderstorms may also originate *in situ* in Bangladesh or regenerate from the downstream propagation of the storms originated over the Sub-Himalayan West Bengal, Sikkim, Assam valley and the plateau of the Meghalaya (IMD, 1944). Usually, these thunderstorms have the spatial extent of a few kilometers and life span less than an hour. However, multi-cell thunderstorms developed due to organized intense convection may have a life span of several hours and may travel over a few hundred kilometers (Islam *et al*., 2005). These thunderstorms reach severity when continental air meets warm moist air from ocean. Squalls are typical mesoscale systems dominated by intense convection. The understanding and prediction of these weather events are, therefore, the challenges to the atmospheric scientists. However, it is essential to know the typical cloud top altitudes of the squalls, the typical altitude and intensity of core precipitation, the typical speeds of movement and length of squall lines, the typical magnitudes of updrafts and downdrafts, the typical structures of hydrometeor profiles inside these squalls over Bangladesh and adjoining region.

In this study, attempts are made to carry out detailed study on the observed characteristics of squalls using precipitation distributions obtained from ground based weather radar and the Tropical Rainfall Measuring Mission (TRMM). Subsequently, the squalls have been simulated using the Weather Research and Forecasting (WRF) model and their microphysical and dynamical characteristics are determined. The main objective of this study is to determine the usefulness of high resolution Advance Research WRF (ARW) model to determine physical and dynamical characteristics for the simulation of MCS associated with squalls over Bangladesh.

OBSERVED PHYSICAL CHARACTERISTICS OF THE NOR' WESTERS UNDER STUDY

Dates and Places of Squalls along with Wind Speeds and Rainfall

The 4 squall events were selected for further investigation based on surface synoptic observations. The list of the events is presented in Table 1.

Table 1: Selected Nor'wester events

Date	Reported Stations	Reported Time (UTC)	Wind Speed (m s^{-1})	Wind dir.	Rainfall 24h (mm)
03-05-2012	Khulna	1420	18.00	NW	3.60
17-05-2012	Sylhet	0300-0330	17.49	SW	16.00
	Faridpur	1200	19.03	NW	18.90
22-03-2013	Brahmanbaria	1055-1110	F2 Tornado	NE	31.50
01-05-2014	Rajshahi	1600-1630	25.72	NW	33.40
	Sylhet	1930	18.52	SW	7.00

Upper Air Observations and Instability of the Troposphere

Atmospheric instability is one of the major factors for convection to develop and can be assessed by examining various thermodynamic indices. Previous studies demonstrated the efficiency of different stability indices, such as CAPE, Lifted Index (LI) and K Index (KI) for thunderstorm initiation/prediction (Anthes, 1977; Schultz, 1989). Miller (1972) introduced the Total Totals Index (TTI) for identifying areas of potential thunderstorm development.

Table 2: Observed instability indices for all squall events

Date of occurrence	RS Station	Time (UTC)	CAPE	LI	KI	TTI	SWEAT
03-05-2012	Dhaka	0000	893.5	-3.25	23.50	41.80	167.1
	Kolkata	0000	2976	-7.67	33.70	53.00	302.4
17-05-2012	Dhaka	0000	2460	-6.92	33.80	48.10	407.3
	Kolkata	0000	3338	-10.3	27.90	48.00	119.8
22-03-2013	Dhaka	0000	1690	-6.07	41.20	54.20	284.7
	Kolkata	0000	2656	-5.28	29.50	45.00	297.4
01-05-2014	Dhaka	1200	4813	-10.0	33.10	52.20	321.2
	Kolkata	0000	1939	-6.54	33.9	50.40	157.4

The physical meaning of the indices is explained in previous works (e.g., Yamane *et al*., 2010). The critical values of the indices are studied by Karmakar (2005), Karmakar *et al*. (2017) and Tyagi *et al.* (2011) in this region. CAPE is the positive buoyancy, which measures the instability of the atmosphere. LI is also a measure of the instability of the atmosphere. It is calculated when the air parcel is adiabatically lifted to 500 hPa pressure level by taking the temperature difference between the air parcel and environment at that level. It could be positive (negative) when the atmosphere is stable (unstable). CAPE, LI, KI and TTI were calculated on the day where squalls occurred at selected stations namely, Kolkata and Dhakaon squall days (Table 2). It turns out that most of the stations reported thunderstorms when the CAPE was greater than 850 J kg^{-1}. It is clearly observed that LI has negative values on all the squall days, ranging from -3.25 to -10.3, which indicate sufficient instability in and around Bangladesh. The K-index ranges mostly between 23.5 and 41.20 and TTI is found to range between 41.8 and 54.20 mostly. The SWEAT index ranges between 119.8 and 407.3 on the dates of occurrence of Squalls over Dhaka or at some Indian stations. These values of SWEAT Index indicate severe instability of the atmosphere. It was documented that 88% of Squalls occurred in Bangladesh when the TTI values range from 40 to 58 (Karmakar and Alam, 2005, 2006). The results given in the Table 2 are in compliance with the previous results of the difference studies.

Common Synoptic Features

A trough of low persisted over the north BoB. There were strong southerly and southwesterly wind flows from the BoB in the lower levels over the region of squall events.The upper air cyclonic circulation was over north Chhattisgarh, Assam and nearby regions in lower levels. A north-south oriented trough persisted from Sub-Himalayan West Bengal (SHWB) to the North BoBin the middle of the troposphere.Trough in mid-troposphere is found from Arunachal Pradesh to the North BoB. Sub-tropical westerly jet maxima were found over the region.

