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Simulation of severe storms of tornadic intensity over Indo-Bangla region

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सार – 30 अगस्त से 14 सितम्बर 2008 के दौरान बंगलादेश के उत्तरी पश्चिमी भागों में टॉरनेडिक तीव्रता वाले कई प्रचंड गर्ज के साथ तूफान आए हैं। इनमें से दो तूफान 30 अगस्त को निलफामारी और कुरीग्राम तथा 3 सितम्बर को निलफामारी में आए। फील्ड सर्वेक्षण, सतह आँकड़ों, रेडार और उपग्रह प्रेक्षणों तथा मॉडल अनुरूपण के आधार पर टॉरनेडिक तूफानों का अध्ययन किया गया। ऊपरी स्तर के पश्चिमी जेट प्रवाह के संयोजन से बंगाल की खाड़ी में दक्षिणी प्रवाह द्वारा निम्न स्तर की आर्द्रता फलक्स के कारण पवन क्षेत्रों में तीव्र अस्थिरता और अनुरूपण से दो सप्ताहों में कई तूफान आए। बंगलादेश स्थित ढाका के मौसम विज्ञान विभाग (BMD) के एस. बैंड रेडार से प्राप्त किए गए घंटेवार वर्षा के आँकड़ों का उपयोग करते हुए तूफानों के सही समय और स्थानों का पता लगाया गया। इसी प्रकार 6 घंटेवार FNL विश्लेषणों और NCEP परिसीमा की स्थितियों के आधार पर 9 और 3 कि. मी. क्षैतिज विभेदनों पर दुहरी नेस्टेड क्षेत्रों में WRF-ARW मॉडल का उपयोग करते हुए तूफानों को सिमूलेट किया गया।

तूफानों के विशिष्ट अभिलक्षणों में CAPE, तूफान - सांपेक्षिक पर्यावरण हेली सिटी (SREH), बल्क रिचर्डसन नम्बर शीयर (BRNSHR), ओसांक अवदाब और संभाव्य भ्रमिलता के अध्ययन किए गए। परिणामों से पता चला है कि जबकि तूफानों के प्रेक्षित और अनुकरित समय के बीच 2-3 घंटों की भिन्नता रही, तूफानों के प्रेक्षण और अनुकरित स्थानों के मध्य किलोमीटर के कई टेनस की दूसरी रही है। अधिकतम CAPE, सामान्यत: 2400 $J\ kg^{-1}$ से अधिक रहे। मॉडल द्वारा अनुकरित संवहन गति के कारण तूफान अपड्राफ्ट (हेलीसिटी) में दिशात्मक अपरूपण द्वारा अंतरित भ्रमिलता की अधिकतम मात्रा 766 $m^2\ sec^{-2}$ है और उस क्षेत्र में बताए गए BRNSHR के उच्चतम मान जिसमें निम्न स्तर के मेसोसाइक्लोजेनेसिस के 2 मामलों में 168 $m^2\ sec^{-2}$ के रहने की संभावना अधिक है और इसमें सामान्यत: निर्धारित रेंज के अनुसार धूर्णनाकार तूफान आने की संभावना रहती है।

ABSTRACT. Many severe thunderstorms of tornadic intensity were reported in the northwestern parts of Bangladesh during 30 August to 14 September, 2008. Two among them occurred at Nilphamari and Kurigram districts on 30th August, and at Nilphamari district on 3rd September. The tornadic storms are studied based on a field survey, surface data, radar and satellite observations and model simulations. Low level moisture influx by southerly flow from the Bay of Bengal coupled with an upper level westerly jet stream causing intense instability and shear in the wind fields triggered a series of storms for two weeks. The exact time and locations of the storms are investigated by using the hourly precipitation data retrieved from a S-band radar of Bangladesh Meteorological Department (BMD) located at Dhaka. Subsequently, the storms are simulated by using the WRF-ARW model on double nested domains at 9 and 3 km horizontal resolutions based on 6 hourly FNL analyses and boundary conditions of NCEP.

Among the typical characteristics of the storms, the CAPE, Storm-Relative Environment Helicity (SREH), Bulk Richardson Number Shear (BRNSHR), dew point depression, and potential vorticity are studied. Results show that while there are differences of 2-3 hours between the observed and simulated time of the storms, the distances between observed and simulated locations of the storms are several tens of kilometers. The maximum CAPE is generally above 2400 $J\ kg^{-1}$. The maximum amount of vorticity transferred by directional shear in the storm updraft (helicity) due to convective motion simulated by the model is 766 $m^2\ sec^{-2}$, and the highest value of BRNSHR that define the region in which low-level mesocyclogenesis is more likely is 168 $m^2\ sec^{-2}$ among the 2 cases, which is generally supposed to produce rotating storms according to the prescribed range.

Key words – Tornado, Storm, Simulation, WRF, Model, Indo-Bangla.

1. Introduction

A series of severe thunderstorms of tornadic intensity occurred in the Northwestern parts of Bangladesh from 30 August to 14 September, 2008. On 30th August, a tornadic storm lashed about 300 houses in Nilphamari and Kurigram districts affecting 300 families at 1500 UTC (2100 BST; BST = UTC + 6h) according to media reports. On 3rd September, a tornadic storm hit the Nilphamari region again in the night time. On 4 September (0930 UTC, *i.e.*, 1530 BST) a tornado hit Jamalpur injuring 17 people and affected about 100 families. On 14 September, a tornadic storm lashed 10 villages, destroying about 200 homes and uprooting hundreds of trees in Thakurgaon region at 0800 UTC (1400 BST) and lasted several minutes. Fig. 1 shows the locations of the tornado affected districts in Bangladesh. Frequent occurrences of such phenomena in the same region warranted investigation. It is particularly important because the tornadic storms are unusual in the month of September as it is a retreating monsoon season. Severe thunderstorms/ tornadoes occur generally during the pre-monsoon season (March-May) in this region.

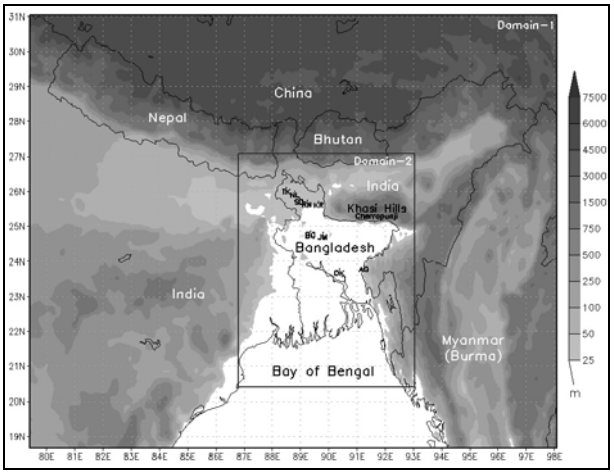


Fig. 1. Locations of Tornado affected districts Thakurgaon (TK), Nilphamari (NL), and Kurigram (KR) in Bangladesh with topography shaded in meters. Other locations marked in the diagram are Syedpur (SD), Rangpur (RN), Bogra (BG), Jamalpur (JM), Dhaka (DK) and Agartala (AG). The two domains (outer Domain-1 and inner Domain-2 at 9 and 3 km resolutions respectively) nested within each other illustrate the WRF model domains used for simulations

