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ORIGINAL PAPER

Prediction of heavy rainfall events over Rangamati, Bangladesh using high-resolution MM5 model

M. N. Ahasan · M. A. Mannan Chowdhury · D. A. Quadir

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Abstract In this study, prediction of the heavy rainfall events over Rangamati, Bangladesh has been carried out using the Fifth-Generation PSU/NCAR Mesoscale Model (MM5) conducting two historical rainfall events. The model was run on two-way triple-nested domains at 45, 15, 5 km horizontal resolutions using Anthes-Kuo cumulus parameterization schemes (CPS) with MRF planetary boundary layer (PBL). Bangladesh is the main focus area in this study. Thus, Bangladesh is taken as inner most domain (D3) with 5 km horizontal resolution. The model-predicted rainfall was compared with TRMM 3B42V7 and BMD observed rainfall. Both subjective and objective evaluation methods have been followed. The MM5 model produces realistic prediction of heavy rainfall events in terms of intensity and structure. The results show that the model performed all the Day 1 (24 h), Day 2 (48 h) and Day 3 (72 h) predictions reasonably well. The predictions are more accurate for Day 2 (48 h) and worse for Day 4 (96 h) in both cases. The prediction deteriorates as the prediction time increases. Thus, the prediction may be updated in every 24 h which would provide more realistic prediction. The RMSE shows that the value for 24 h prediction lies within 10–20 mm range. The prediction error is minimal for 48 h prediction, the error ranging from 8 to 12 mm. The error increases thereafter for 72 and 96 h of predictions. The errors range from around 10–20 and 15–25 mm, respectively. The topography/terrain over the southeast hilly region of Bangladesh has not been resolved by USGS terrain data which was used in the MM5 model. Thus, accurate and high-resolution terrain data of this region is expected to improve the performance of the model over the southeast hilly regions of Bangladesh.

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1 Introduction

Bangladesh (latitudes 20°34′–26°38′ north and longitudes 88°01′–92°41′east) is a disaster prone country. Most of the natural disasters of the country have meteorological origin. The heavy rainfall event causing flash flood is one of those disasters. The main socio-economic sectors affected by such rainfall events are: agriculture, infrastructures, human health and social services, etc. It is therefore, obvious, that an accurate and reliable prediction of the heavy rainfall events during summer monsoon season poses to be an important and challenging task. There are very limited facilities available in Bangladesh to forecast the heavy rainfall events of summer monsoon season. The Numerical weather prediction (NWP) model is one of the useful tools to predict the monsoon activities including such heavy rainfall events of Bangladesh. It is also important to investigate the performance of the NWP model for prediction of weather activities including the heavy rainfall events.

Rangamati (22.53°N, 92.20°E)—the southeastern hilly city of Bangladesh, situated on the western slopes of Mizo hills and Arakan Mountains. Rangamati is very different in

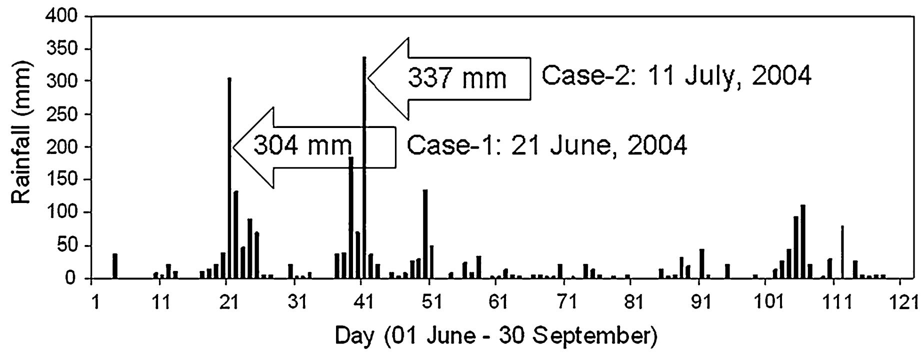


Fig. 1 Temporal distribution of daily rainfall at Rangamati, Bangladesh during summer monsoon 2004. The high impact rainfall events are indicated by *arrow sign*

terms of topography from the rest of Bangladesh, as the city is built on the hilly regions. On 21 June 2004 and 11 July 2004, Rangamati received 304 and 337 mm rainfall, respectively, within 24 h (Fig. 1). These unprecedented rainfall events were localized over Rangamati region. This torrential rain disrupted life in the city by causing severe flash floods. In addition to the floods, the rains triggered devastating landslides in the deforested hills and caused loss of life and properties.