SATELLITE DERIVED CLOUD TOP TEMPERATURE (CTT)

Squalls and gusty events were reported at many stations over Bangladesh on the dates of occurrence of squalls under study. All these squall events were accompanied by rain (24 hours accumulated) as recorded at many stations of Bangladesh Meteorological Department (BMD) (Table 1). Monitoring of the four events is done by using half-hourly Kalpana-1 imageries (Fig. 1).

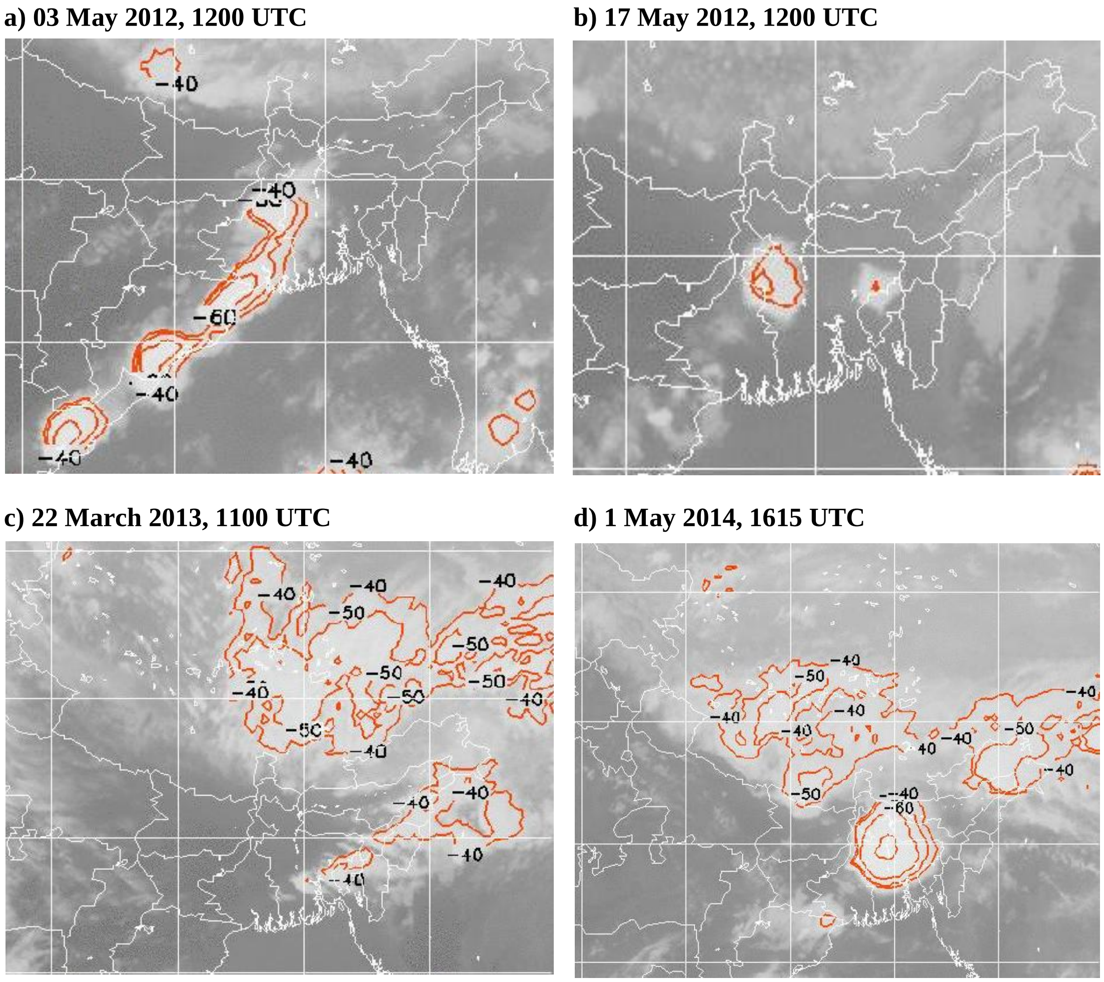

Fig. 1: Kalpana-1 satellite derived cloud top temperature (°C) imageries (a-d) of squall events.

Moderate (CTT < -30 °C) to strong convection (CTT < -60 °C) was seen over the region where squalls reported. All the systems are merging of several cloud convections which intensified continuously and propagated towards Bangladesh region. Comparing the CTT of the convective cloud clusters, the convection over the Brahmanbaria tornado site had minimum CTT of -20 °C at 0800 UTC, -30 °C at 0900 UTC and -40 °C to -50 °C during 1110-1200 UTC (Fig. 1 c). The CTT decreased thereafter and the convection became insignificant at 1800 UTC.

TRMM RETRIEVED PRECIPITATION

The TRMM is a joint mission between National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA) designed to measure rainfall for weather and climate research. The TRMM satellite provides unique measurements of horizontal and vertical profiles of precipitation. Study of TRMM Lightning Imaging Sensor data reveals that Sunamganj in Bangladesh is the place of the highest lightning (24.35 Flash km^{-2} $year^{-1}$) in the world during March-May.