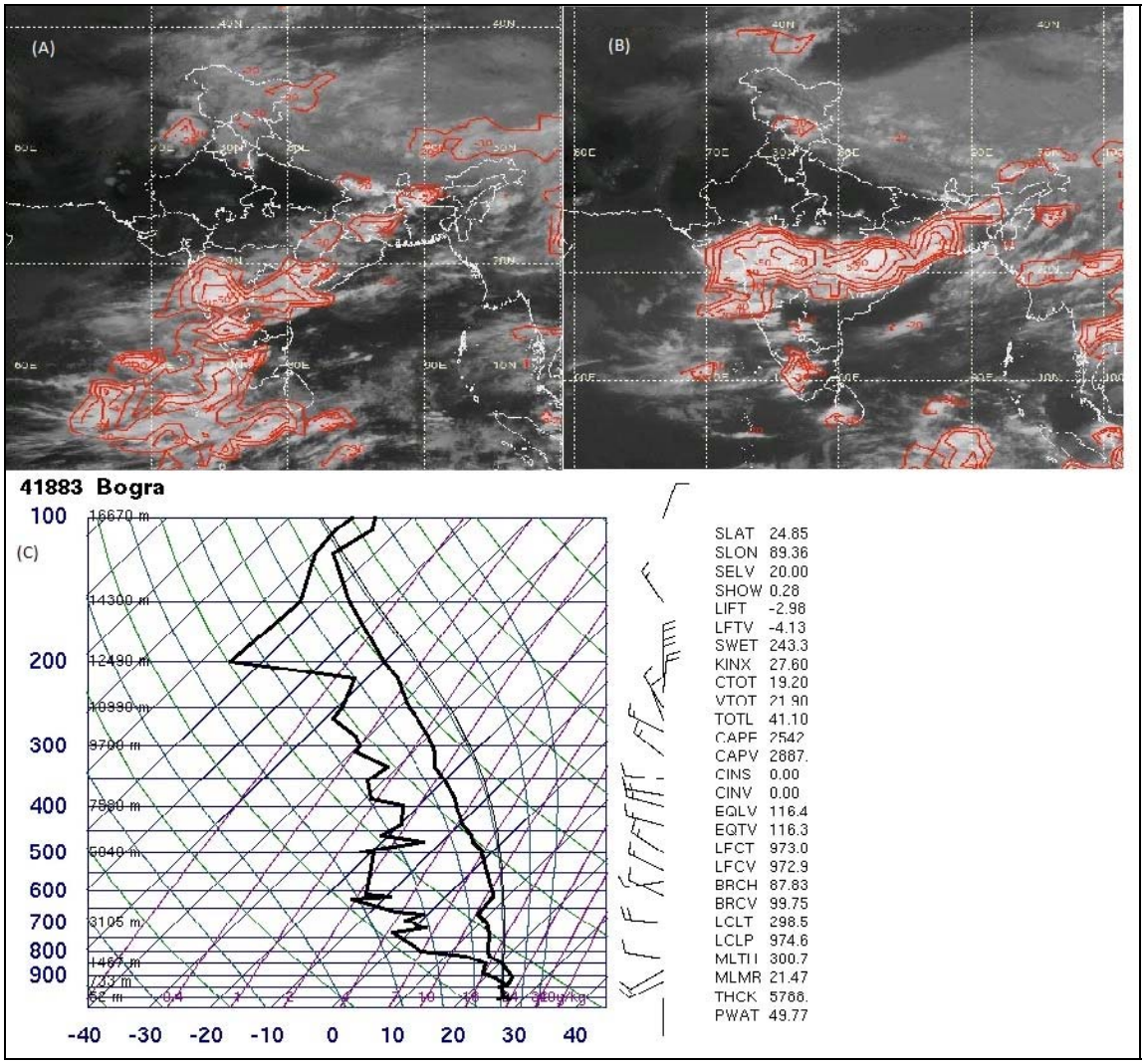
A detailed documentation of tornadoes of Bangladesh is made by Finch and Dewan (2003). Several factors lead to the active thunderstorm season across Bengal (Bangladesh and its adjoining regions in India). North and central India heats up and dries out in late March or early April. A deep, dry mixed layer develops. Low level flow from the Bay of Bengal increases markedly during this time. Westerly mid-level flow around the Tibetan Plateau advects the Indian mixed layer over the Bengal moist tongue. This leads to the Elevated Mixed Layer (EML). It may be noted that parts of the East Indian plateau are 'elevated' (1-3000 ft) compared to Bangladesh which has elevation near sea level. The mid level flow is fairly strong in April with 30-50 kt (~15-25 m sec^{-1}) speed at 700 hPa and 35 to 50 kt (~18-25 m sec^{-1}) at 500 hPa. The high level jet is usually over or just north of Bengal in April. The southern branch of the polar jet often retreats north of the Tibetan Plateau by May, leaving light, mid to high level flow across the Bengal region. By June the high level flow is light. Nocturnal storms over the Khasi Hills near Cherrapunji in India leave outflow boundaries over northern Bangladesh. These nocturnal storms are probably caused by the low level jet impinging on the Khasi Hills of Meghalaya, India. All these factors result in a tornado maximum in early to mid April. In summary, vertical wind shear and instability are maximized and the jet is in a favorable position during this time.

In this study, we have analyzed the characteristics of two unusual tornadic events (30 August and 3 September 2008) based on Dhaka radar, satellite and surface observations and attempted to simulate them using the Weather Research and Forecasting (WRF) model. Section 2 presents large-scale synoptic situations prevailing during the period. The observations of Dhaka radar are discussed in Section 3. A brief description of the WRF model configuration used in this study is given in Section 4. The results of simulation are also discussed in this section. Finally, the summary of the results and concluding remarks are presented in Section 5.

2. Large scale synoptic conditions

Past studies of tornadoes over the India and Bangladesh region (Mandal *et al.*, 1978; Hussain and Karmakar, 1998) indicated that a horizontal vortex sheet is created by the presence of horizontal and vertical wind shear in association with low / middle level wind core. The vortex is fuelled by the advection of dry air by westerly current into a region of warm and moist air. The vortex is tilted by the wind shear. The cyclonic vorticity thus created is helpful for the formation of severe storms such as tornadoes.

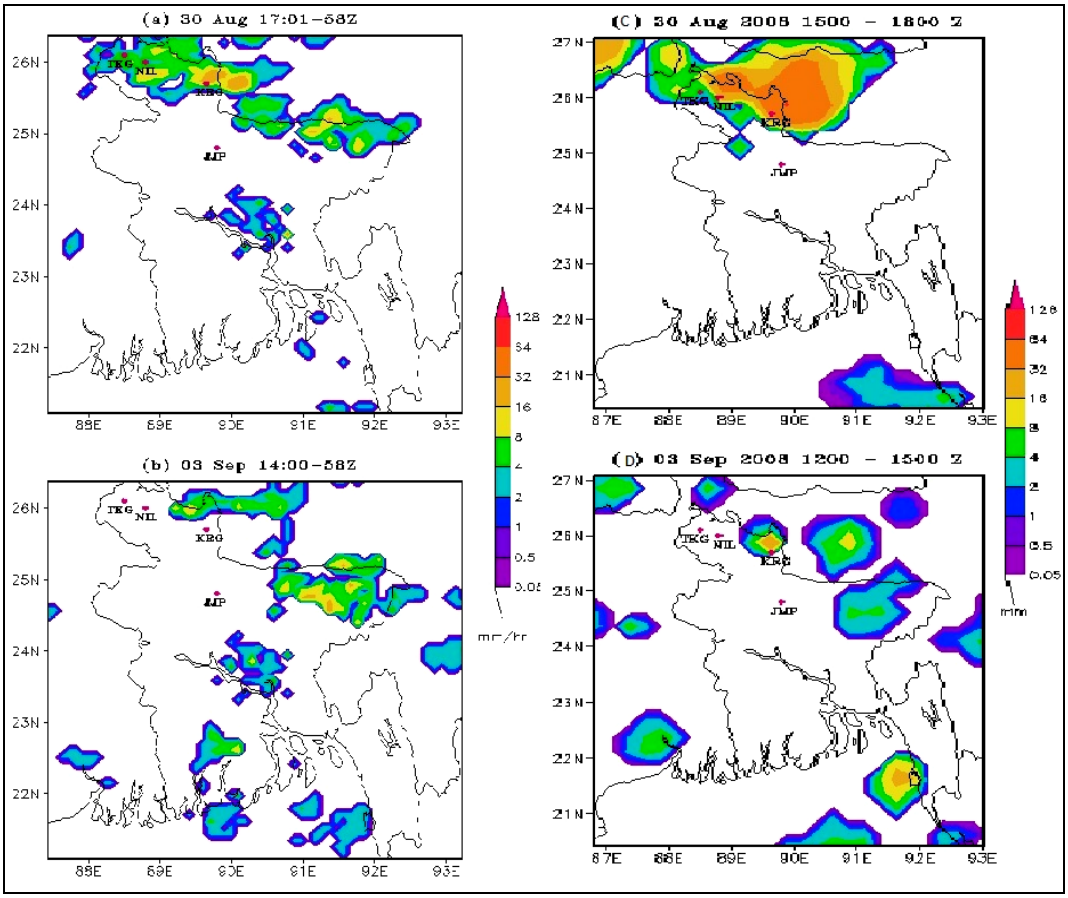
The large-scale synoptic conditions were analyzed at 500 and 850 hPa during the days of tornadic events (diagrams are not shown for brevity). Details are available in Das *et al.* (2009). It was seen that during most of the tornadic events, a feeble trough existed north of Bangladesh at 500 hPa. At lower level 850 hPa, the flow was southerly or south-westerly feeding moisture from the



Figs. 2(a-c). Cloud top temperatures observed by the Kalpana-1 satellite at (a) 1700 UTC (2300 BST), 30 August, (b) 1400 UTC (2000 BST), 3 September 2008 and (c) Observed Skew-T diagram of Bogra on 3 September 2008 at 0000 UTC (0600 BST)

Bay of Bengal over Bangladesh. The low level moisture incursion in the zone of convergence coupled with the upper level trough made conditions conducive for development of severe thunderstorms over the region. Owing to lack of dense network of observatories in the area, the exact measurement of maximum wind speed, drop in surface pressure, the pressure tendency, the observed vertical profiles of temperature, moisture, etc. are not available in the region. Some of these features are diagnosed through the model simulations. The synoptic conditions led to the formation of convective cloud clusters over the region.

