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Simulation of a heavy rainfall event of 11 June 2007 over Chittagong, Bangladesh using MM5 model

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सार – इस शोध पत्र में पांचवी पीढ़ी (जेनरेशन) के पी. एस. यू./एन. सी. ए. आर. मेसोस्केल मॉडल 5 (एम. एम. 5) का उपयोग करते हुए बंगलादेश के चिट्टगांव में दिनांक 11 जून, 2007 को हुई भारी वर्षा की घटना को समझाने का प्रयास किया गया है। यह असामान्य वर्षा की घटना चिट्टगांव क्षेत्र में हुई और उस दिन 24 घंटे की अवधि में 425 मि. मी. वर्षा अभिलेखित की गई। इसके परिणामस्वरूप आकस्मिक बाढ़ आ जाने और भू–स्खलन होने से जान–माल का भारी नुकसान हुआ। मध्य अवधि पूर्वानुमान (एम. आर. एफ.) ग्रहीय परिसीमा स्तर (पी. पी. एल.) योजना के साथ एन्थीस-कुओ (अर्थात ए. के.) कपासी प्राचलीकरण योजना (सी. पी. एस.) का उपयोग करते हुए त्रि–स्तरीय क्षेत्रों में 45, 15, 5 कि.मी. के क्षैतिज विभेदन में इस एम. एम. 5 मॉडल को चलाया गया। एम. एम. 5 से प्राप्त किए परिणामों से पता चला है कि चिट्टगांव के स्थानीय क्षेत्र में भारी वर्षा का कारण वृहत्त पैमाने पर सक्रिय मॉनसून प्रणाली के साथ मेसोस्केल के तीव्र संवहनीय पक्रियाओं का परस्पर प्रभाव था। विश्लेषण से पता चला है कि चिट्टगांव के ऊपर निर्मित संवहनीय सेल (मेघपुंज) अत्याधिक सघन परंतु अल्पकालिक थे और उसके लिए बंगाल की खाड़ी से आवश्यक नमी मिली थी। इस एम. एम. 5 मॉडल में कपासी प्राचलीकरण का सुग्राहिता परीक्षण भी किया गया है। इन परिणामों से पता चलता है कि प्रेक्षित टी. आर. एम. एम. वर्षा की तुलना में डब्ल्यू. आर. एफ. पी. बी. एल. सूत्रीकरण से ए. के. सी. पी. एस. द्वारा इस मॉडल में चिट्टगांव में हुई वर्षा की अधिक मात्रा का आकलन किया गया है और गेल, के. एफ., बी. एम. द्वारा के. एफ. 2 के कपासी मेघ प्राचलीकरण योजनाओं द्वारा वर्षा की कम मात्रा का आकलन किया गया है तथा बी. एम. डी. आर. एन. सी. की तुलना में संपूर्ण सी. पी. एस. का कम आकलन किया गया है। अंततः एम. आर. आफ. पी. बी. एल. के साथ एन्थीस कुओ कपासी योजना को बंगलादेश में हुई वर्षा के आकलन के लिए बेहतर पाया गया है। इस मॉडल के कार्यनिष्पादन का आकलन औसत समुद्र तल दाब, ऊपरी एवं निचले स्तर में वायु परिसंचरण, पवन अपरूपण, सापेक्षिक भ्रमिलता, अभिसरण, नमी एवं वर्षा जैसे पूर्वानुमान के भिन्न–भिन्न प्राचलो की जांच करके किया गया है। इन परिणामों से पता चलता है कि एम. एम. 5 मॉडल को छोट–छोटे क्षेत्रों, क्षैतिज विभेदन एवं कपासी प्राचलीकरण योजनओं के सही मिश्रण से भारी वर्षा की घटना और इससे संबंधित सिनॉप्टिक विशेषताओं की सही जानकारी दी जा सकती है फिर भी वर्षा के पैटर्न के संबंध में कुछ पूर्वाग्रह है।

ABSTRACT. The present study attempts to simulate a heavy rainfall event that occurred on 11 June 2007 over Chittagong, Bangladesh using the Fifth-Generation PSU/NCAR Mesoscale Model (MM5). This extraordinary rainfall event was localized over Chittagong region and recorded 425 mm of rainfall within a span of 24 hrs on that eventful day. The event resulted in large human and economic losses due to flash flood and land slide. The MM5 model was run on triple-nested domains at 45, 15, 5 km horizontal resolution using Anthes-Kuo (*i.e.*, AK) cumulus parameterization scheme (CPS) with medium range forecast (MRF) planetary boundary layer (PBL) scheme. The results obtained through MM5 suggest that the highly localized heavy rain over Chittagong was the result of an interaction of the mesoscale severe convective processes with the large scale active monsoon system. The analysis shows that the convective cells formed over Chittagong were very intense but short-lived and required moisture have been supplied from the Bay of Bengal. A sensitivity test of cumulus parameterizations in MM5 model has also been conducted. The results show that the model simulated rainfall amount over Chittagong has been overestimated by AK CPS with MRF PBL formulation and underestimated by Grell, KF, BM and KF2 cumulus parameterization schemes compared to the observed TRMM rainfall and all CPS are underestimated as compared with BMD RNG. Finally, the Anthes-Kuo cumulus scheme with MRF PBL has been found to perform better in estimating rainfall over Bangladesh. The model performance was evaluated by examining the different predicted parameters like mean sea level pressure, upper and lower level circulations, wind shear, relative vorticity, convergence, moisture and rainfall. The results indicate that the MM5 model with the right combination of the nesting domain, horizontal resolution and cumulus parameterization schemes was able to simulate the heavy rainfall event, and associated synoptic features reasonably well, though there are some biases in the rainfall pattern.

Key words – Heavy rainfall, TRMM, Cumulus parameterization, MM5 model, Convection.

1. Introduction

Chittagong – the southeastern coastal metropolitan city and commercial capital of Bangladesh (latitudes 20° 34´ - 26° 38´ N and longitudes 88° 01´ - 92° 41´ E) is situated on the western slopes of Mizo hills and Arakan Mountains. Chittagong is very different in terms of topography from the rest of Bangladesh, as the city is part of the hilly regions. The location of Chittagong and its surroundings is presented in Fig. 1. On 11 June 2007, Chittagong received unprecedented heavy rainfall and more than one-third of the metropolitan city was inundated. This extraordinary rainfall event was localized over Chittagong region. The meteorological station Ambagan (91.82° E, 22.35° N) located in the centre of the Chittagong city recorded 425 mm of rainfall within a span of 24 hrs. This torrential rain disrupted life in the metropolitan city by causing severe flash floods. In addition to the floods, the rains triggered devastating landslides in the deforested hills. The death tolls caused by the floods and landslides were 130 on June 12 as reported in the print media. Most of the deaths were caused by the landslides or from collapsing of dwelling houses by the floods and landslides.

