Simulation of the Tornado Event of 22 March, 2013 over Brahmanbaria, Bangladesh using WRF Model with 3DVar DA techniques

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A severe thunderstorm produced a tornado (F2 on the enhanced Fujita–Pearson scale), which affected the Brahmanbaria district of Bangladesh during 1100–1130 UTC of 22 March, 2013. The tornado consumed 38, injured 388 and caused a huge loss of property. The total length travelled by the tornado was about 12–15 km and about 1728 households were affected. An attempt has been made to simulate this rare event using the Weather Research and Forecasting (WRF) model. The model was run in a single domain at 9 km resolution for a period of 24 hrs, starting at 0000 UTC on 22 March, 2013. The meteorological conditions that led to form this tornado have been analyzed. The model simulated meteorological conditions are compared with that of a ‘no severe thunderstorm observed day’ on 22 March, 2012. Thus, the model also ran in the same domain at same resolution for 24 hrs, starting at 0000 UTC on 22 March, 2012. The model simulated meteorological parameters are consistent with each other, and all are in good agreement with the observation in terms of the region of occurrence of the tornado activity. The model has efficiently captured the common favourable synoptic conditions for the occurrence of severe tornadoes though there are some spatial and temporal biases in the simulation. The wind speed is not in good agreement with the observation as it has shown the strongest wind of only 15–20 ms⁻¹, against the estimated wind speed of about 55 ms⁻¹. The spatial distributions as well as intensity of rainfall are also in good agreement with the observation. The results of these analyses demonstrated the capability of high-resolution WRF model with 3DVar Data Assimilation (DA) techniques in simulation of tornado over Brahmanbaria, Bangladesh.

1. Introduction

Brahmanbaria (23.95°N, 91.12°E) district is located in the east-central region of Bangladesh (20°34′–26°38′N and 88°01′–92°41′E). A tornado (F2 in enhanced Fujita–Pearson scale) hit over more than 15 villages of three upazila (sub-district) of Brahmanbaria district of Bangladesh between 1100 and 1130 UTC (1700–1730 BST) on 22 March, 2013 (SMRC 2013). As on 31 March, 2013,

38 people died, 388 others were injured, and about 1728 households were affected when it moved through the villages of Brahmanbaria Sadar, Bijoy-nagar and Akhaura upazila of Brahmanbaria district (DMIC 2013). Other damages of this tornado event were the damages and/or collapses of electric lines and poles, boundary wall, entrance gate, communication systems, breaking down of numerous trees, etc. The location of Brahmanbaria (23.95°N, 91.12°E) district in Bangladesh along

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with the estimated path travelled by the tornado that occurred on 22 March, 2013 and the photograph of the tornado are shown in figure 1(a–b). The tornado moved (in a zigzag way) west to east direction first, then east–southeast, and finally east–northeast direction. Approximate maximum wind speed was 55 ms^{-1} . A total distance of about 12–15 km was travelled by the tornado and its width was 100–150 m. The extreme destruction time was only 5–7 minutes (BMD 2013; SMRC 2013).

Bangladesh experiences a high frequency of severe thunderstorms during the pre-monsoon (March–May) periods, which have great destructive potential and are characterized by tornadic violence, often accompanied by high magnitude squalls, torrential rains, and hail. They cause extensive damage to life and property in the areas through which they traverse. Some of the severe thunderstorms develop into tornadoes. Forecasting of severe category thunderstorms, including tornadoes occurring during the pre-monsoon period in the region comprising Bangladesh and nearby territory of India, is a very challenging problem. First, these atmospheric disturbances are of mesoscale dimensions and their life cycle is at best a few hours. They thus enable only short lead time for forecasting. Secondly, the processes in the formation and development of these phenomena are too complex and difficult to capture by conventional methods of synoptic analysis and forecasting.