The heavy rainfall events become significant in human affairs when they are combined with other hydrological elements. The problem of prediction 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 PSU/NCAR Mesoscale Model (MM5), has been attempted by many researchers (e.g., Braun and Tao 2000; Patra et al. 2000; Seaman 2000; Das 2002a, b; Jenamani et al. 2006; Bohra et al. 2006; Litta et al. 2007; Ahasan and Khan 2013; Thomas et al. 2010 and Webster et al. 2011). But, all the above studies are related to India and Pakistan and present study is related to Bangladesh. Application of NWP model in monsoon weather research and prediction is very little in Bangladesh due to limitation of computing platform and technical knowledge. In spite of the limitations, some works have been done on heavy rainfall during summer monsoon season of Bangladesh using NWP models (e.g., Prasad 2005; Islam 2008; Das 2009; Ahasan 2011 and Ahasan et al. 2011, 2013a, b, c). The sensitivity test of different cumulus parameterization schemes for the prediction of summer monsoon rainfall over Bangladesh has been studied by Ahasan et al. (2014) and the Anthes-Kuo schemes has been found suitable. Similar study of sensitivity test of cumulus parameterization schemes for the prediction of rainfall over Bangladesh has been carried out by Akter and Islam (2007). They also found that the Anthes-Kuo scheme is suitable for the rainfall prediction.

The present study is very important of its kind in the context of Bangladesh, and it is firmly believed that it will improve the general understanding of NWP application in prediction of heavy rainfall events during summer monsoon season over the southeast hilly region of Bangladesh. The objective of the present study is to predict the heavy rainfall events which occurred over Rangamati on 21 June 2004 and 11 July 2004 using high-resolution (grid spacing of 5 km) MM5 model.

2 Data used, model experimental setup and methodology

The Fifth-Generation PSU/NCAR Mesoscale Model (MM5) (Grell et al. 1994; Dudhia et al. 2002) version 3.7 has been adopted for mesoscale weather simulation and prediction at SAARC Meteorological Research Centre (SMRC), Dhaka, Bangladesh. The MM5 is a limited area, non-hydrostatic, terrain following, sigma-coordinated model designed to simulate or predict the atmospheric circulation including mesoscale phenomena (Grell et al. 1994; Dudhia et al. 2002).

2.1 Data used

The National Centers for Atmospheric Research (NCEP) high-resolution Global Final (FNL) Analysis data on $1.0° \times 1.0°$ grids covering the entire globe every 6 h were taken as the initial and lateral boundary condition. The 30 s United States of Geological Survey (USGS) data GTOPO30 (Interpolated depending on resolution) were used to simulate topography/terrain field and 25 Categories of USGS were taken to simulate vegetation/land use. The 5 Layer soil moisture data used as land surface process.

The daily Tropical Rainfall Measuring Mission (TRMM) 3B42V7 rainfall data with $0.25° \times 0.25°$ resolution have been downloaded from their website (http://lake.nascom.nasa.gov) to validate the model-predicted rainfall structure, development time and location. Moreover, daily observed rainfall data of 35 rain gauge stations

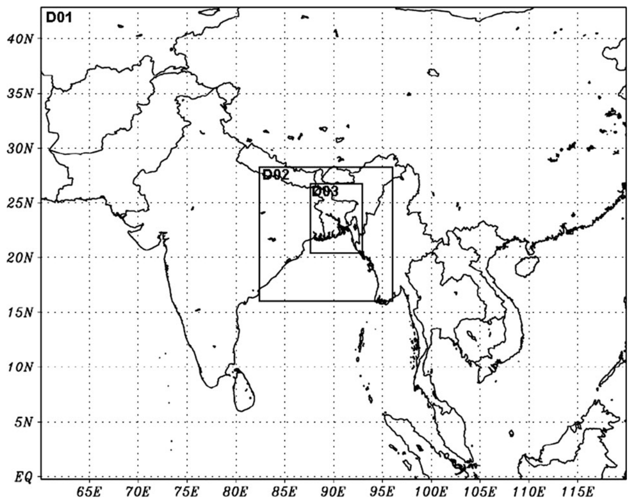


Fig. 2 Triple-nested domains D1, D2 and D3 configuration in MM5 model

have been collected from the archive of BMD for further validation of the model-forecasted rainfall.