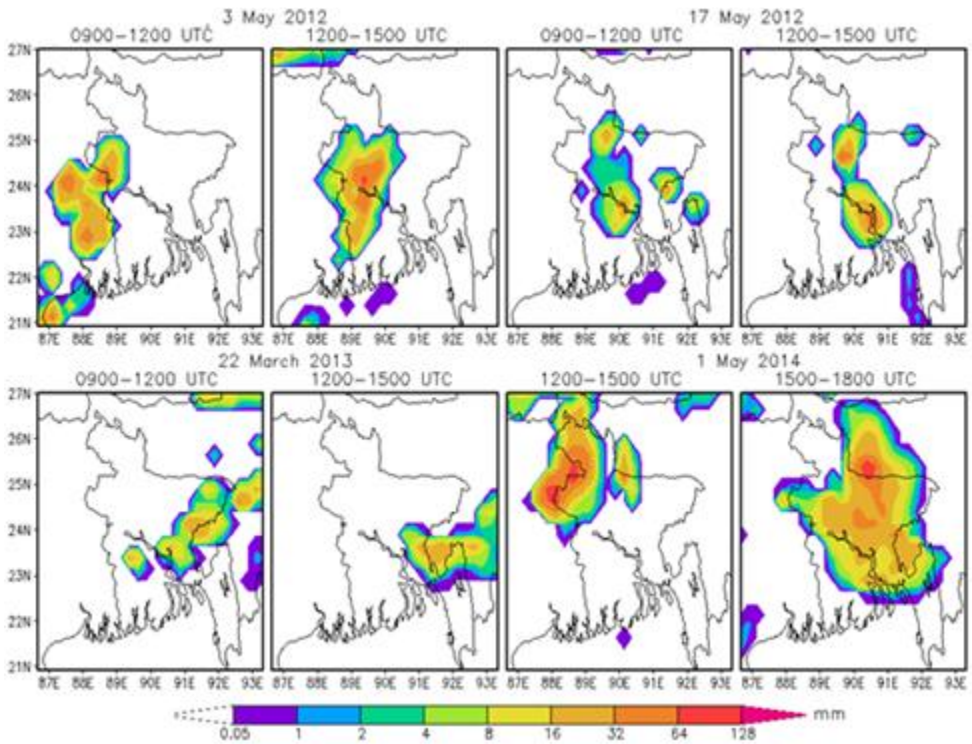

Fig. 2: Accumulated 3 hourly rainfall retrieved from TRMM.

The TRMM carries Precipitation Radar (PR) and a Microwave Imager that measures the outgoing microwave radiation at different frequencies (Simpson *et al.,* 1996). The PR has a data swath of 247 km and TRMM Microwave Imager (TMI) 780 km. The PR and TMI data together provide a unique measure of synoptic-scale rainfall. The instantaneous spatial distribution of rain intensities is designated as 3B42RT in the TRMM products. TRMM 3B42RT is a product of Experimental TRMM Real-Time Multi-Satellite Precipitation Analysis (TMPA-RT). 3B42RT provides gridded estimates in a 0.25 ° x 0.25° spatial resolution in a global belt extending from 50° South to 50° North latitude. The temporal resolution of the product is 3-hourly. It is providing important information about the size and frequency of occurrence of storms in the study region. The spatial distribution of rain intensities are retrieved from 3B42RT for all the squall events over Bangladesh that occurred between March to May of 2008 to 2014 (Fig. 2). For each event, three hourly two time steps rainfall events are presented in the Fig. 2. From the Fig. 2, it is observed that all four events persisted more than six hours from their initiation to dissipation stage. The events covered almost whole Bangladesh. It is seen that the TRMM rainfall is maximum over West Bengal and adjoining western Bangladesh at 0900-1200 UTC on 3 May 2012 and the rainfall area is shifted and enlarged over western Bangladesh at 1200-1500 UTC, having maximum rainfall of 64-128 mm per 3 hour. On 17 May 2012, the Nor'wester started over Dhaka-Faridpur-Tangail-Bogra region at 0900-1200 UTC and the area is shifted a little eastward Dhaka-Mymensingh area, having maximum rainfall of 32-64 mm per 3 hour. On 22 March 2013, the TRMM rainfall is found over Faridpur-Comilla-Srimangal-Sylhet at 0900-1200 UTC with amount of 32-64 mm per 3 hour and the area is shifted eastward during 1200-1500 UTC. On 1 May 2014, the Nor'wester formed over Rajshahi-Dinajpur-Rangpur-Bogra region at 0900-1200 UTC and is shifted eastward and spread over whole Bangladesh at 1200-1500 UTC with maximum rainfall of 32-128 mm per 3 hour.

WRF MODEL AND EXPERIMENTAL SETUP

Experimental Design and Study Domain

The numerical model used in this study is the Advanced Research Weather Research and Forecasting model (ARW), version 3.7.1 (Skamarock *et al.*, 2008; NCAR 2009), which is a three-dimensional, fully compressible, non-hydrostatic Cloud Resolving Model (CRM). The vertical coordinate is a terrain-following hydrostatic pressure coordinate and the model uses the Runge–Kutta third-order integration scheme.