Fig. 1. Map showing the location of Chittagong (91.82° E, 22.35° N) and surroundings of Bangladesh

Heavy rainfall events become significant in human affairs when they are combined with other hydrological elements. The problem of forecasting heavy precipitation is especially difficult since it involves creating a quantitative precipitation forecast, recognized as a challenging task (Charles, 1993). Simulation of active mesoscale systems such as western disturbances, severe thunderstorms, tropical cyclones and heavy rainfall episodes during active monsoon season, with high-resolution mesoscale models such as the Fifth-Generation NCAR/PSU Mesoscale Model (MM5), has been attempted by many researchers (Braun and Tao, 2000; Patra *et al*. 2000; Seaman, 2000; Das, 2002; Jenamani *et al*. 2006; Bohra *et al*. 2006 and Litta *et al*. 2007). Application of NWP model in weather research and forecasting is very new in Bangladesh. Some works have been done on thunderstorm activities during pre-monsoon (Prasad, 2006; Akter and Islam, 2009; Das, 2009; Ahasan *et al*. 2009) and on heavy rainfall during summer monsoon (Prasad, 2005 and Ahasan *et al*., 2011) using NWP model.

The present study has been undertaken to simulate the heavy rainfall event which occurred over Chittagong, Bangladesh on 11 June 2007 using the MM5 model with triple nested high resolution domain with grid spacing of 45, 15 and 5 km in the horizontal. The study was also aimed to identify the atmospheric conditions, which triggered and maintained such an event. A sensitivity test of the different cumulus parameterization schemes of MM5 model for rainfall prediction over Bangladesh was performed with the objective of selecting the most suitable scheme for this study. The study is the first of its kind in the context of Bangladesh and will improve the general understanding of the heavy rainfall processes during summer monsoon.

2. Data used, model experimental setup and methodology

The Fifth-Generation PSU/NCAR Mesoscale model (Grell *et al*. 1994; Dudhia *et al*. 2002) version 3.7 as adopted for real time mesoscale weather research and simulation at SAARC Meteorological Research Centre (SMRC), Dhaka, Bangladesh has been used for this study. The data used, experimental setup of the model and methodology of the study are provided in this section.

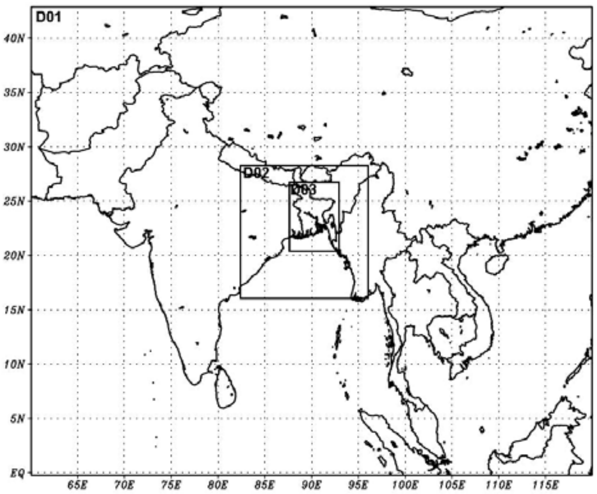


Fig. 2. Triple nested domains of MM5 model

2.1. *Data used*

The NCEP high-resolution Global Final (FNL) Analysis data on 1.0° × 1.0° grids covering the entire globe every 6 hrs were used for model initialization and as lateral boundary conditions. The USGS topographic data GTOPO30 (Interpolated depending on resolution) were used as earth surface topography and 25 Categories USGS data were used as vegetation / land use. The 5 Layer soil moisture data were used as land surface processes.

The daily 0.25° × 0.25° resolution TRMM 3B42V6 rainfall data have been downloaded from their website (http://lake.nascom.nasa.gov) to justify the model simulated rainfall structure, development time and location. Meteosat cloud pictures have been downloaded from the website (www.sat.dundee.ac.uk) of Dundee Satellite Receiving Station to see the signature of cumulus cloud at the rainfall occurrence time. Moreover, daily observed rainfall data of 34 meteorological stations of Bangladesh have been collected from the archive of Bangladesh Meteorological Department (BMD) to validate the model derived rainfall.

2.2. *Model experimental setup and methodology*

For the present study, the model is run on triple-nested domains at 45, 15 and 5 km resolutions using Anthes-Kuo parameterization scheme (Anthes, 1977) based on 0000 UTC of 10 June 2007 (more than 24 hrs before the event) initial condition. The configured domains are shown in Fig. 2. Domain 1 (D1) is the coarsest mesh and has 120 × 105 grid points in the north-south and east-west directions respectively with a horizontal grid spacing of 45 km. Within the domain D1, domain 2 (D2) is nested with 100 × 94 grid points at 15 km grid spacing. The fine-mesh domain 3 (D3) is 151 × 115 points with 5 km grid spacing. Bangladesh is the main focus area in this study. The model uses two way nesting, where coarse grid data are interpolated to finer grid boundaries and the finer grid provides updated data to the coarse grid. All these 3 domains are centered at 20° N, 90° E over Bangladesh to represent the regional-scale circulations and to extract the complex meteorological features in the synoptic and sub-synoptic scales. All these domains were configured to have the same vertical structure of 23 unequally spaced non-dimensional pressure levels in the sigma coordinate. The other physical parameterization schemes used in this study are the medium range forecast (MRF) scheme for a planetary boundary layer (Hong and Pan, 1996), Simple ice for an explicit moisture scheme (Dudhia, 1989), Simple cooling as radiation scheme and Five layer soil model as land surface processes.

Different formulations of cumulus parameterization schemes, such as Anthes-Kuo (Anthes, 1977; Grell, 1993; Kain & Fritsch, 1993; Betts & Miller, 1993 and Kain, 2002) were used to conduct the sensitivity test of these schemes. The scheme with best performance is used for the study. The different predicted parameters like mean sea level pressure, upper and lower level circulations, wind shear, relative vorticity, convergence, moisture and rainfall fields were analyzed and discussed. The model simulated rainfall was compared against the rainfall recorded in the meteorological stations of Bangladesh and through TRMM observations.