2.2 Model experimental setup and methodology

The MM5 model was run on triple-nested domains at 45, 15 and 5 km horizontal resolutions using Anthes-Kuo (AK) cumulus parameterization schemes (CPS) (Anthes 1977). The configured domains are shown in Fig. 2. Domain 1 (D1) was 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 Domain 1, Domain 2 (D2) was nested with 100 × 94 grid points at 15 km grid spacing. The fine-mesh Domain 3 (D3) was 151 × 115 points with 5 km grid spacing. The model used two-way nesting, where coarse grid data were interpolated to finer grid boundaries and the finer grid provides updated data to the coarse grid. Bangladesh was the main focus area in this study. Thus, all domains were centered (20°N, 90°E) over Bangladesh to represent the regional scale circulations and to solve the complex flows in this region. All these domains were configured to have the same vertical structure of 23 unequally spaced sigma (non-dimensional pressure) levels. The other physical parameterization schemes used in this study were the Medium Range Forecast (MRF) scheme for a planetary boundary layer (PBL) (Hong and Pan 1996), Simple ice for an explicit moisture scheme (Dudhia), Simple cooling as radiation scheme and Five layer soil model as land surface processes. The Physics and Dynamics employed in MM5 model setup for this study used are shown in Table 1.

The MM5 model was run for 24 h (Day 1), 48 h (Day 2), 72 h (Day 3) and 96 h (Day 4) in advance for rainfall

Table 1 Physics and dynamics employed in MM5 model setup for this study

Physics/dynamics options	Parameterization scheme
CPS	Anthes-Kuo
PBL	MRF
Cloud microphysics	Simple ice (Dhudia)
Radiation	Simple cooling
Land surface process	Five layer soil model
Time integration	Semi implicit
Vertical differencing	Arakawa's energy conserving scheme
Time filtering	Robert's method
Horizontal diffusion	4th order for inner domains, 2nd order for the coarser domains

prediction valid for 21 June, 2004 and 11 July, 2004 based on the different initial conditions which are shown in details in Table 2. The model-simulated precipitation at surface level was considered as rainfall throughout this study. Bangladesh is the main focus area in the present study. Thus, amongst three domains, only finest domain D3 (Bangladesh region) is used for rainfall prediction. The model-forecasted rainfall was compared with TRMM 3B42V7 and BMD observed rainfall for validating the model-predicted rainfall. Both subjective and objective evaluation methods have been followed. These daily BMD and TRMM observed rainfalls are past 24 h accumulated rainfall valid at 00 UTC. The model-predicted rainfall used here is also valid at 00 UTC.

3 Results and discussion

The results obtained through modeling experiments are presented and discussed below.

3.1 Case-1: 21 June, 2004

The MM5 model was run for 24 h (Day 1), 48 h (Day 2), 72 h (Day 3) and 96 h (Day 4) in advance for rainfall prediction valid for 21 June, 2004 which is presented in Fig. 3a–d. The model-predicted rainfall was compared with TRMM 3B42V7 (Fig. 3e) and BMD observed rainfall (Fig. 3f) for validating the model-predicted rainfall.

The results of the model predictions for the forecast hours for 21 June, 2004 show that the high values of predicted rainfall for 24 h (Day 1), 48 h (Day 2), 72 h (Day 3) and low values of 96 h (Day 4) were exhibited in the areas of Rangamati. For 24 h (Day 1) prediction, model produced rainfall is reasonably well over Rangamati and neighborhoods, but it also exhibited rainfall over the northeast Bangladesh which is not seen in TRMM and

Table 2 Different initial conditions used for the prediction of the selected heavy rainfall events

Selected heavy rainfall events	Dates for initial conditions			
	24 h (Day 1)	48 h (Day 2)	72 h (Day 3)	96 h (Day 4)
Case-1: 21 Jun, 2004	00Z21JUN04	00Z20JUN04	00Z19JUN04	00Z18JUN04
Case-2: 11 Jul, 2004	00Z11JUL04	00Z10JUL04	00Z09JUL04	00Z08JUL04