A single domain with 4 km horizontal spatial resolution is configured (Fig. 3), which is reasonable in capturing the mesoscale cloud clusters. Data from the NCEP 6 h Final (FNL) Operational Global Analysis data at 1.0° × 1.0° grids were used as initial and Lateral Boundary Conditions (LBC) for the domain. Main features of the model employed for this study are summarized in Table 3. This combination of parameterizations has been used in the present study. In the present simulation, the model was integrated for a period of 24 h, starting at 0000 UTC of the occurrence day, as initial values.

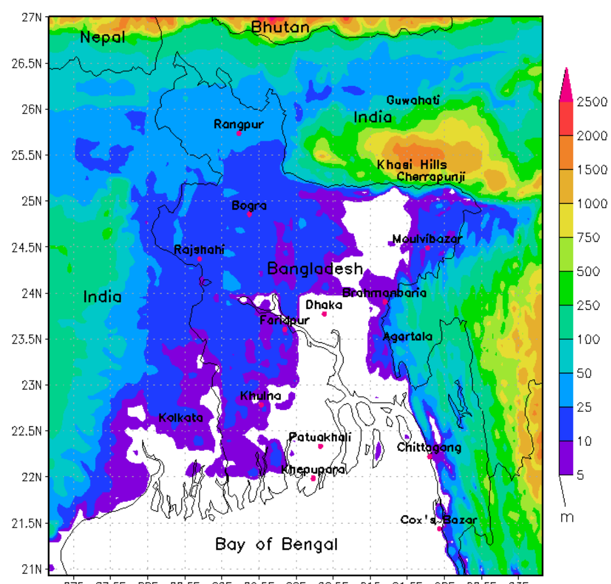

Fig. 3: WRF model domain used for simulations and topography (shaded).

Table 3: WRF model configurations

Model Features	Configurations
Horizontal Resolution	4 km
Vertical Levels	40
Topography	USGS
Dynamics	
Time Integration	Semi Implicit
Time Steps	20 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 (KF)
PBL	Yonsei University (YSU)
Cloud Microphysics	WRF single-moment 6-class (WSM6) (Hong and Lim 2006)
Surface Layer	Monin-Obukhov
Radiation	RRTM (LW) Dudhia (SW)
Gravity Wave Drag	No
Land Surface Processes	Unified NOAH Land Surface Model

SIMULATED DIAGNOSTICS

In this section, certain diagnostics of the thunderstorm squalls simulated by the model are presented. The structure of the squalls has been obtained by the model, and compared with available observations from TRMM and meteorological observations are diagnosed. Though it is not possible to measure all the cloud microphysical and dynamical characteristics such as the updrafts, downdrafts, and the hydrometeor species, etc. through instruments, attempt is made to study and verify at least some of them.

24 Hours Accumulated Precipitation

Precipitations were simulated by the model for all the observed events presented in Fig. 4. The model did simulate the 24 hours precipitation on all the days of the events. The rainfall obtained from the model simulations is compared with TRMM-3B42RT precipitation data (Fig. 2).

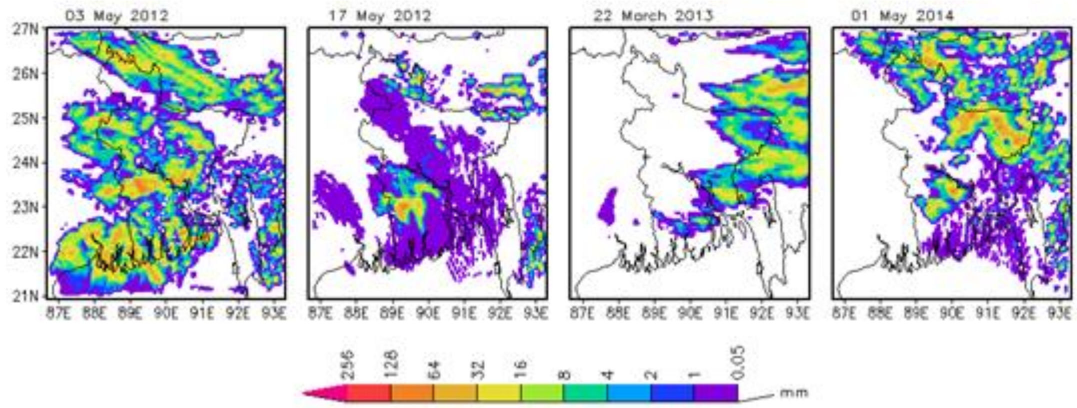

Fig. 4: 24 hours accumulated precipitation (mm) simulated by the WRF model.

The model shifted the areas of precipitation both in time and locations. But the intensities of the precipitation rates are simulated very well. From the spatial pattern of rainfall, it can be clearly seen that, the rainfall amount well captured for the all events (Fig. 4). The easterly low pressure was active and sub-tropical high in the BoB was weak that caused rainfall in the Himalayan region in India.The simulated maximum precipitation for the all the cases is of the order of 64-128 mm. On 3 May 2012, thunderstorms with rainfall occurred in most places of Bangladesh. On 17 May 2012, higher simulated rainfall is found in the Jessore-Kushtia region whereas higher rainfall is found over Chandpur-Comilla region on 22 March 2015. On 1 May 2014, maximum simulated rainfall is over north-northeast region of Bangladesh.