3. Case description

The heavy rainfall event which occurred over Chittagong on 11 June 2007 is a significant meteorological event in Bangladesh. The event is well observed with conventional surface raingauges of the BMD. It has already been mentioned that the meteorological station Ambagan (91.82° E, 22.35° N) of Chittagong received 425 mm of rainfall within a span of 24 hrs on that eventful day. Other nearby weather stations of BMD recorded rainfall 225 mm at Sandwip (91.43° E, 22.48° N), 146 mm at Rangamati (92.20° E, 22.53° N), 110 mm at Kutubdia (91.85° E, 21.82° N) and 101 mm at Cox’s Bazar (91.98° E, 21.43° N). The station Patenga (91.82° E, 22.27° N) in south Chittagong received about 348 mm rainfall which was also the highest rainfall on that day.

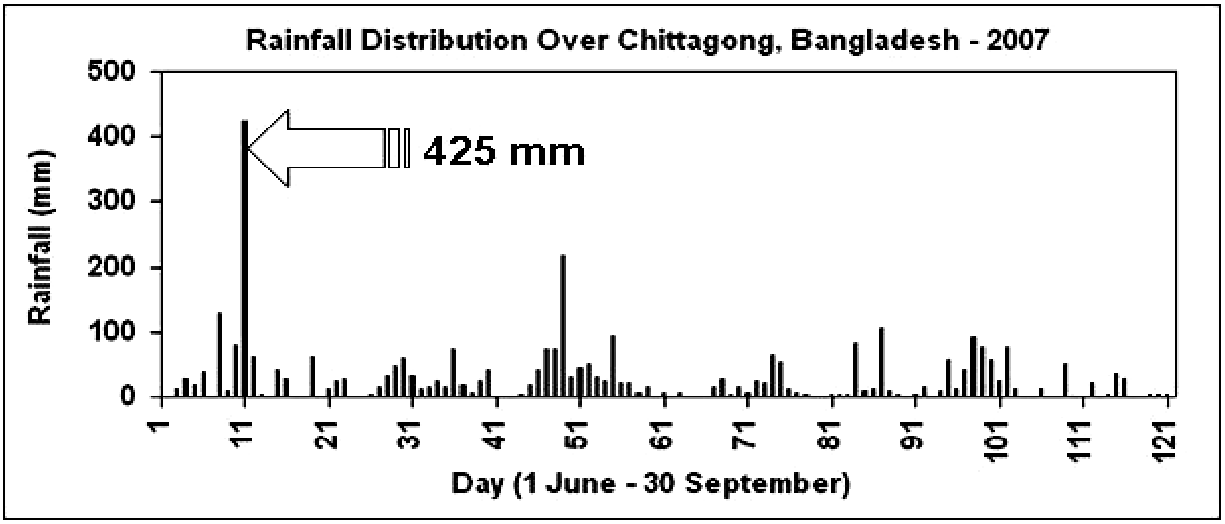


Fig. 3(a). Time series of observed daily accumulated rainfall of Chittagong during summer monsoon 2007. The heavy rainfall event on 11 June 2007 is indicated by arrow sign

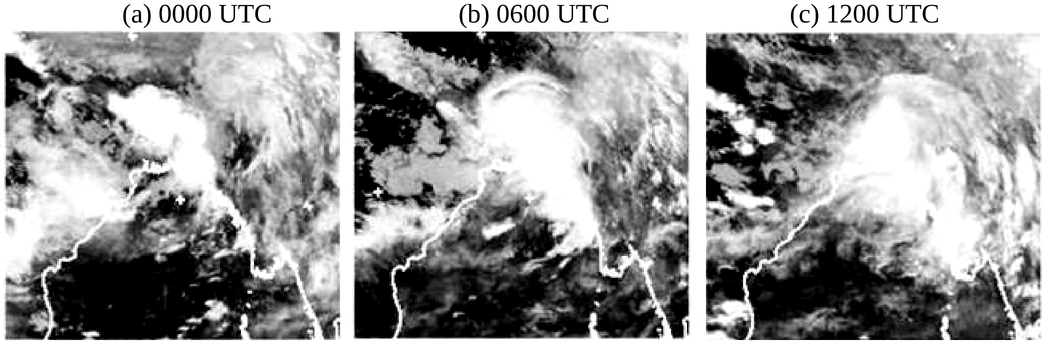


Fig. 3(b). Meteosat-5 VISSR (IODC) Infrared cloud image at (a) 0000 UTC, (b) 0600 UTC and (c) 1200 UTC on 11 June, 2007

TABLE 1

Suitable cumulus parameterization schemes obtained through comparative analysis of model derived rainfall with that of TRMM and BMD RNG

Model simulated rainfall compared with	Form of comparisons	Domain	Suitable scheme
TRMM 3B42V6	Spatial comparison	D3	AK, KF
	Quantitative comparison	D3	AK, Gr
BMD RNG	Spatial comparison	D3	AK, KF
	Quantitative comparison	D3	AK

The time series of daily accumulated rainfall of Chittagong recorded by the BMD during summer monsoon 2007 is presented in Fig. 3(a). The heavy rainfall event on 11 June 2007 is clearly seen in the figure which is indicated by arrow sign. The 6 hourly Meteosat IR images have been presented in Fig. 3(b) to visualize spatial pattern of the distribution of the convective clouds in relation to the occurrence of the unprecedented rainfall event. The dense and organized convective clouds are observed over Chittagong and its neighborhoods on 11 June, 2007 in the cloud images, specially in the image of 0600 UTC [Fig. 3(b)].

TABLE 2

Comparison of model derived rainfall (with and without CPS option) with that of TRMM and BMD RNG for D3 region

SN	CPS			Rainfall (mm) For D3
	D1	D2	D3	
01	AK	AK	AK	65.09
	AK	AK	-	46.54
02	Gr	Gr	Gr	43.14
	Gr	Gr	-	40.38
03	KF	KF	KF	28.30
	KF	KF	-	14.96
04	BM	BM	BM	26.74
	BM	BM	-	17.97
05	KF2	KF2	KF2	22.71
	KF2	KF2	-	16.52
06	-	-	TRMM	52.31
07	-	-	BMD	67.24

4. Results & discussion

4.1. *Sensitivity test*

A sensitivity test has been conducted to find out most suitable cumulus parameterization scheme in MM5 for rainfall estimation over Bangladesh. Five cumulus parameterization schemes like Anthes-Kuo (AK), Grell (Gr), Kain-Fritsch (KF), Betts-Miller (BM) and Kain-Fritsch2 (KF2) are used with MRF PBL to simulate the heavy rainfall case of 11 June 2007. Both subjective analysis through visualization of the spatial pattern of the rainfall distribution and quantitative evaluation by averaging the rainfall amount within D3 domain have been followed for comparing the MM5 outputs with TRMM 3B42V6 and BMD rain gauge (RNG) data. The D3 domain just covers the territory of Bangladesh and its close adjacent areas of the surrounding countries. The most suitable cumulus parameterization scheme is identified out of 5 options under consideration based on the results obtained from this spatial and quantitative analysis. The comparative results are given in Table 1. It is found that the Anthes-Kuo scheme was able to simulate this heavy rainfall case reasonably well both through spatial and quantitative analysis though it is found to overestimate the rainfall as compared with both TRMM and BMD observations.