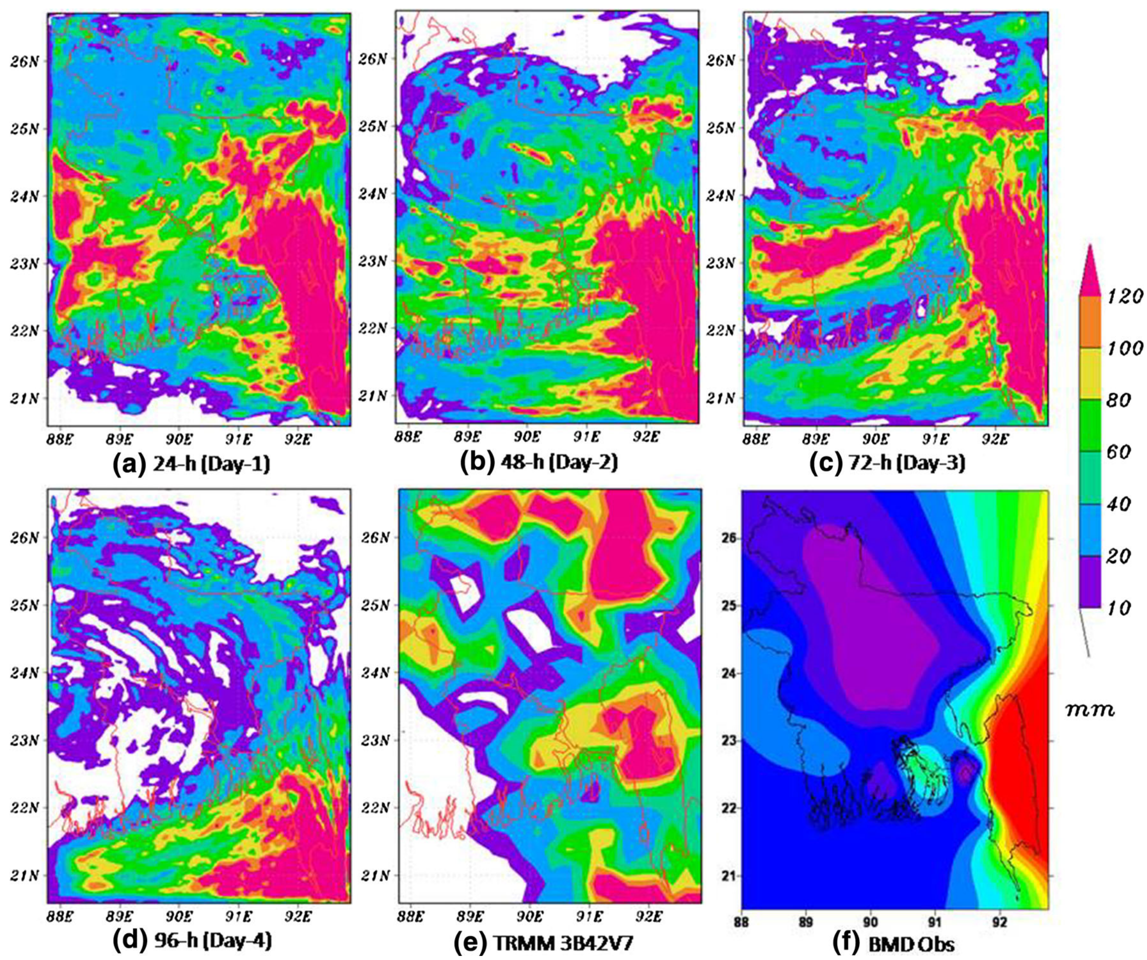


Fig. 3 Model-predicted **a** 24 h (Day 1), **b** 48 h (Day 2), **c** 72 h (Day 3), **d** 96 **h** (Day 4) rainfall (mm), and **e** TRMM 3B42V7 and **f** BMD observed rainfall (mm) valid for 21 June, 2004 over Bangladesh

BMD observation. For 48 h (Day 2) prediction, the model has shown more or less realistic distribution of high rainfall over Rangamati and neighborhoods are fairly good. The 72 h (Day 3) predicted rainfall was found to be considerably good as compared with TRMM and BMD observations. It also predicted some rain over the west-central part of the country which is in consistent with TRMM, and which is not visible in BMD observed rainfall product. For 96 h (Day 4) prediction, model predicted very low rainfall over the country as compared with TRMM and BMD observed rainfall.