Hourly analysis of cloud top temperatures (CTT) obtained from the Kalpana-1 satellite [Figs. 2(a&b)] reveal that on 30 August large cloud clusters existed over West Bengal and Bihar region in India. An *in-situ* cloud formed over northwest Bangladesh around 1400 UTC (2000 BST), which quickly developed into deep clouds (CTT~ -40 °C) by 1700 UTC (2300 BST) as shown in [Fig. 2(a)]. Severe storms of tornadic intensity were reported in the Nilphamari and Kurigram districts of northwest Bangladesh around 1500-1600 UTC (2100-2200 BST). On 3rd September cloud clusters were present over northwest Bangladesh since morning [Fig. 2(b)]. Another large band of deep convective clouds (CTT ~ -60 °C) over adjoining Indian region in West Bengal extended to northwest Bangladesh and merged with the existing clouds by 1000 UTC (1600 BST). Convection developed further and severe storms of tornadic intensity were reported in the Nilphamari district in Bangladesh around 1400 UTC (2000 BST).



Figs. 3(a-d). Left panel shows the precipitation rates (mm/h) derived from the S-band radar at Dhaka during (a) 1701-1758 UTC (2301-2358 BST), 30 August and (b) 1400-1458 UTC (2000-2058 BST), 3 September 2008. The right panel shows observed accumulated rainfall by TRMM (c) 1500-1800 UTC (2100-0000 BST), 30 August, and (d) 1200-1500 UTC (1800-2100 BST), 3 September, 2008

Skew-T diagram based on observed upper air sounding at Bogra (24.85° N, 89.36° E) is shown in Fig. 2(c) for 3 September, 2008. The observed upper air sounding was not available over northwest Bangladesh on 30th August. Therefore, we compared the model simulated skew - T diagram of 30th August for an Indian station (Agartala), but the diagram is not shown here for brevity. The convective characteristics of the air parcel such as the lifted index (LI), Total Totals index (TTI), Showalter index (SWI), CAPE, CINE, wind hodograph and wind profiles were examined from the T-ϕ grams.

The T- ϕ grams of the 2 cases showed instability in the atmosphere. The CAPE values were greater than 1500 J Kg^{-1} and the CINE values were negative. The lifted indices were usually less than -3. When the LI values are between -2 and -6, the atmosphere is unstable with possibility of severe thunderstorms. The TTI values ranged between 41 and 46. The TTI values above 40 are indicative of possibility of severe thunderstorms. Values greater than 47 are indicative of severe thunderstorms with tornado intensity.

3. Observed characteristics by radar

The Bangladesh Meteorological Department (BMD) has S-band weather radar (~10 cm wave length) at Dhaka (90.4° N, 23.7° E) since the year 2000. It has a maximum radius about 400 km horizontally and effective radius about 250 km. It is operated at frequency of 2700-2900 MHz, and beam width of 1.7°. The radar is operated at zero elevation angle to collect hourly PPI scan data (pixel size 2.5 km) from 2300 UTC (0500 BST) to 1700 UTC (2300 BST). The radar is operated for one hour followed by a gap of 2 hours during the period. The radar collects reflectivity data, which are stored in six rain status categories. In this study, the radar data is converted into precipitation rates for each cases of the tornadic storms based on the algorithm described in Islam *et al*. (2005).

The precipitation rates derived from the Dhaka radar for 30 August and 3 September, 2008 are discussed below.

3.1. *The event of 30 August, 2008*

The precipitation rates observed by radar on 30th August, 2008 are depicted in Fig. 3(a). The frame by frame analysis of the radar observations indicate that 3 convective cells developed around Nilphamari, Rangpur and Kurigram area at about 1200 UTC (1800 BST). By about 1500 UTC (2100 BST) the cells intensified into major storms and remained almost stationary over the region till about 1800 UTC (0000 BST) and dissipated afterwards. The maximum precipitation rates observed by radar were about 25-35 mm hr^{-1}. The exact rain rate is about 4 times the BMD radar estimated values (Islam *et al*., 2005). Therefore, actual rain rates may exceed 100 mm hr^{-1}. Observed accumulated precipitation from TRMM during 1500-1800 UTC (2100-0000 BST) as depicted in Fig. 4(a) shows about 64 mm. However, higher precipitation rates observed by radar may not imply that the storm was at its peak intensity at that time. It has been often reported that the strongest wind and the vortex are generally followed by the occurrences of hail and rainfall. The gust front and the downdrafts arrive before the heaviest rainfall.

3.2. *The event of 3 September, 2008*

Frame by frame analysis of precipitation rates observed by radar from 2200 UTC of 2 September till 1700 UTC (2300 BST) of 3rd September, 2008 were carried out. Fig. 3(b) depicts the precipitation rates observed by radar between 1400 - 1458 UTC (2000 - 2058 BST). Analysis indicates that a line of convective cells developed over the northwestern parts of Bangladesh at around 0600 UTC (1200 BST) on 3rd September. The convective line was oriented in the northeast to southwest direction. The convective band gradually organized and intensified like squall line and moved from the northwest to southeast direction. Convective cloud clusters were also seen in the Meghalaya region of India. At around 0900-1000 UTC (1500-1600 BST) the northeastern part of the squall line developed into severe storm in the Nilphamari-Kurigram regions and caused damages to the houses. Observed accumulated precipitation from TRMM during 1200-1500 UTC (1800-2100 BST) as depicted in Figs. 3(c&d) show isolated rainfall about 64 mm in the Kurigram district.