Cloud Water Mixing Ratio

The vertical profiles of simulated total cloud hydrometeors (Liquid Water + Snow + Ice) obtained by the WRF model on the days of Squalls are shown in Fig. 5. The values are converted to mg m^{-3} from kg kg^{-1}. The profiles of cloud hydrometeors are drawn across the regions of where squalls are reported.The figure shows the cloud water mixing ratio is found from 0000 UTC to 1500 UTC over Khulna on 3 May 2012; initially the cloud water mixing ratio is found at around 950-850 hPa and then the mixing is shifted between 900 and 500 hPa over Khulna, the values range between 5-800 mg m^{-3}. On 17 May 2012, the cloud water mixing is at 0000-0600 UTC between 950 and 850 hPa, having maximum value of 100 mg m^{-3} and the secondary mixing is at about 0900 to 1200 UTC in the level of 800-200 hPa with less value of 5-1600 mg m^{-3}. On 22 March 2013, maximum concentrations of the hydrometeors are present at around 975 to 250 hPa over Brahmmanbaria having maximum value of 1200 mg m^{-3} at 1000 to 1100 UTC. On 1 May 2014, simulated hydrometeors is found to concentrate between 800-250 hPa at 0900-1600 UTC, having maximum cloud water mixing ratio of 5-200 mg m^{-3}. The results are comparable with the results obtained by Das *et al*. (2015a-d).

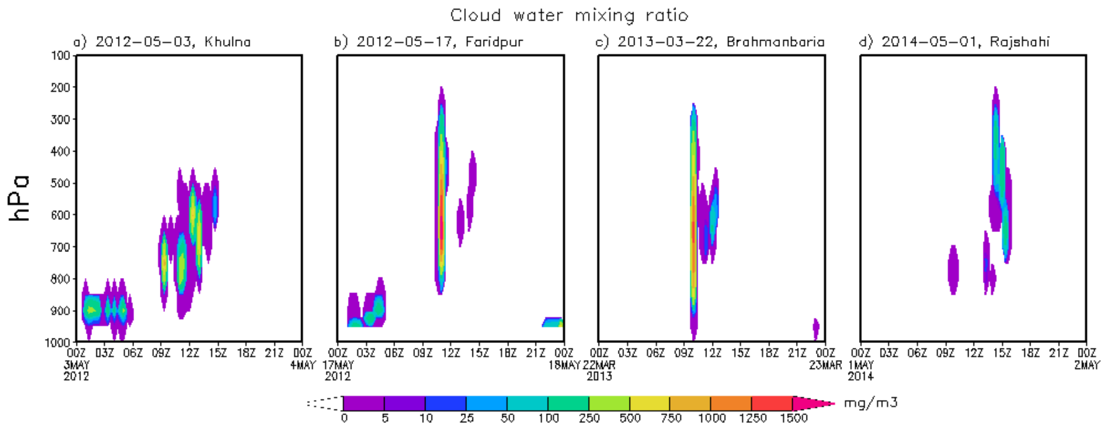

Fig. 5: Time-pressure cross section of cloud water mixing ratio (mg m^{-3}) on the days of the squalls.

Rainwater Mixing Ratio

Fig. 6 illustrates the vertical profiles of rainwater mixing ratio obtained by the WRF model on the days of squalls. The values are converted to mm h^{-1} from kg kg^{-1}. Rain water assuming a saturated environment, the amount of rainwater within a column is a function of the fall speed of the droplets. Basically, the faster the fall speed, the lower the rainwater mixing ratio will be since the rain water leaves the column more rapidly.

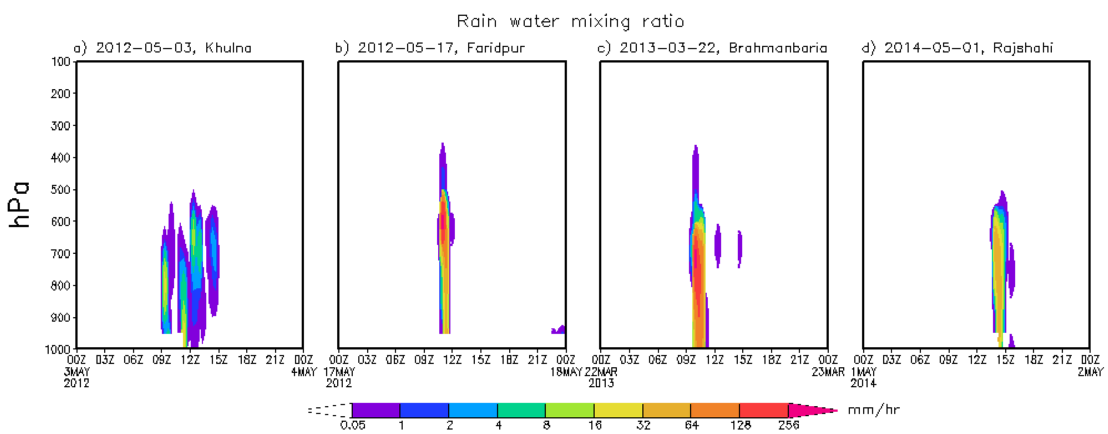

Fig. 6: Time-pressure cross section of rainwater mixing ratio (mm h^{-1}).

The simulated profiles indicate that the core of maximum precipitation ranges from lower level to about 500 to 350 hPa in all the cases with some variations, having the maximum value of 24 mm h^{-1}, 300 mm h^{-1}, 270 mm h^{-1} and 55 mm h^{-1} for Khulna, Faridpur, Brahmanbaria and Rajshahi respectively (Fig. 6a-d). The maximum value of rainwater mixing ratio at Faridpur may be due to the existence of water bodies (rivers) which supply sufficient moisture.