Considering the quantitative comparison of the domain average rainfall with TRMM and BMD observations (Fig. 4), it is found that the model overpredicts rainfall by 12, 7 and 3 % in the 24 h (Day 1), 48 h (Day 2) and 72 h (Day 3) and underpredicts the 96 h (Day 4) rainfall by 39 % as compared with TRMM. It is also seen that the model overpredicts the 24 h (Day 1), 48 h (Day 2) and 72 h (Day 3) rainfall by 83, 75 and 67 % and underpredicts the 96 h (Day 4) rainfall by 1 % as compared with BMD observed rainfall.

3.2 Case-2: 11 July, 2004

The MM5 model was run to predict the rainfall of 11 July, 2004 for 24 h (Day 1), 48 h (Day 2), 72 h (Day 3) and 96 h

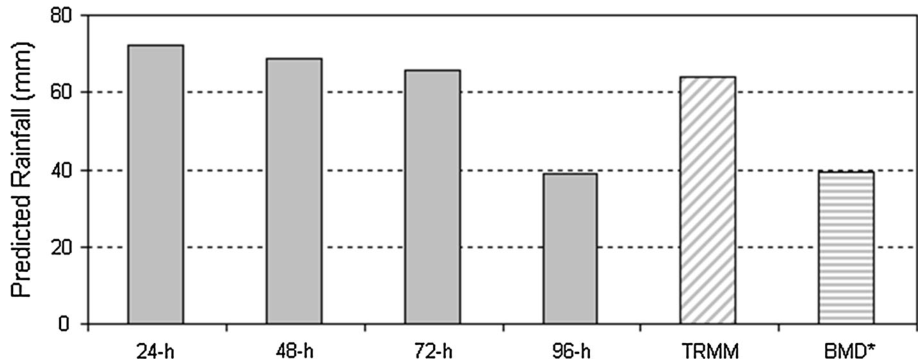


Fig. 4 Quantitative comparison of model-predicted domain average rainfall (mm) with that of TRMM and country average BMD observed rainfall on 21 June, 2004 over Bangladesh