4. Simulated characteristics

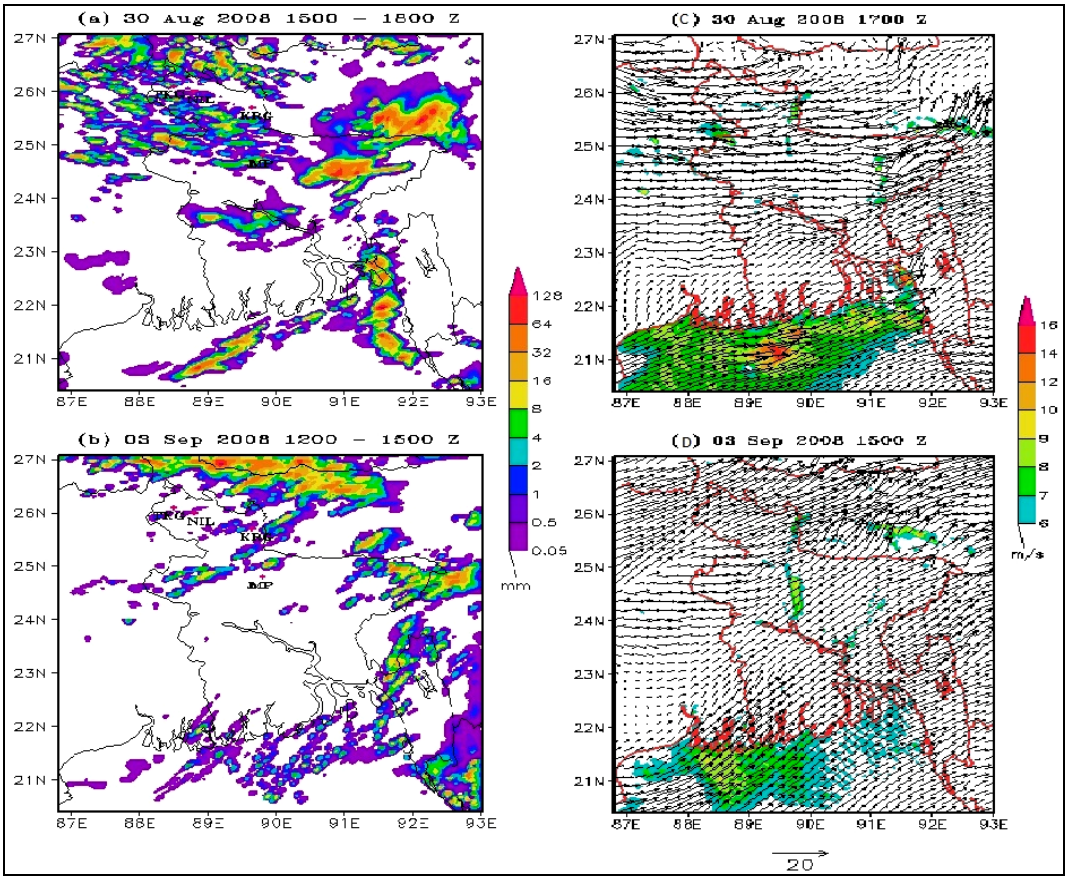
4.1. *The model*

The Weather Research and Forecasting (WRF) model (version 3.4.1) has been used for simulation of the tornadic storms in this study. The WRF Model is a new-generation mesocale Numerical Weather Prediction (NWP) system designed to serve both operational forecasting and atmospheric research needs (NCAR, 2009). It features multiple dynamical cores, a 3-dimensional variational (3DVAR) data assimilation system and a software architecture allowing for computational parallelism and system extensibility. WRF is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers. Applications of WRF include research and operational numerical weather prediction (NWP), data assimilation and parameterized-physics research, downscaling climate simulations, driving air quality models, atmosphere-ocean coupling and idealized simulations (*i.e*., boundary-layer eddies, convection, baroclinic waves). There are two dynamics solvers in the WRF system: the Advanced Research WRF (ARW) solver (originally referred to as the Eulerian mass or "em") developed primarily at NCAR, and the NMM (Nonhydrostatic Mesoscale Model) solver developed at NCEP. The ARW system consists of the ARW dynamics solver with other components of the WRF system needed to produce a simulation. For the purpose of simulating the tornadoes the model was run on double nested domains at 9 and 3 km resolutions (Fig. 1) with 27 vertical levels using initial and boundary conditions data obtained from NCEP FNL (Final) Operational Global Analysis, which is at about 1° × 1° horizontal resolution. Two-ways nesting were used for simulations implying that both domains could influence/ interact with each other. Das *et al*. (2015) conducted several sensitivity experiments with different combinations of physical parameterization schemes of the model and found that the best skill scores were obtained by the combinations of no-cumulus, Milbrandt and YSU schemes for cumulus convection, cloud microphysics and planetary boundary layer respectively for the simulation of Nor'westers over Indian and Bangladesh region. This combination of physical processes provided least RMSE values for rainfall, wind speed at surface and time of occurrences of storms in the model simulations. We have used this combination of physics in the present study.

TABLE 1

Observed and simulated diagnostics

	30 August 2008 at 1200 UTC		3 September 2008 at 0000 UTC	
	Observed	Model	Observed	Model
CAPE (J/kg)	4489	553	2542	1720
Lifted Index (LI)	-7.26	-1.4	-2.98	-3.0
Total-Totals Index (TTI)	46.80	40	41.10	41



Figa. 4(a-d). Left panel shows the model simulated precipitation as in *Figs. 3(a&b)*. The right panel shows simulated wind speed at 10 m above surface and wind vectors at 850 hPa for (c) 1700 UTC (2300 BST), 30 August and (d) 1500 UTC (2100 BST) 3 September, 2008

4.2. *Diagnostics*

In this section, we have investigated many simulated characteristics of the 2 tornadic events such as the Convective Available Potential Energy (CAPE), surface wind speed, flow patterns, rainfall, Storm-relative Environment Helicity (SREH), Bulk Richardson Number Shear (BRNSHR), dew point depression, and potential vorticity. All results discussed here correspond to the inner domain at 3 km resolution. Hourly variations of these parameters were studied over the Northwest part of Bangladesh. Table 1 presents a summary of these parameters. The diagrams shown here correspond to the hours when model indicated favourable signals for the occurrence of the tornadoes.

4.2.1. *Convective Available Potential Energy (CAPE) and simulated precipitation*

The Convective Available Potential Energy (CAPE) is the positive buoyancy of an air parcel. It is the amount of energy a parcel of air would have if lifted a certain distance vertically through the atmosphere. It is an indicator of atmospheric instability. It is defined as:

$$\text{CAPE} = \int_{Zf}^{Zn} g \frac{(Tvp - Tve)}{Tve} dz \qquad (1)$$

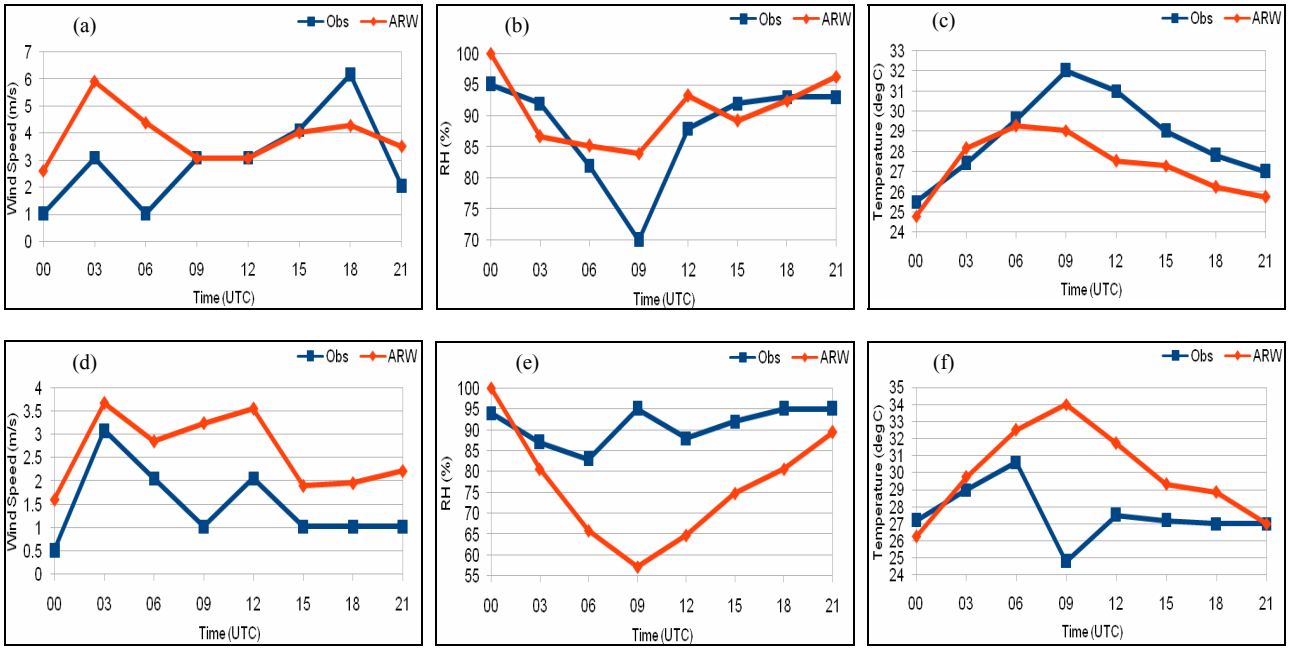
where, *Zf* and *Zn* are the levels of free convection and neutral buoyancy respectively. *Tvp* and *Tve* are the virtual temperatures of the air parcel and environment respectively. The threshold values of CAPE for different stability regimes are given below:

CAPE < 1000 : Instability is weak

CAPE > 1000 < 2500 : Moderate instability

CAPE > 2500 : Strong instability

The simulated CAPE by the model is not shown for brevity. However, analysis showed that CAPE started building up in the north of the analysis area since morning