Time Pressure Cross Section of Vertical Velocity

Fig. 7 depicts the vertical profiles of the vertical velocity (m s^{-1}) simulated by the model for the all squall events. The cross sections in x-z plane are taken along the location of squall reported as earlier. The diagram shows cores of upward motion reaching above 150 hPa sometimes. The magnitudes of the maximum updrafts are about 24 m s^{-1} or more at Brahmanbaria for the event on 22 March 2013 which is similar to the values obtained by Das *et al*., (2006a, b and 2015a, d) for the West Bengal and Bangladesh region. The updraft cores are generally surrounded by mesoscale downdrafts with values ranging from -0.5 to -2 m s^{-1}.

The cores of updrafts are the regions where the maximum cloud hydrometeor contents are located (Fig. 4). There are also indications of possible thunderstorm at least 3 to 6 hours before the squall events. The updraft and downdraft cores of vertical profile of the all events are closer to the time of squall report. For the Brahmanbaria tornado, the updraft is >24 m s^{-1} and downdraft is < 2 m s^{-1}. On 3 May 2012, the vertical velocity ranges -1 to 3 m s^{-1} and on 1 May 2014, the value is -2 to 3.5 m s^{-1}. The event of 17 May 2012 showed strong vertical updraft (>16 m s^{-1}) and downdraft (<2 m s^{-1}) at 1200 UTC which is very closer to the reported time of squall event over the location of Faridpur.

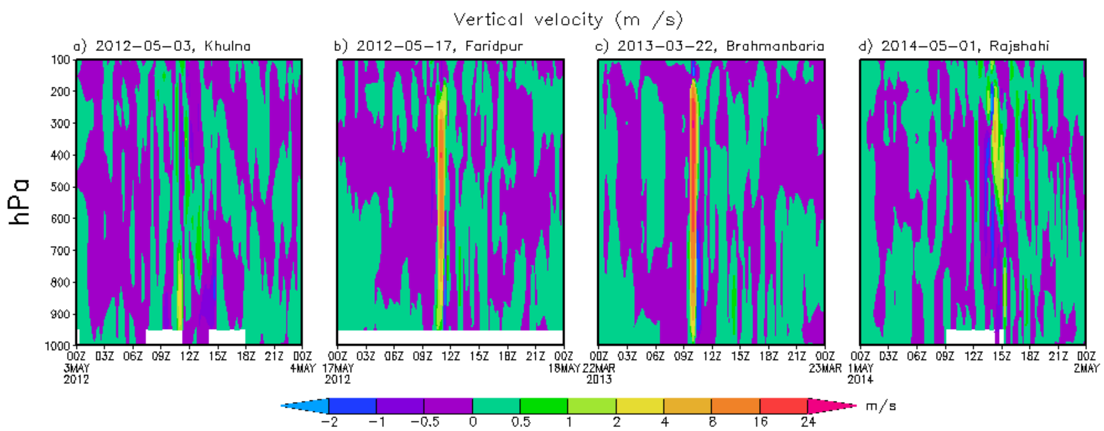

Fig. 7: Time-pressure cross section of vertical velocity (m s^{-1}) on the days of the squalls.

Wind Flow Pattern at 950 and 500 hPa

The low level simulated wind field at 950 hPa is shown in Fig. 8 for all the events of squalls. The diagrams show that in almost all the events the low level wind flow is strong southerly (10-15 m s^{-1}) from the BoB. The southerly flow fuels the moisture in the lower levels. A circulation over Jharkhand and adjacent Bihar is consistent with the observed. Convergence aided by cyclonic circulation in the lower levels is one of the important factors for providing the initial impulse for the growth of a prominent cumulonimbus (Cb) cell and its subsequent development into a squall over the study domain. The feature is consistent with surrounding radiosonde/rawinsonde observation stations. The stronger south-southwesterly winds help provide moisture convergence over the domain which is a necessary condition to help trigger convective activity.

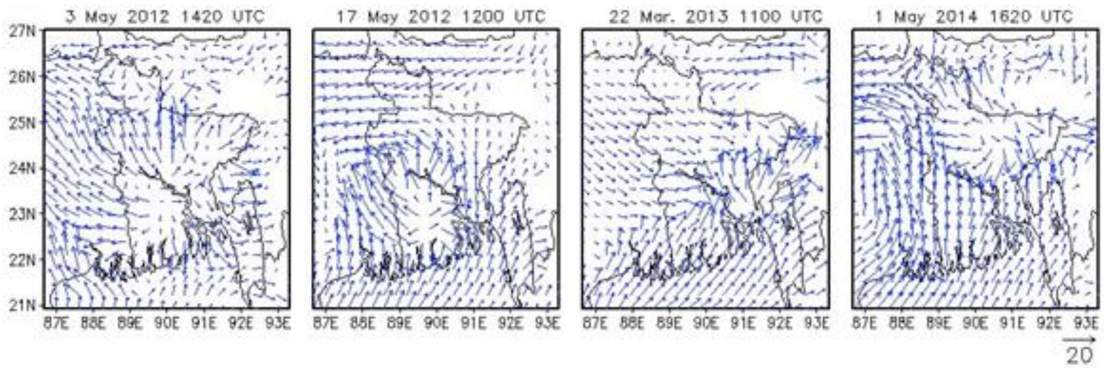

Fig. 8: Model simulated vector wind at 950 hPa.