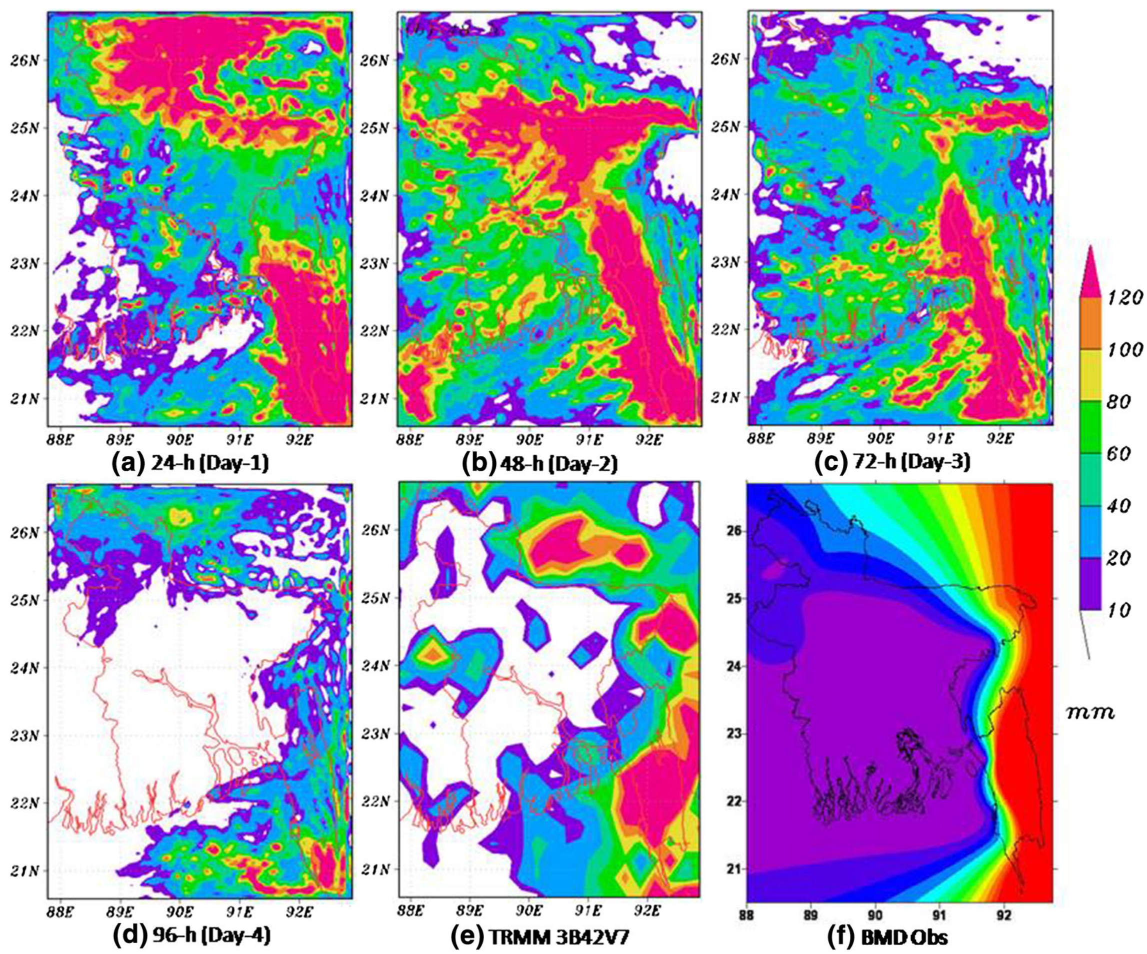
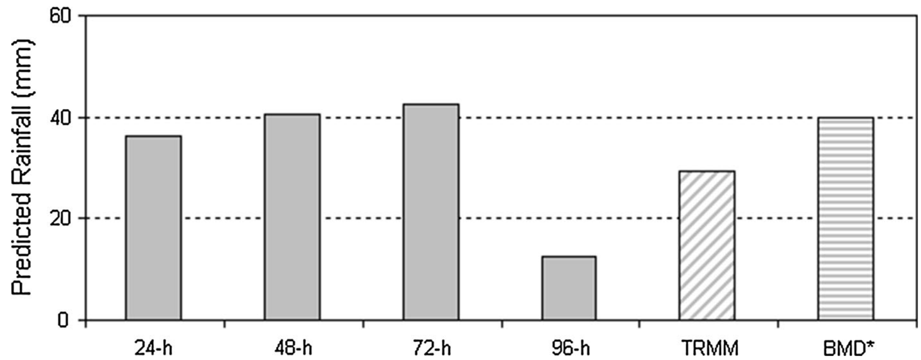


Fig. 5 Model-predicted **a** 24 h (Day 1), **b** 48 h (Day 2), **c** 72 h (Day 3), **d** 96 **h** (Day 4) rainfall (mm), and **e** TRMM 3B42V7 and **f** BMD observed rainfall (mm) valid for 11 July, 2004 over Bangladesh

(Day 4) prediction which are shown in Fig. 5a–d. The model rainfall was compared with TRMM 3B42V7 (Fig. 5e) and BMD observed rainfall (Fig. 5f) for validating the predicted rainfall. The results of the model run for predicting the case of 11 July, 2004 show that the model-predicted rainfall has captured the realistic features of the event.

In 24 h (Day 1) prediction, the results show that the predicted rainfall in Rangamati and its neighborhoods appear to be reasonably good as compared to TRMM and BMD observed rainfall. In 48 h (Day 2) prediction, model indicated excessive rainfall over the country compared to that by TRMM and BMD observed rainfall except over Rangamati where the prediction depicted the rainfall fairly

Fig. 6 Quantitative comparison of model-predicted domain average rainfall (mm) with that of TRMM and country average BMD observed rainfall on 11 July, 2004 over Bangladesh



good. The predicted rainfall pattern over Rangamati for 48 h (Day 2) appears to be slightly shifted to the west. The 72 h (Day 3) prediction provides higher rainfall compared to the 24 h (Day 1) and 48 h (Day 2) predictions. It also shows some rainfall over the southwestern and northeastern part of the country which is neither seen in TRMM nor in BMD observed rainfall. But the model-predicted rainfall over Rangamati and neighborhoods is fairly good matching with observations. For 96 h (Day 4) prediction, model showed much lower rainfall over the southwestern part of the country, although the spatial distribution was found to be quite good.