Figs. 5(a-f). Time series of observed and model simulated (a) wind speed, (b) relative Humidity and (c) temperature at surface on 30 August, 2008 at Syedpur (25.8° N, 88.95° E), (d) to (f) are for 3 September, 2008

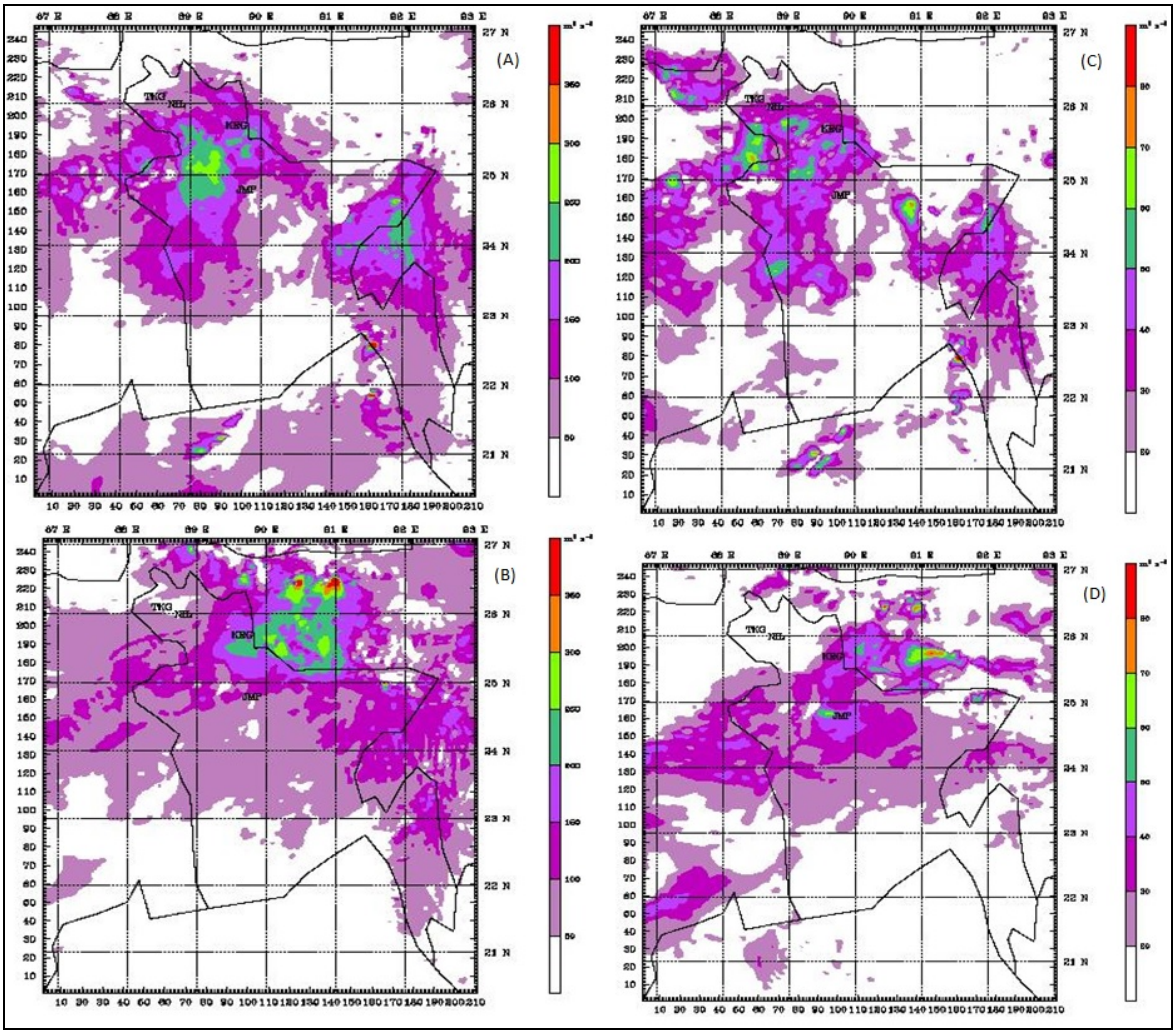
0300 UTC (0900 BST) on 30th August and was maximum 2800 J kg^{-1} around 1700 UTC (2300 BST). It decreased afterwards. On 30th August, the storm was reported around 1500 UTC (2100 BST) in Nilphamari and Kurigram districts. Simulated precipitation by the model during 1500-1800 UTC (2100-0000 BST) over the region [(Fig. 4(a)] shows rainfall values of about 64 mm which are comparable to the TRMM observations [Fig. 3(c)].

On 3rd September the storm was reported at night around 2000 BST (1400 UTC). The CAPE started increasing after 0800 UTC (1400 BST) and the maximum value (3537 J kg^{-1}) reached around 1300 UTC (1900 BST). The maximum value was far southwest of the area of the storm. These results show that the highest simulated CAPE values preceded the time of occurrences of the storms. The highest CAPE values were simulated south / west of the locations where the storms were reported. Pockets of high CAPE values gradually propagated towards the locations where the storms were reported. The highest values were simulated 2-6 hours before the occurrences of storms. Simulated precipitation by the model during 1200-1500 UTC (1800-2100 BST) over the region [Fig. 4(b)] shows isolated pockets of rainfall (8-16 mm) which are less than the TRMM observations [Fig. 3(d)].

4.2.2. *Surface wind, temperature and relative humidity analyses*

The wind speed at 10 meters above the ground as simulated by the model are depicted in Figs. 4(c&d). The maximum surface wind speed simulated by the model on 30th August was about 7-8 m sec^{-1} near Nilphamari-Kurigram region [Fig. 4(c)] associated with a zone of mass convergence. The gust came from west. The prevailing wind direction was westerly-southwesterly. Similar flow pattern was also simulated on 3rd September, but the maximum wind was slightly stronger on this day (~ 9-10 m sec^{-1} at 1000 UTC, *i.e.*, 1600 BST) near Nilphamari region [Fig. 4(d)]. However, the simulated results showed a major line of convergence passing about 70-80 km southeast of the affected areas between 1300-2100 UTC (1900-0300 BST).

Figs. 5(a-f) depicts the time series of observed and model simulated wind speed, relative humidity (RH) and temperature at surface on 30 August and 3 September, 2008 at Syedpur (25.8° N, 88.95° E), which is a nearby observatory of BMD. The observed and simulated values show fairly good correspondences. The wind speeds are generally overestimated by the model by about 1-2 m s^{-1}. The maximum difference between observed and simulated relative humidity and temperature is seen at 0900 UTC



Figs. 6(a-d). Left panel shows Storm-relative Environment Helicity (SREH) (m^2 s^{-2}) simulated by the model for (a) 1700 UTC (2300 BST), 30 August and (b) 1500 UTC (2100 BST) 3 September, 2008. Values are shaded above 50. The right panel shows the Bulk Richardson number Shear (BRNSHR) in m^2 s^{-2} for the same times as in (a) & (b). The BRNSH values are shaded above 20

(1500 BST) when the convection is generally at peak. The simulated temperature and RH on 3rd September shows opposite phases between observation and model simulation. The simulated moisture is drier and temperature is warmer than compared to observations at Syedpur. This may happen when we compare a point observation with the nearest grid point value. Rainfall may be occurring at the station, but the model may not be raining at that grid point. Mixed trends between observed and simulated values (overestimation/underestimation) are seen at surface.

4.2.3. *Storm-Relative Environment Helicity (SREH)*

The helicity is a measure of the amount of rotation found in a storm's updraft air. If there is significant rotation in a storm's updraft air, the storm will more than likely become a supercell and possibly spawn one or more tornadoes. Helicity is a parameter that defines the amount of stream-wise vorticity (*i.e.*, directional shear) a steady storm updraft will ingest as a result of a given storm motion. In meteorology (Thompson *et al.*, 2007), helicity corresponds to the transfer of vorticity from the environment to an air parcel in convective motion. Here the definition of helicity is simplified to only use the horizontal component of wind and vorticity:

$$H = \int \vec{V}_h \cdot \vec{\zeta}_h dZ = \int \vec{V}_h \cdot \nabla \times V_h dZ \qquad (2)$$

where, Z = altitude, V_h is the horizontal velocity and ζ_h is the horizontal vorticity. According to this formula, if

the horizontal wind does not change direction with altitude, H will be zero as the product of V_h and $\nabla \times \vec{V}_h$ are perpendicular one to the other making their scalar product nil. H is then positive if the wind turns (clockwise) with altitude and negative if it backs (counter-clockwise). Helicity has energy units per units of mass (m^2 s^{-2}) and thus is interpreted as a measure of energy transfer by the wind shear with altitude, including directional.