At 500 hPa level, there was westerly trough along north-south direction over near Nepal, Sub-Himalaya West Bengal and northern part of Bangladesh which then intensified and an individual wind convergence zone formed over northeast angle of BoB and adjoining Bangladesh coast. At 500 hPa level (Fig. 9), the flow was usually westerly to northwesterly over Bangladesh, which brought cold dry air over the region. The warm moist air in the lower level coupled with cold dry air in the upper level and a heated land mass were favorable for the generation of convective instability and triggering severe thunderstorms. Location specific chaotic circulation simulated by model for the events 3 May 2012, 17 May 2012 and 1 May 2014. 22 March 2013 event showed very strong wind over Brahmanbaria and nearby region (Fig. 9).

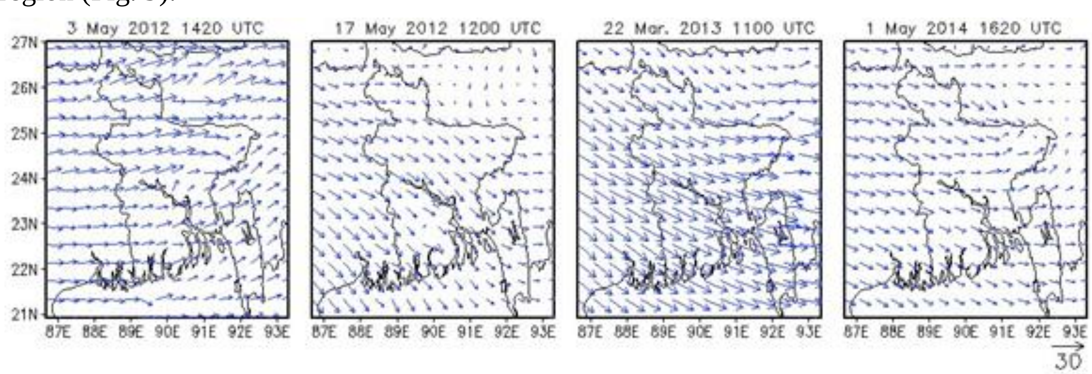

Fig. 9: Model simulated vector wind at 500 hPa.

Convective Available Potential Energy (CAPE)

Fig. 10 depicts the distribution of CAPE as simulated by the model. High CAPE values greater than 3000 J kg^{-1} are present over the head BoB and adjoining Bangladesh on most of the days. Values greater than 4500 J kg^{-1} are also noticed on some of the days (Fig. 10), particularly during severe Nor'wester. The CINE values (Fig. not shown for brevity) were very less (< 100 J Kg^{-1}) on most of the days. The combination of high CAPE and low CINE is very conducive for triggering thunderstorms. Such distributions of CAPE and CINE values were also found during the Pilot experiments on thunderstorms conducted over India, i.e., Mohanty *et al.* (2007) and Prasad (2006).

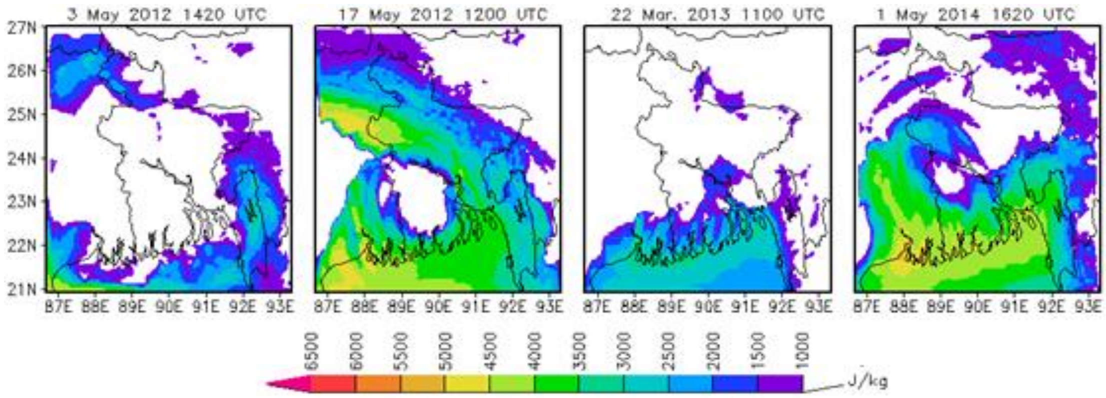

Fig. 10: Model simulated Convective Available Potential Energy (CAPE).

Temperature and Geopotential Heights of 850 hPa

Fig. 11 illustrates the temperature and geopotential heights of 850 hPa. The diagram shows that pockets of warm temperature (> 297 K) are extending to Bangladesh. The contours of geopotential cut across the isotherms forming cross isothermal flow over the region. This results in solenoidal field and warm advection over Bangladesh. Similar solenoidal field is also observed at 300 hPa (Fig. not shown for brevity), where cold air advection from north takes place over the region. Such solenoidal field is conducive for the formation of thunderstorms and was also noted in the studies of Prasad (2006) and Das *et al*., (2015b, d).