The model-predicted domain average rainfall is further compared quantitatively with that of TRMM and country average BMD observed rainfall (Fig. 6). It is seen that the model overpredicts rainfall by 24, 39 and 45 % in the 24 h (Day 1), 48 h (Day 2) and 72 h (Day 3), and underpredicts the 96 h (Day 4) rainfall by 57 % as compared with TRMM. When compared with BMD observation, it is seen that the model overpredicts the 24 h (Day 1), 48 h (Day 2) and 72 h (Day 3) rainfall by 9, 2 and 7 % and underpredicts the 96 h (Day 4) rainfall by 68 %.

3.3 Analysis of the prediction results taking both the cases together

Percentage of the model-predicted area averaged rainfall (mm) for inner most domain D3 as compared with TRMM and BMD observed rainfall over Bangladesh for both the events is shown in Table 3. It is found that the model prediction for 24, 48 and 72 h overestimates the TRMM and underestimates the same for 96 h prediction for all the selected cases. Model also shows the same result as compared with BMD observed rainfall for the most of the cases (except case-2, day 1). On an average, the model overestimates the TRMM observed rainfall by 23, 14, 17 %, respectively, for 24, 48 and 72 h predictions and underestimates for 96 h by 50 %. While compared with BMD observation, the model overestimates by 31, 22, 22 % for 24, 48 and 72 h predictions and underestimates for 96 h by 43 %.

Based on the above analysis, it may be concluded that the MM5 model produces more or less realistic prediction of heavy rainfall events in terms of intensity and structure. The results show that the MM5 performed all the Day 1 (24 h), Day 2 (48 h) and Day 3 (72 h) predictions in reasonably well. The predictions are more accurate for Day 2 (48 h) and worse for Day 4 96 h in both cases. The prediction deteriorates as the prediction time increases. The prediction may be updated in every 24 h which would provide more realistic prediction.

4 Root-mean-square error (RMSE) of the model-predicted rainfall

The root-mean-square error (RMSE) is used to measure the prediction errors against observed values. The RMSE of 3 hourly model rainfall with the maximum ranges of 24, 48, 72 and 96 h predictions has been calculated with respect to the corresponding observed rainfall of the representative meteorological stations of BMD for all the selected rainfall cases. The results of this RMSE are shown in Fig. 7. According to the distribution of RMSE, it is found that 48 h prediction comes out to be the best ranging from 5 to 15 mm while the 96 h prediction shows the largest error.

The results show that the MM5 performed well in all the 24, 48 and 72 h predictions. It shows that the RMSE for 24 h prediction lies within 10–20 mm range. The prediction error is minimal for 48 h prediction, the error ranging from 8 to 12 mm. The error increases thereafter for 72 and 96 h of predictions. The errors range from around 10–20 and 15–25 mm, respectively.

4.1 Model-simulated topography over the southeast region of Bangladesh

The topography of a region plays a significant role in intensity and distribution of rainfall (Smith 1979). Figure 8 shows the topography in and around Bangladesh used by MM5 model. The highest peak of Bangladesh—Tahjingdong (Bijoy) is situated over the extreme southeast region

Table 3 Percentage of the model-predicted area averaged rainfall (mm) for inner most domain D3 as compared with TRMM and BMD observed rainfall over Bangladesh

Case no.	Percentage of the model-predicted area average rainfall (mm) for inner most domain D3 as compared with TRMM and BMD observation							
	24 h		48 h		72 h		96 h	
	TRMM (%)	BMD (%)	TRMM (%)	BMD (%)	TRMM (%)	BMD (%)	TRMM (%)	BMD (%)
Case-1: 21 Jun, 2004	12	83	7	75	3	67	−39	−1
Case-2: 11 Jul, 2004	24	−9	39	2	45	7	−57	−68
Mean	18	37	23	38.5	24	37	−48	−34.5