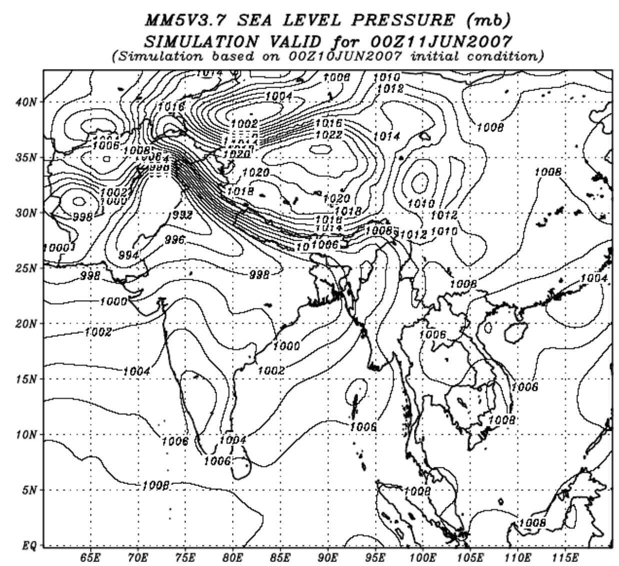
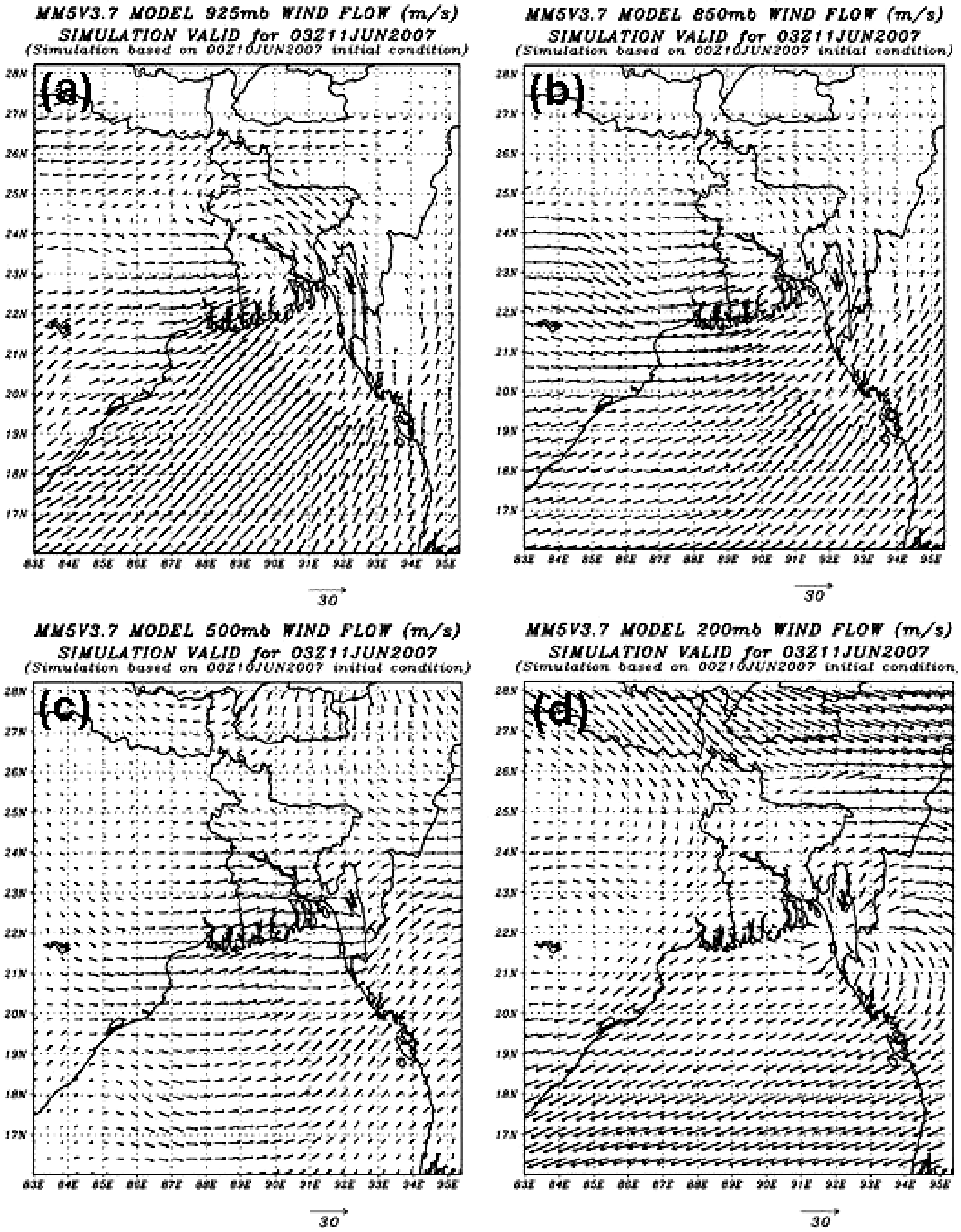


Fig. 4. Analysis of mean sea level pressure (hPa) field valid for 0000 UTC of 11 June 2007 as obtained from the MM5 model run

The study has further been continued with and without cumulus parameterization schemes (CPS) for D3 domain. The area average rainfall is collected from each of the model output at D3 resolution and



Figs. 5(a-d). Wind flow (m/s) analysis at (a) 925 hPa, (b) 850 hPa, (c) 500 hPa and (d) 200 hPa valid for 0300 UTC of 11 June 2007

compared them with TRMM and BMD RNG which are presented in Table 2. It is found that the simulated rainfall with Anthes-Kuo (*i.e.*, AK) scheme produces rainfall of 65.09 mm which is very close to the observed rainfall of BMD RNG (67.24 mm) and TRMM (52.31 mm). Finally, the Anthes-Kuo cumulus parameterization scheme with MRF PBL has been considered as the best MM5 option for rainfall estimation over Bangladesh.