This notion is used to predict the possibility of tornadic development in a thundercloud. In this case, the vertical integration is limited below cloud tops (generally 3 km or 10,000 feet) and the horizontal wind is calculated to wind relative to the storm in subtracting its motion:

$$\text{SREH} = \int (\vec{V} - C).\nabla \times V_h \, dZ \qquad (3)$$

where, C is the cloud motion to the ground. Critical values of SRH (Storm Relative Helicity) for tornadic development, as researched in North America, are:

- SREH = 150-299 … supercells possible with weak tornadoes according to Fujita (1973) scale
- SREH = 300-499 ... very favourable to supercells development and strong tornadoes
- SREH > 450 ... violent tornadoes
- When calculated only below 1 km (4,000 feet), the cut-off value is 100.

Helicity in itself is not the only component of severe thunderstorms and those values are to be taken with caution. Therefore, the Energy Helicity Index (EHI) has been created. It is the result of SRH multiplied by the CAPE and then divided by a threshold CAPE. This incorporates not only the helicity but the energy of the air parcel and thus tries to eliminate weak potential for thunderstorms even in strong SRH regions. The critical values of EHI are:

- EHI = 1 indicate possible tornadoes
- EHI = 1-2 indicate moderate to strong tornadoes
- EHI > 2 indicate strong tornadoes

Figs. 6(a&b) present the distribution of SREH for the 2 events. The values are integrated for 0-3 km layer. The SREH values reached maximum around 1700 UTC (2300 BST) on 30th August [Fig. 6(a)] southwest of Kurigram, where the storm was reported. High CAPE values were also simulated around the same place. Similar value of SREH (250-300 m^2 s^{-2}) was also simulated on 3rd September [Fig. 6(b)] in the same area. As mentioned earlier when the SREH value is greater than 150 m^2 s^{-2}, supercells are possible with weak tornadoes, and when the values are greater than 450 m^2 s^{-2}, voilent tornadoes are possible. Therefore, the chances of tornado event existed on both the days as predicted by the model.

Time evolution of the maximum SREH obtained from the model simulations were investigated, but are not shown for brevity. However, the results indicate that the SREH values have generally 2 maxima; one in the morning (0300-0400 UTC, *i.e*., 0900-1000 BST)) and the second in the afternoon (1400-1800 UTC, *i.e*., 2000-0000 BST). Comparison between the observed time of occurrence of the storms and the peak values indicate that the storms occurred when SREH is persistently high for at least 4-5 hours. At most of the time the SREH values were higher than the threshold value (150 m^2 s^{-2}) for the formation of weak tornadoes.

4.2.4. *Bulk Richardson Number Shear (BRNSHR)*

The Bulk Richardson Number (BRN) is used to quantify the relationship between buoyant energy and vertical wind shear (Moncrieff and Green, 1972) and is defined as,

$$BRN = \frac{CAPE}{0.5(\bar{u}^2 + \bar{v}^2)} \qquad (4)$$

where, u and v are the wind components of the difference between the density-weighted mean winds over the lowest 6000 m and the lowest 500 m above ground level. As discussed in Droegemeier *et al*. (1993), the BRN is only a gross estimate of the effects of vertical wind shear on convective storms, since it does not measure the turning of the wind profile with height. However, Weisman and Klemp (1984) showed using cloud-scale model simulations that the BRN can distinguish between supercell and multicell storms, with modeled supercells likely when $10 \leq BRN \leq 50$ and multicells storms likely when BRN > 35. It is important to note that there is no well-defined threshold value for BRN, since there is an overlap in these values used to specify storm type.

BRNSHR is defined by the denominator of equation (4) and has been found to be highly correlated with the maximum vertical vorticity of modeled thunderstorms by Droegemeier *et al*. (1993), despite the fact that it does not account for the turning of the wind vector with height, or the magnitude of the low-level storm-relative winds (Lazarus and Droegemeier, 1990). Brooks *et al*. (1994a, b) hypothesized that the midlevel, storm-relative winds are

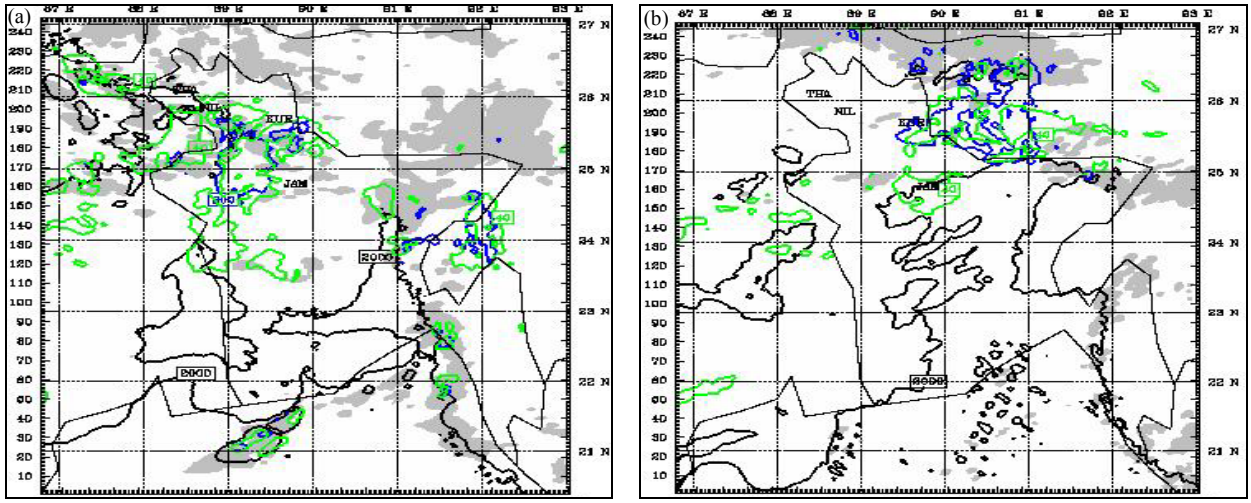
important to the development of low level rotation in thunderstorms. Since their conceptual model indicated that the strength and lifetime of low level mesocyclones is a function of the balance between low-level baroclinic generation of vorticity and outflow development, they examined the redistribution of rain in modeled supercells. Their results indicated that for very weak midlevel storm-relative winds, the low-level mesocyclones are short lived, occur early in the storm life cycle, and low-level outflow dominates the storm. Storms forming in this type of environment are more likely to evolve into squall lines owing to the strong organizing influence of the outflow. For very strong storm-relative winds, low-level mesocyclones develop very slowly, or do not develop at all, and outflow is weak, since the rain is being blown away from the storm by the strong midlevel winds. In the middle of these two extremes, the results of Brooks *et al*. (1994a, b) show that low-level mesocyclones tend to be long lived, owing to the balance between the mesocyclone circulation and the storm-relative winds. These results are related to the values of BRNSHR, since an examination of the supercell thunderstorm proximity sounding dataset from Brooks *et al*. (1994b) indicated that the BRNSHR can be used as a proxy for the storm-relative wind. The use of BRNSHR instead of the storm-relative wind is a valuable simplification, since BRNSHR is both independent of storm motion and vertically integrated, making BRNSHR values better behaved than values of storm-relative midlevel winds calculated from mesoscale model output where the storm motion must be estimated. In addition, using the proximity dataset of Brooks *et al*. (1994b) and subjectively determining the best fit line to discriminate between tornadic and non-tornadic thunderstorms using only the values of SREH and BRNSHR, Stensurd *et al*. (1997) found that as the value of BRNSHR increases the value of SREH also must increase to support mesocyclogenesis. No observed tornadic storms occur with BRNSHR values less than 20 m^2 s^{-2} and, except for one outlier, for BRNSHR values greater than 140 m^2 s^{-2}. Thus, in more highly sheared environments we expect that the value of SREH must be significantly higher than the guidance value of 100 in order to increase the likelihood of developing tornadic supercell thunderstorms.