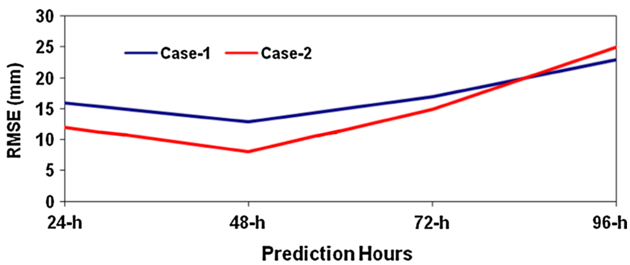


Fig. 7 Root mean square errors (RMSE) of rainfall (mm) obtained from the MM5 model with respect of BMD observations over Bangladesh

(i.e., Bandarban district) of the country. The height of Tahjingdong (Bijoy) is 1,280 m (Banglapedia 2006) which has not been resolved in the MM5 terrain database. The same area covering the Tahjingdong peak has been resolved at around 600 m by the MM5 model, which does not represent the actual topography of the hilly region of Bangladesh. It is found in the prediction that the extreme rainfall areas are slightly dislocated for the cases over the hilly areas. It is assumed that the cause of this dislocation is due to the smoothed topography of MM5 model. Thus, accurate and high-resolution terrain data of this region are expected to improve the performance of the model over the hilly areas of Bangladesh.

5 Conclusions

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

1. The MM5 model produces realistic prediction of heavy rainfall events in terms of intensity and structure. The results show that the MM5 performed all the Day 1 (24 h), Day 2 (48 h) and Day 3 (72 h) predictions in reasonably well. The predictions are more accurate for Day 2 (48 h) and worse for Day 4 96 h in both cases.

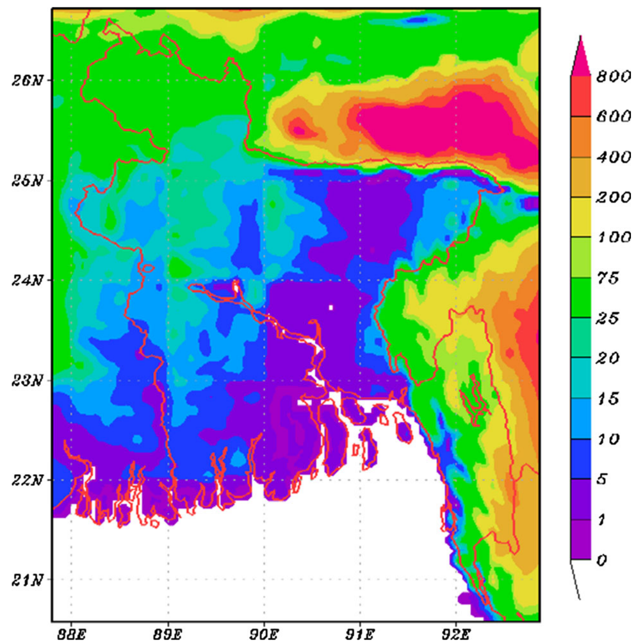


Fig. 8 Topography in and around Bangladesh used in MM5 model. The highest peak of Bangladesh (1,280 m) is situated over Bandarban district which has not been resolved in the map

2. The prediction deteriorates as the prediction time increases. Thus, the prediction may be updated in every 24 h which would provide more realistic prediction.
3. The RMSE shows that the value for 24 h prediction lies within 10–20 mm range. The prediction error is minimal for 48 h prediction, the error ranging from 8 to 12 mm. The error increases thereafter for 72 and 96 h of predictions. The errors range from around 10–20 and 15–25 mm, respectively.
4. The topography/terrain over the southeast hilly region of Bangladesh has not been resolved by USGS terrain data used in the MM5 model. Thus, accurate and high-resolution terrain data of this region are expected to

improve the performance of the model over the southeast hilly regions of Bangladesh.

Finally, it may be concluded that the MM5 Model version 3.7 with the right combination of the nesting domain, horizontal resolution and cumulus parameterization schemes might be able to predict the heavy rainfall events over Bangladesh, though there are some spatial and temporal biases in the simulated rainfall pattern.

Therefore, the Fifth-Generation PSU/NCAR Mesoscale Model MM5 may be adopted for the prediction of the heavy rainfall events of summer monsoon over Bangladesh up to Day 3 (72 h) by doing more case studies.

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