4.2. *Mean sea level pressure analysis*

Summer monsoon rainfall over Bangladesh is characterized by significant wet (active) or dry (break)

TABLE 3

Types of thunderstorm based on vertical wind shear (Summarized from Holton, 2004)

Vertical wind shear (m/s)	Types of thunderstorm	Lifetime
Weak vertical wind shear ($<10\ ms^{-1}$, in the lowest 4 km of troposphere)	Only single cell may be expected to form	These tend to be short lived (~30 min) and move with the mean wind in the lowest 8 km
Moderate vertical wind shear (10-20 ms^{-1}, in the lowest 4 km of troposphere)	Multi-cell may be expected to form. New cell tends to develop in every 15-30 minutes	The individual cells have lifetimes of ~30 min, but the storm lifetime may be many hours
Large vertical wind shear ($>20\ ms^{-1}$, in the lowest 4 km of troposphere)	Super cell and tornado may be expected to form	A single super cell can last several hours

spell on a time scale of about two weeks (Prasad, 2005). The primary cause of these active and break spells are the fluctuations of the intensity and position of the monsoon trough. Monsoon trough is an extended trough of low pressure which runs across the Gangetic plains of north India with western end anchored to the monsoon heat low over northwest India and Pakistan, and eastern end emerging into the head Bay of Bengal.

Model simulated mean sea level pressure (hPa) for D1, valid for 0000 UTC of 11 June 2007 is presented in Fig. 4. It is found that the model has simulated the large-scale processes such as seasonal monsoon trough reasonably well. The intense and northerly positioned seasonal monsoon trough which indicates the break monsoon condition over central and southern India and active monsoon condition over Bangladesh and nearby territory of northeast India and Bhutan (Quadir *et al.*, 2007) seems to be a prominent feature responsible for this event. The heat low over Pakistan is very strong. The pressure at the centre of the heat low is about 992 hPa and that over the southern part of India is about 1008 hPa. Monsoon flow is strong due to high north-south pressure gradient. About three isobars lie over Bay of Bengal with a trough over south-east Bangladesh. The above synoptic features generated favourable conditions for developing the severe mesoscale convections resulting heavy rainfall over the areas of southeast Bangladesh.

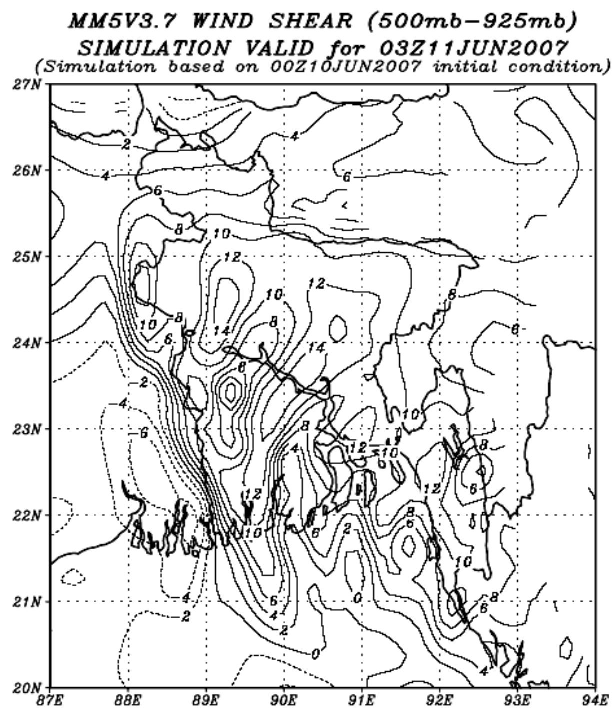


Fig. 6. Vertical wind shear of the u component of wind (m/s) in the lower troposphere (500-925 hPa), valid time 0300 UTC of 11 June 2007

4.3. *Low level and upper level wind flow analysis*

One of the main synoptic conditions for occurrence of heavy rainfall in Bangladesh and neighbourhood is the southerly and / or southwesterly low level flow streaming from the head Bay of Bengal into Bangladesh during summer monsoon period (Prasad, 2005). The distribution of low level wind flow at 925 hPa and 850 hPa levels, and mid and upper level wind flow at 500 hPa and 200 hPa levels valid for 0300 UTC of 11 June 2007 has been presented in Figs. 5(a-d). The prominent feature is a strong southwesterly low level flow transporting moisture from the Bay of Bengal into southeast Bangladesh at

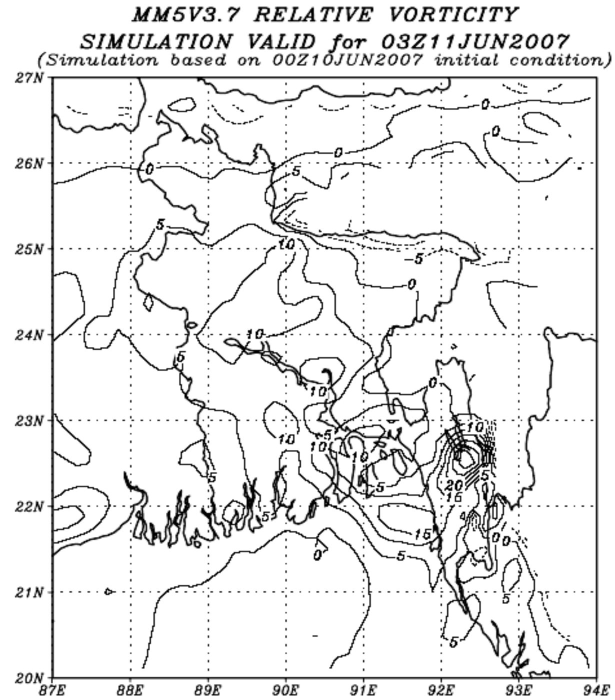


Fig. 7. Low level relative vorticity (unit: $\times10^{-5}s^{-1}$) at 925 hPa, valid for 0300 UTC of 11 June 2007

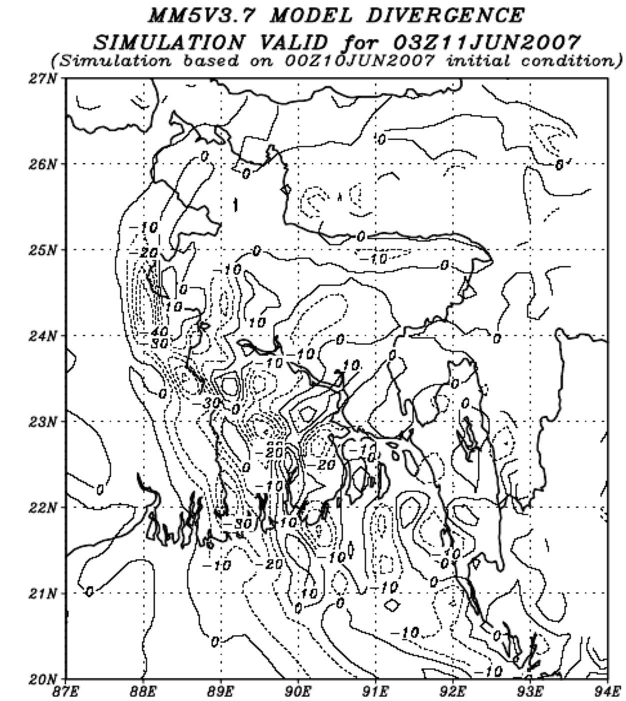


Fig. 8. Low level divergence at 925 hPa (unit: $\times10^{-5}s^{-1}$) at 925 hPa, valid for 0300 UTC of 11 June 2007