Small values of BRNSHR correspond to low values of midlevel storm-relative winds and storms that are outflow dominated with a tendency to produce damaging winds (Stensurd *et al*., 1997). The results of Weisman (1993), who examined bow echoes using a cloud-scale model showed that bow echoes are more prevalent for lower values of BRNSHR, while supercells are more prevalent for larger values of BRNSHR, assuming that there is sufficient shear to generate long-lived rotating storms. For the largest values of BRNSHR used, the results of Weisman (1993) indicate that no organized convective activity occurred in the numerical simulations. Thus, in general agreement with the conceptual model, his results show that it is in the middle range of BRNSHR values that supercell thunderstorms develop. The results of Stensurd *et al*. (1997) suggest that values of BRNSHR between 40 and 100 m^2 s^{-2} indicate a greater likelihood of tornadic supercell thunderstorms if the SREH values are large enough to produce rotating storms. The value of 40 m^2 s^{-2} used for the modeled BRNSHR threshold is larger than that suggested by the proximity sounding data, likely owing to the difficulties in simulating low-level winds. Also, although BRNSHR and SREH are measures of the vertical wind profile, they can vary in the opposite directions. It is not unusual for BRNSHR to decrease as SREH increases, as can occur with the development of a low-level jet.

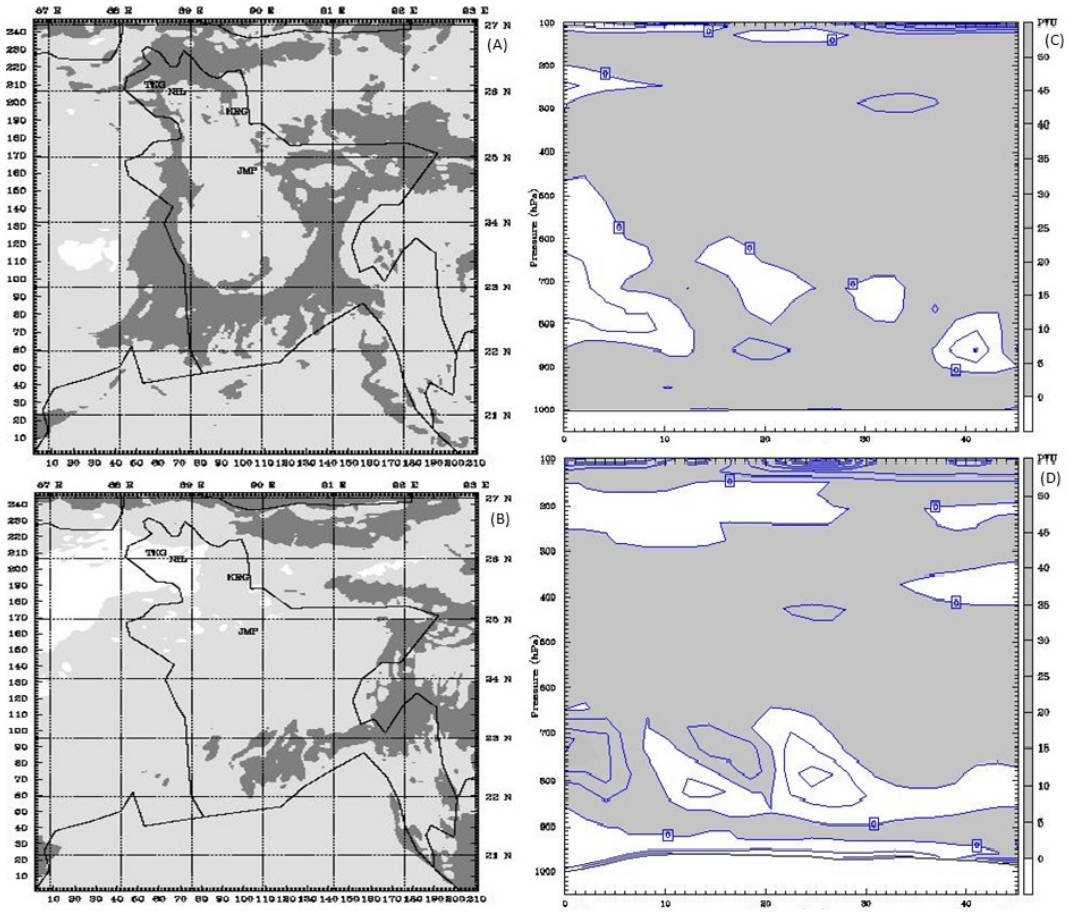
Figs. 6(c&d) illustrate the spatial distribution of BRNSHR for the 2 cases. High values of BRNSHR (60-70 m^2 s^{-2}) are simulated on 30 August [Fig. 6(c)] and 3 September [Fig. 6(d)] around 1700 and 1500 UTC (2300 and 2100 BST), indicating sheared environment (when CAPE and SREH are also conducive for producing rotating storms). Such values of BRNSHR may help the formation of tornadic storms. Since both CAPE and SREH values are also higher in this region, the necessary convective energy and rotation of wind field may be produced, leading to occurrence of tornadic storms.

Time evolution of the maximum BRNSHR obtained from the model simulations were investigated, but are not shown here for brevity. However, the results indicate that the BRNSHR values have generally 3 maxima; one in the morning (0300-0500 UTC, *i.e*., 0900-1100 BST), the second in the afternoon (1200-1800 UTC, *i.e*., 1800-0000 BST), and the third at late night/ early morning (2100-2300 UTC, *i.e*., 0300-0500 BST). At most of the time the BRNSHR values were higher than the threshold value (40 m^2 s^{-2}) for the formation of supercell thunderstorms. The maximum values of both SREH and BRNSHR are simulated higher on 3rd September than on 30th August.

In thunderstorm forecasting, CAPE is used to define the region in which convection is possible, SREH is used to define the region in which thunderstorms are likely to be supercells, and BRNSHR is used to define the region in which low-level mesocyclogenesis is more likely. These results highlight the potential value of analyzing various severe weather parameters in forecasting tornadic thunderstorms. By combining the storm characteristics suggested by these parameters, it is possible to use mesoscale model output to infer the dominant mode of severe convection. There are many



Figs. 7(a&b). CAPE (> 2000 J kg^{-1} in black contours), SREH (> 200 m^2 s^{-2} in blue contours) and BRNSHR (> 40 m^2 s^{-2} in green contours) as simulated by the model for (a) 1700 UTC (2300 BST), 30 August, and (b) 1500 UTC (2100 BST), 3 September, 2008. Rainfall (> 0.25 mm) are shaded



Figs. 8(a-d). Left panel shows Dew point depression (°C, shaded) and Surface pressure (hPa, contours) as simulated by the model for (a) 1700 UTC (2300 BST), 30 August and (b) 1500 UTC (2100 BST) 3 September, 2008. Shading information: 0-2 °C dark gray, 2-7 °C light gray, and > 7 °C is white. The right panel shows Vertical profile of potential vorticity (PVU) simulated by the model for (c) 1700 UTC (2300 BST), 30 August and (d) 1500 UTC (2100 BST), 3 September, 2008. Shaded region indicates positive values. The contours are drawn at the intervals of 2. The cross sections are drawn from 25.58° N, 89.12° E to 25.8° N, 89.4° E for 30 August and 25.53° N, 90.11° E, 25.8° N, 90.4° E for 3 September representing the areas of maximum convection

other parameters that should be used in forecasting severe-weather threat (Johns and Doswell, 1992; Thompson, 1998). But we focus here on these three parameters CAPE, SREH and BRNSHR for simplicity. It should be recognized that there remains great uncertainty in, and debate about, the best parameters to use for forecasting tornadoes. Fig. 7 depicts the combined graphic of the three fields of CAPE (> 2000 J kg^{-1} in black contours), SREH (> 200 m^2 s^{-2} in blue contours) and BRNSHR (> 40 m^2 s^{-2} in green contours). It highlights areas in which all the three fields are in the ranges that are favourable for low-level mesocyclones in both the cases of tornadic storms.

Rainfall values above 0.25 mm have been shaded in the diagrams to indicate areas of convection. Results show that on 30 August [Fig. 7(a)], the most favourable region for the development of tornadic storms was near the Nilfamari-Kurigram districts. On 3 September [Fig. 7(b)], the border areas between Bangladesh-Assam-Meghalaya were favourable for the development of tornadic storms. All the three parameters suggested the development of the storms.