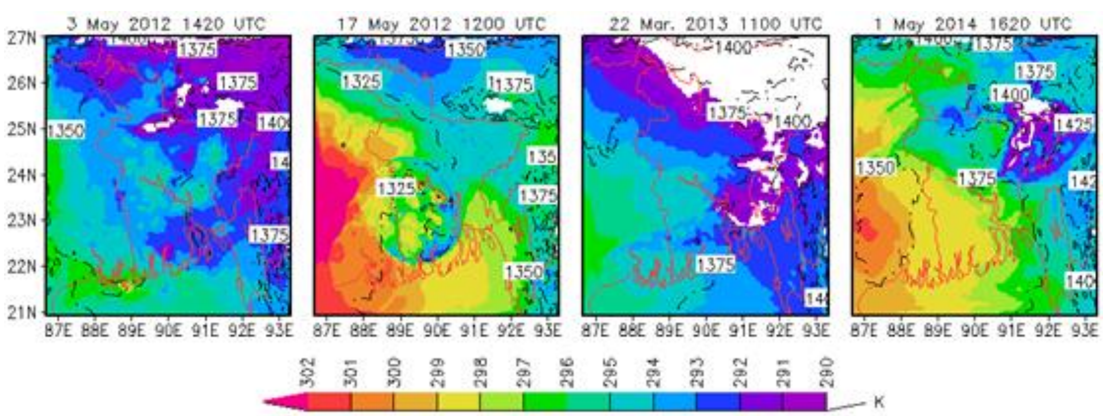

Fig. 11: Model simulated temperature (shaded) and geopotential meter (gpm) at 850 hPa.

Vorticity at 850 hPa

The vorticity field at 850 hPa is depicted in Fig. 12. Positive values of vorticity are shaded in the Fig. 12. The vorticity is positive (> 1.0×10^{-5} s^{-1}) in the lower level over Bangladesh and adjoining area.

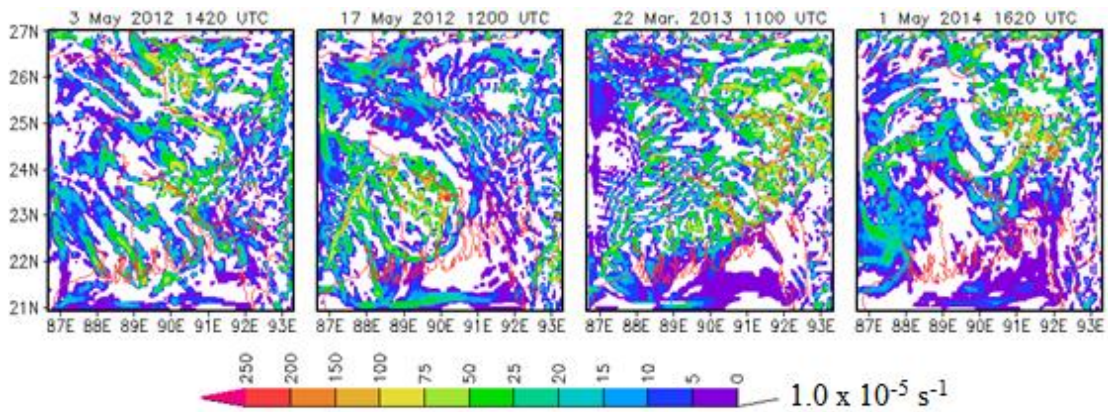

Fig. 12: Model simulated vorticity (1.0 x 10^{-5} s^{-1}) at 850 hPa. Positive values are shaded.

The high values of vorticity support condensation of the available moisture, and the resultant latent heat helps to further increase instability leading to convection. Strong convergence and divergence is found in the simulation at a lower atmosphere during the thunderstorm period (Fig. 12). Positive vorticity of 75-150×10^{-5} s^{-1} is present on the dates of Nor'westers under study and this vorticity is responsible for the formation of the squalls.

CONCLUSIONS

On the basis of the study following conclusions may be drawn:

i) CTT has shown -40 to -70 ^{o}C for all the events which indicate vertical extension of Cb cloud in between 12 to 18 km or more.

ii) TRMM retrieved precipitation has shown mature stage of all four events. Three hourly accumulated precipitation amount ranges from 64 to 128 mm.

iii) Model simulated 24 h accumulated rainfall has shown that all the squall events produce enormous amount of rainfall except on 1 May 2014, which is underestimated by model over the Rajshahi region. Model has simulated rainfall in and around the place of occurrence of Brahmanbaria tornado on 22 March 2013.

iv) Simulated cloud hydrometeors indicate maximum value above 1600 mg m^{-3}

v) The model underestimated the strength of the squall lines in general in term of the wind speeds. The simulated circulations reveal that the low level wind flow is strong southerly (10 to 15 m s^{-1}) from the BoB for almost all the events and the wind flow is in agreement with the previous studies.

vi) The speed of updrafts and downdrafts simulated by the model are comparable to those found over the West Bengal region. Strong rising motion of 24 m s^{-1} or more is present in the troposphere.

vii) The simulation has shown wind shear values of 6 to 8 m s^{-1} in the lower to middle troposphere (950 to 500 hPa). Strong vertical wind shear has been found over Assam and Meghalaya region.

viii) Low level moist southerly wind from the BoB in combination with positive vorticity and strong surface heating resulted in the formation of the squalls in all the events.

Further studies are required to minimize the spatial and temporal differences between the observed and simulated squalls through high resolution study for this region.

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