0300 UTC of 11 June 2007 [Fig. 5(a)]. The southwesterly at 850 hPa and westerly at 500 hPa are dominant. A jet streak of about 30-40 knots in the neighbourhood of southeast Bangladesh is a prominent feature marking the strong vertical wind shear in the lower troposphere. The low level southwesterly winds take sharp anti-clockwise turning over the Chittagong area where the marking event of heavy rainfall had occurred. An area of convergence of low level wind flow [Fig. 5(a)] and an area of divergence of upper level wind flow [Fig. 5(d)] are the signs of strong convective activity over these areas.

4.4. *Vertical wind shear analysis*

Vertical wind shear is an important dynamical factor in the development of convective systems in the form of thunderstorm, tornadoes and determination of thunderstorm types and potential storm severity (Holton, 2004) which is summarized in Table 3.

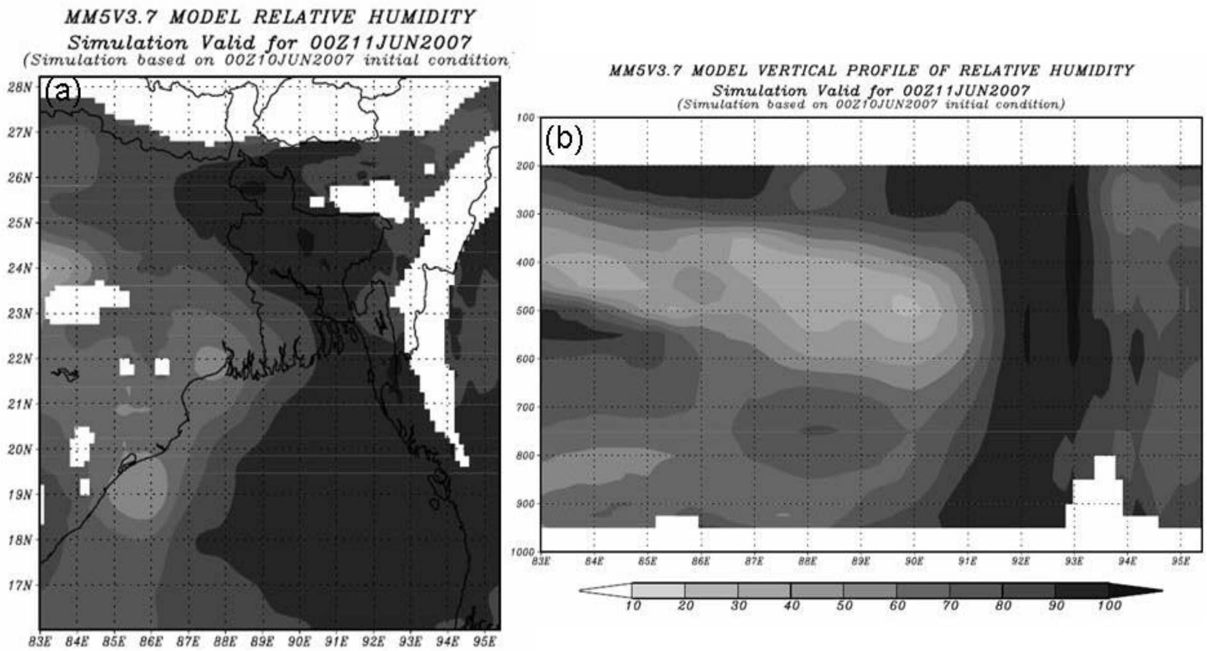
Vertical wind shear of the u component of wind (m/s) in the lower troposphere (500-925 hPa), valid time 0300 UTC of 11 June 2007 is presented in Fig. 6. It is found that the atmosphere of Chittagong and neighbourhood was characterized by the strong vertical wind shear. A core of strong vertical wind shear of the order of 12-15 m/s is seen in the southeast of Bangladesh and its neighbourhood. This wind shear helps to developed intense and short lived multi cell thunderstorm over Chittagong and other parts of Bangladesh which being combined with the monsoon flow gives heavy rainfall.

4.5. *Low level relative vorticity analysis*

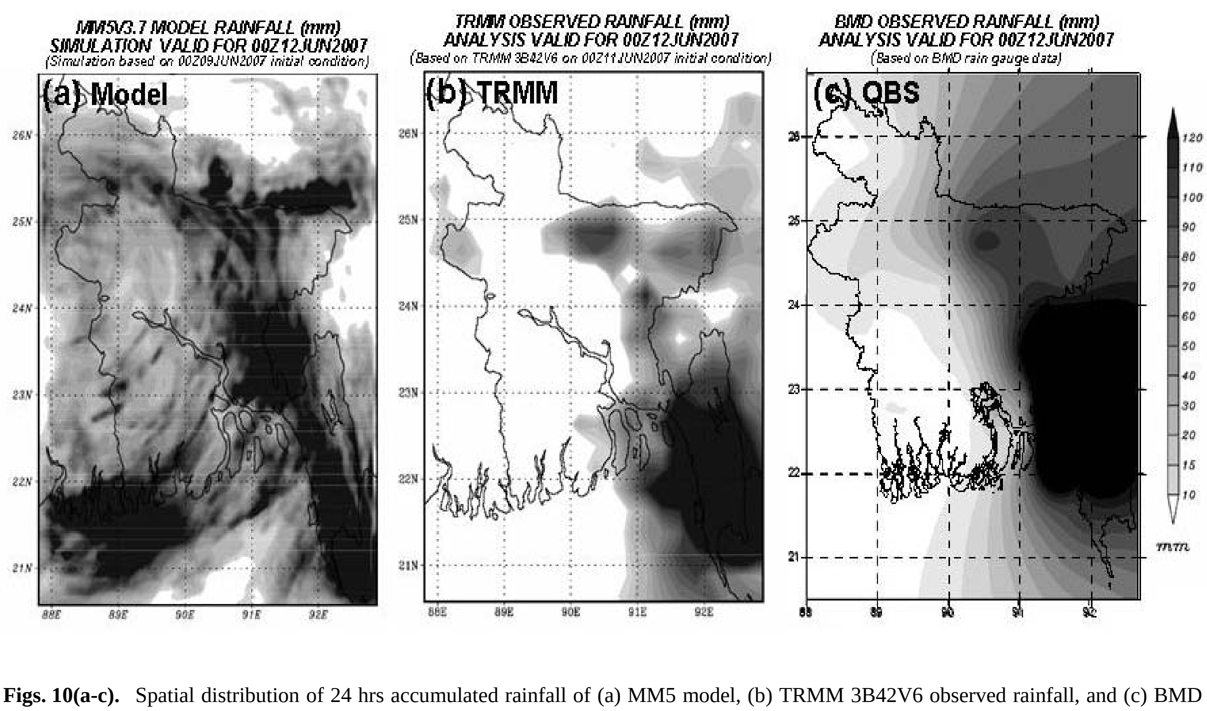
The low level relative vorticity is the important field for formation of the convective systems. The low level relative vorticity field at 925 hPa level valid for 0300 UTC of 11 June 2007 is presented in Fig. 7. It is found that an elongated area of vorticity maxima was observed over Chittagong and neighbourhood due to horizontal wind shear in the southerly and / or southwesterly flow over the head Bay of Bengal. The relative vorticity field shows strong vorticity maxima of the order of 15-20 $\times$ 10^{-5} s^{-1} across Chittagong and neighbourhoods which make the condition favourable for formation of the convective systems.