4.2.5. *Dew point depression*

The presence of a dry-line is often considered as a signal to the convective initiation and tornadogenesis. The dry-line is defined by the leading edge of the dewpoint temperature gradient greater than or equal to 15 °C (100 km) $^{-1}$ (Roebber *et al*., 2002; Stensurd and Weiss, 2002). The dry-line acts as a boundary between dry and moist air mass, and may be conducive for the development of convection by forcing a deep layer of dry air above a moist boundary layer. Sometimes a double dry-line structure is also found in the regions of tornado genesis (Roebber *et al*., 2002). For simplicity, in this study we have analyzed the dewpoint depression, TDD [Figs. 8(a&b)]. The dry and moist areas are demarcated by shading the TDD values less than 7 °C. Figs. 8(a&b) show that the dew point depression values were as much as 2-7 °C in the vicinity of the places where storms were reported. Hourly time sequence of the simulated values depicted the swapping of dry (moist) air by moist (dry) air many times prior to and after the occurrences of the storms. However, the dry-lines generally remained fairly ill-defined.

4.2.6. *Potential vorticity*

The potential vorticity (PV) is the absolute circulation of an air parcel that is enclosed between two isentropic surfaces. In adiabatic, frictionless flow, (Ertel) potential vorticity (PV) is defined as a product of absolute vorticity and static stability on a constant potential temperature surface, *i.e*.,

$$\mathrm{PV} = -g\left(\varsigma_\Theta + f\right)\frac{d\theta}{dp} \approx \frac{\varsigma + f}{D} \qquad (5)$$

where, g is the acceleration due to gravity, ς_Θ is the relative isoentropic vorticity, ζ is the relative vorticity, f is the coriolis parameter, θ is the potential temperature, p is the pressure and D is the depth of layer. If PV is displayed on a surface of constant potential temperature, then it is called IPV (Isentropic Potential Vorticity). Of course, PV could also be displayed on another surface, for example a pressure surface. From the above relation it may be noted that, PV is simply the product of absolute vorticity on an isentropic surface and static stability. So PV consists, in contrast to vorticity on isobaric surfaces, of two factors, a dynamical element and a thermodynamical element. The potential vorticity has the SI unit m^2 s^{-1}K kg^{-1}. It has become accepted to define 1.0×10^{-6} m^2 s^{-1}K kg^{-1} as one potential vorticity unit (1 PVU). PV remains conserved in adiabatic, frictionless, non-compressible and homogeneous conditions. PV can only be changed by diabatic heating (such as latent heat released from condensation) or frictional processes. When the air converges, to maintain potential vorticity, the air speed increases, resulting in a stretched rince vortex. Divergence causes the vortex to spread, slowing down the rate of spin. PV is a useful concept for understanding the generation of vorticity in cyclogenesis and flow over mountains.

The percentage of supercell storms that produce low-level mesocyclones is not known. Moreover, the fraction of low-level mesocyclones that subsequently produce tornadoes is not known. Studies of the conceptual model of mesocyclones by Brookes *et al*. (1994a,b) indicated that the strength and lifetime of low level mesocyclones is a function of the balance between low-level baroclinic generation of vorticity and outflow development. An important question is whether non tornadic supercell storms are simply ones that fail to produce low-level mesocyclones or are unable to produce tornadoes once a low-level mesocyclone develops. Preliminary observations from the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX; Rasmussen *et al*., 1994) examined some of these issues. Several storms intercepted during the experiment generated moderate to strong low-level mesocyclones yet failed to produce a tornado (Wakimoto and Atkins, 1996; Trapp, 1997; Wakimoto and Huaqing, 2000). Trapp (1997) examined three tornadic and three nontornadic supercells using airborne Doppler radar data. At the time of tornado formation or failure, his results suggested that tornadic mesocyclones have smaller core radii, stronger low-level vertical vorticity, and are associated with stronger vortex stretching.

Given that many severe convective outbreaks are associated with mobile upper-level troughs, it is natural to ask whether the characteristics of severe convection are sensitive to the presence and intensity of such mobile troughs. Several researchers have used PV concept to infer the balanced dynamics of predominately synoptic-scale weather features. Gold and Nielsen-Gammon (2008) showed that, local increases in PV produced proportional increases of CAPE. They also studied the response of various shear parameters and vertical motion to upper-level PV modifications during an outbreak of 56 tornadoes in six states from Texas to Illinois on 13 March, 1990. Their results showed that the 0-6 km vertical shear and the storm-relative environmental helicity (SREH) are useful for distinguishing between environments supporting tornadic and nonsevere thunderstorms. The SREH depends on both the vertical shear and the estimated storm motion vector (SMV). Amplifying (reducing) the magnitude of the upper-level PV anomalies reduces (increases) the SREH downshear of the modification. A positive upper-level PV perturbation, such as is produced when an upper-level trough is amplified, will always produce a cyclonic circulation of the perturbation shear vector such that the shear is generally opposed (enhanced) on the trough's cyclonic (anticyclonic) shear side. Davenport (2009) used the non-linear balance PV inversion developed by Davis and Emanuel (1991) to atmospheric features and motions on the order of the meso- and storm-scale. He examined the low level thunder-storm dynamics from a PV perspective for an idealized super cell using the WRF model and showed that the PV diagnostic can be applied to thunderstorm dynamics.

The vertical profiles of the potential vorticity simulated by the model are presented in Figs. 8(c&d) for the 2 cases. The cross sections are drawn across the areas of maximum convection. The simulation of 30th August case of Nilphamari and Kurigram [Fig. 8(c)] shows mostly positive values having maximum of about 2-4 PVU located between 600-800 hPa. The other event of 3rd September [Nilphamari; Fig. 8(d)] showed similar values. It is not known what is the critical value of PV for the tornadic mesocyclones. But, thunderstorms of tornadic intensity did occur in both the events presented here. More research is required to differentiate between the cases of supercell thunderstorms, supercell thunderstorms with tornadic intensity and supercell thunderstorms that eventually developed into tornadoes.

5. Summary and concluding remarks

Bangladesh is prone to severe thunderstorms of tornadic intensity due to its geophysical location. Four tornadic storms were reported in the Northwestern parts of Bangladesh during 30 August to 14 September, 2008 by news media. We have presented detailed model analyses of two events that occurred on 30 August and 3 September. The tornadic thunderstorms were produced due to low level moisture incursion by southerly flow from the Bay of Bengal coupled with upper level westerly jet stream causing intense instability and shear in the wind fields. Owing to lack of dense network of observatories in the area, many vital observations could not be collected during the severe thunderstorms.

Investigations are carried out based on hourly precipitation data derived from a S-band radar located at Dhaka. The two tornadic events are simulated using the WRF-ARW model nested at 9 and 3 km horizontal resolutions using 6 hourly NCEP analyses. Results indicate that the model simulated the storms about 2 hours after the observed time. There were differences of tens of kilometers between the observed and simulated locations of the storms.

The maximum and minimum values of CAPE simulated by the model were about 3688 and 2413 J kg^{-1}. The maximum surface wind speed simulated by the model was generally underestimated. It seems that the funnel vortex did not reach the ground, and might have passed a few hundred meters above the surface. The maximum values of SREH simulated by the model were 250-300 m^2 sec^{-2}, which were generally in the prescribed range for the occurrence of the supercells possible with weak tornadoes according to Fujita scale. The maximum values of the BRNSHR simulated by the model were about 60-70 m^2 sec^{-2} when CAPE and SREH are also conducive for producing rotating storms according to the prescribed range.

This study is the first attempt to simulate tornadic storms over Bangladesh by using the WRF model at 3 km horizontal resolution. Results have provided many interesting findings, but also indicated many weaknesses in our present understanding and capability to forecast the tornadic storms with sufficient lead time and accuracy. There is a severe scarcity of data to understand the observational characteristics of the tornadoes in this region. Such data will have to be supplemented by intensive field observations. The modeling studies will have to be carried out at much higher resolution (few hundred meters) considering the scale of such storms. Many sensitivity studies with the physical processes need to be carried out to unravel the dynamical and physical mechanisms of the tornado genesis and intensification of the updraft vortex in this region. Assimilation of radar, satellite and dense network of surface observations in the model may improve the accuracy of the forecasts.

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