4.6. *Analysis of low level divergence fields*

Low level divergence is one of the important parameters to analyze the convection systems. The



Figs. 9(a&b). (a) Spatial distribution of relative humidity analysis at 0000 UTC of 11 June 2007 and (b) vertical profile of relative humidity field along the latitude of 22.35° N over Chittagong at 0000 UTC of 11 June 2007



Figs. 10(a-c). Spatial distribution of 24 hrs accumulated rainfall of (a) MM5 model, (b) TRMM 3B42V6 observed rainfall, and (c) BMD rain gauge (RNG) observed rainfall over Bangladesh on 11 June 2007 distribution of low level divergence field at 925 hPa is shown in Fig. 8. Most of the study area and its vicinity show high negative values of divergence indicates strong convergence. Mean sea level pressure distribution (Fig. 4) and low level wind patterns [Fig. 5(a)] also indicate the convergence of strong jet streams over Chittagong, which carries enormous energy in the form of latent heat of evaporation to these areas. This strong low level convergence associated with strong outflow (divergence) in the high level (200 hPa) [Fig. 5(d)] has provided favourable conditions for strong convection and production of very high rainfall.

4.7. *Horizontal and vertical distribution of humidity field*

Spatial distribution of relative humidity of 11 June 2007 at 0000 UTC of 11 June 2007 is presented in Fig. 9(a). It is found that the magnitude of humidity is very high over south-central, southeast, north and northeast of Bangladesh at 0000 UTC of 11 June, 2007. The circulation of southwesterly low level flow [(Fig. 5(a)] transports plentiful moisture from the Bay of Bengal to the plains of southeast Bangladesh and its neighbourhoods. It is seen that the high humidity spreads over a large area of the Bay of Bengal which converges along a narrow zone in and around Chittagong and Meghna estuary situated to the west of Chittagong. This convergence of moisture field enforces the air to rise up causing convection over this area. The vertical profile of the relative humidity field at 0000 UTC of 11 June, 2007 along the latitude 22.35° N passing across Chittagong is presented in Fig. 9(b). It is found that the vertical extent of high humidity reaches up to 200 hPa over Chittagong at 0000 UTC of 11 June, 2007 along a narrow vertical column of the troposphere. The width of this column is around 150 km in the E-W direction in the narrowest zone. This clearly indicates the vertical growth of the convective system that produced the rainfall of high intensity.

4.8. *Rainfall analysis*

The MM5 model simulated 24 hrs accumulated rainfall on 11 June 2007 for domain 3 (D3) at 5 km resolution which is given in Fig. 10(a). The model simulated rainfall has been compared with the TRMM 3B42V6 and BMD RNG rainfall which are shown in Figs. 10(b&c). The model simulated rainfall indicates high values over Chittagong and its surrounding areas agreeing well with observations produced by TRMM and BMD rain gauges [Fig. 10(b)]. TRMM distribution shows large spatial variability between north and south of Chittagong. The distribution of BMD RNG data shows good rainfall in the southern part of Bangladesh, but low rainfall over the rest of the country. It is found that model simulated rainfall over the country using AK cumulus parameterization scheme with MRF PBL overestimated the rainfall compared to that of TRMM and BMD RNG. However, the MM5 model not only captured the location of the heavy rainfall area over Chittagong and its neighbourhoods but also in many other places providing a picture of spatial variability. Thus it is expected that the model would have generated higher than realistic rainfall throughout the country. It is seen from the spatial distribution of rainfall [Figs. 10(a-c)] that, the model results do not match with TRMM and BMD RNG observation over the other areas except the Chittagong and its neighbourhoods. It is to mention in this regards that the network of raingauge stations of Bangladesh is not dense enough to capture the realistic picture of mesoscale processes unless one or more stations are located on the passage of convective systems. So far the TRMM data is concerned, it was found by Islam and Uyeda (2007) that TRMM underestimates the monsoon rainfall in this region. Thus, the MM5 model-simulated rainfall seems to be more or less realistic both for quantitative assessment of rainfall and geographical distribution.

5. Conclusions

On the basis of the present study, the following conclusions are drawn:

(*i*) The Anthes-Kuo cumulus parameterization scheme was found to be the most suitable one through a sensitivity test experiment performed with 5 cumulus parameterization schemes.

(*ii*) The MM5 model suggests that the highly localized heavy rain over Chittagong was resulted by the large scale weather circulation associated with active conditions of southwest summer monsoon over the head Bay of Bengal which generated favourable conditions for developing the severe mesoscale convections resulting heavy rainfall. During this time the monsoon trough had more northerly orientation close to the foot hills of Himalayas characterizing weak/break monsoon condition for most part of India. But for Bangladesh this was an exceptional situation when Bangladesh specially its southern part experienced an active phase of monsoon. The intensity of the heat low was 992 hPa which is below normal (994 hPa). The intensity of north-south pressure gradient was also strong.

(*iii*) The strong confluence of southwesterly low level flow transporting large amount of moisture from the Bay of Bengal towards southeast Bangladesh and its neighbourhoods appears to be one of the striking features behind the strong convection over southeast Bangladesh.

(*iv*) The other favourable conditions are strong low level vertical wind shear, strong low level convergence and strong high level divergence, strong low level relative vorticity and advection of strong humidity fields by low level jet streams from extended areas of the Bay of Bengal which confluence in a relatively small area over Chittagong and its neighbourhoods due to the strong convergence of wind field over these areas. The vertical extent of relative humidity reaches up to upper troposphere along a narrow vertical column situated in the areas of the high rainfall activity.

(*v*) The model simulation produces realistic pattern of rainfall over Chittagong and its neighbourhoods as compared with TRMM and BMD RNG observations. Model simulation using D3 domain produces detailed structure of the spatial patterns of rainfall over Bangladesh.

Finally, it may be concluded that the Fifth-Generation PSU/NCAR Mesoscale Model MM5 version 3.7 with the right combination of the nesting domain, horizontal resolution and cumulus parameterization scheme was able to simulate the heavy rainfall event over Chittagong and associated favourable synoptic features reasonably well, though there are some spatial and temporal biases in the simulated rainfall pattern.

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References

Ahasan, M. N., Chowdhury, M. A. M. and Quadir, D. A., 2011, “Simulation of a heavy rainfall event on 14 September 2004 over Dhaka, Bangladesh using MM5 model”, *J. Sci. Res*., **3**, 2, 261-270.

Ahasan, M. N., Islam, M. N. and Ferdousi, N., 2009, “A diagnostic study on synoptic and environmental conditions favourable for the formation of the Nor’westers in and around Bangladesh using MM5 model”, Proceedings of the SAARC seminar on Nor’westers and tornadoes over the SAARC Region and their Forecasting & Preparedness, 20-21 August, 2008, Dhaka, Bangladesh, 143-156.

Anthes, R. A., 1977, “A cumulus parameterization scheme utilizing a one dimensional cloud model”, *Mon. Wea. Rev.*, **105**, 270-286.

Akter, N. and Islam, M. N., 2009, “Employment of MM5 in simulating MCSs developed in and around Bangladesh, *Mausam*, **60**, 2, 137-146.

Braun, S. A. and Tao, W. K., 2000, “Sensitivity of high-resolution simulations of hurricane Bob (1991) to planetary boundary layer parameterizations”, *Mon. Wea. Rev.*, **128**, 3941-3961.

Betts, A. K. and Miller, M. J., 1993, “In The Betts-Miller Scheme. The Representation of Cumulus Convection in Numerical Models”, Emanuel, K. A., Raymond, D. J. (eds), *American Meteorological Society*, Boston, MA, 246.

Bohra, A. K., Basu, Swati, Rajagopal, E. N., Iyengar, G. R., Gupta, M. Das., Ashrit, R. and Athiyaman, B., 2006, “Heavy rainfall episode over Mumbai on 26 July 2005: Assesment of NWP guidance”, *Current Science*, **90**, 9.

Charles, A. D., 1993, “Scientific approaches for very short-range forecasting of severe convective storms in the United States of America”, International Workshop on Observation/Forecasting of Meso-scale Weather and Technology of Reduction of Relevant Disasters, Tokyo, Japan, 22-26 February, 1993, 181-188.

Das, S., 2002, “Mesoscale and cloud resolving scale simulation of a heavy precipitation episode and associated cloud system using MM5 model”, INDO-US Workshop on Weather and Climate Modeling, New Delhi, 7-9 February, 2002.

Das, S., 2009, “Composite Characteristics of Nor’Westers observed by TRMM & Simulated by WRF Model”, SAARC Meteorological Research Centre (SMRC), SMRC Scientific Report No. 25.

Dudhia, J., Gill, D., Manning, K., Wang, W. and Bruyere, C., 2002, “PSU/NCAR Mesoscale Modeling System (MM5 version 3) tutorial class notes and user’s guide”, National Center for Atmospheric Research, Boulder, Colorado, USA, June 2002.

Dudhia, J., 1989, “Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model”, *Journal of Atmospheric Sciences*, **46**, 3077-3107.

Grell, G. A., Dudhia, J. and Stauffer, D. R., 1994, “A description of the 5^{th} generation Penn State/NCAR Mesoscale model (MM5)”, *NCAR technical note*, NCAR/TN-398+STR, **117**, p122.

Grell, G., 1993, “Prognostic evaluation of assumptions used by cumulus parameterizations”, *Mon. Wea. Rev.*, **121**, 764-787.

Holton, James R., 2004, “An Introduction to Dynamic Meteorology”, Fourth Edition, *International Geophysics Series*, **88**, Ch. 9.

Hong, S. Y. and Pan, H. L., 1996, “Non-local boundary layer vertical diffusion in a medium-range forecast model”, *Mon. Wea. Rev.*, **124**, 2322-2339.

Islam, Md. N. and Uyeda, H., 2007, “Use of TRMM in determining the climatic characteristics of rainfall over Bangladesh”, *Remote Sensing of Environment*, **108**, 264-276.

Jenamani, R. K., Bhan, S. C. and Kalsi, S. R., 2006, “Observational/forecasting aspects of the meteorological event that caused a record highest rainfall in Mumbai”, *Current Science*, **90**, 1344-1362.

Kain, J. S. and Fritsch, J. M., 1993, "Convective parameterization for mesoscale models: The Kain-Fritsch scheme, the representation of cumulus convection in numerical models", K. A. Emanuel and D. J. Raymond, Eds., *American Meteorological Society*, 246.

Kain, J. S., 2002, "The Kain-Fritsch Convective Parameterization: An Update", *Journal of Applied Meteorology*, **43**, 170-181.

Litta, A. J., Chakrapani, B. and Mohnakumer, K., 2007, "Mesoscale simulation of an extreme rainfall event over Mumbai, India, using a high-resolution MM5 model", *Meteorol. Appl*., **14**, 291-295.

Patra P. K., Santhanam, M. S., Potty, K. V. J., Tewari, M. T. and Rao, P. L. S., 2000, "Simulation of tropical cyclones using regional weather prediction models", *Current Science*, **79**, 70-78.

Prasad, K., 2006, "Environment and Synptic Conditions Associated with Nor'Westers and Tornadoes in Bangladesh: An Appraisal Based on Numerical Weather Prediction (NWP) Guidance Products", SAARC Meteorological Research Centre (SMRC), SMRC Scientific Report No. 14.

Prasad, K., 2005, "Monsoon Forecasting with a Limited Area Numerical Weather Prediction System", SAARC Meteorological Research Centre (SMRC), SMRC Scientific Report No. 11.

Quadir, D. A., Hussain, M. A. and Ahasan, M. N., 2007, "Climatic characteristics of temperature and precipitation of Bhutan", *Mausam*, **58**, 9-16.

Seaman N. L., 2000, "Meteorological modeling for air-quality assessments", *Atmospheric Environment*, **34**, 2231-2259.