The common favourable synoptic conditions for the occurrence of severe category thunderstorms including tornadoes are outlined below (Prasad 2006; Ahasan *et al.* 2008):

- presence of an active elongated trough of low over the Gangetic plains of north India running across north Bangladesh;
- presence of southerly low level jet (LLJ) with a poleward meridional component in the lower troposphere wind flow;
- high magnitude of moisture content in the humidity field intruding from the Bay of Bengal into Bangladesh and thereafter northeast India;
- presence of subtropical jet stream with strong vertical wind shear in the low to middle troposphere levels over Bangladesh and neighbourhood;
- a well marked convergence line in the lower levels extending from the eastern parts of peninsular India to northeast India across Bangladesh;
- a pocket of strong warm temperature advection at 850 hPa and cold temperature advection at 300 hPa;
- intrusion of a high convective available potential energy (CAPE) from the Bay of Bengal into Bangladesh and presence of a low convective inhibition energy (CINE) regime.

Although the above conditions for occurrence of severe category thunderstorms including tornadoes are known to the forecasters, their visualization through the routine conventional synoptic weather analyses is not possible. A constant monitoring of the day-to-day behaviour of synoptic and environmental conditions may provide a green signal for potentially dangerous synoptic situations and thus act as a valuable aid to the forecasters. Useful signals for the occurrence of severe category thunderstorms including tornadoes seem to be provided

Figure 1. (a) Map showing the location of Brahmanbaria (23.95°N , 91.12°E) district in Bangladesh and the estimated path travelled by the tornado on 22 March, 2013 and (b) the photograph of the tornado over Brahmanbaria on 22 March, 2013.

by a chosen combination of these synoptic conditions for which any mesoscale model, i.e., Weather Research and Forecasting (WRF) may work as a very useful tool to the forecasters.

Application of WRF model in research and forecasting of severe category thunderstorms including tornadoes during premonsoon season is very less in Bangladesh. However, very little work has been done regarding synoptic situations, environmental conditions, and composite characteristics of severe thunderstorms including tornadoes during premonsoon season over Bangladesh using WRF model by Das (2009) and Basnayake *et al.* (2010), FSU model by Prasad (2006) and MM5 model by Ahasan *et al.* (2008).

The primary objective of this study is to identify and document the common favourable synoptic conditions for the occurrence of the tornado event on 22 March, 2013 over Bangladesh. The secondary objective is to test the performance of the WRF model with radiance data assimilation technique to simulate the selected tornado event.

2. Model experimental setup, data used and methodology

2.1 Model introduction

The Weather Research and Forecasting (WRF) model (version 3.5.1, release August 2013) has been used to carry out the present study. The WRF Model is a new-generation mesoscale Numerical Weather Prediction (NWP) system designed to serve both operational forecasting and atmospheric research needs. It features multiple dynamical cores, a 3-dimensional variational (3DVar) data assimilation (DA) system, and a software architecture allowing for computational parallelism and system extensibility (Skamarock *et al.* 2008). The 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). The ARW system consists of the Eulerian mass-based dynamics solver with other components of the WRF system needed to produce a simulation (Skamarock *et al.* 2008). The ARW dynamics solver of WRF model (WRF-ARW) has been implemented during the present study.

Data assimilation is the technique by which observations are combined with an NWP product (the first guess or background forecast) and their

respective error statistics to provide an improved estimate (the analysis) of the atmospheric (or Oceanic, Jovian, etc.) state (Barker *et al.* 2004). The Variational (Var) data assimilation achieves this through the iterative minimization of a prescribed cost (or penalty) function. Differences between the analysis and observations/first guess are penalized (damped) according to their perceived error. The 3DVar technique is used in the present study in order to provide updated initial and boundary conditions to the model.

2.2 Model experimental setup

The WRF model was run on a single domain at 9 km horizontal resolution using the Kain–Fritsch (new Eta) cumulus scheme (Kain 2004) based on 0000 UTC on 22 March, 2013 (more than 10 hrs before the event), initial condition for 24 hrs. Domain has 163×139 grid points in the north–south and east–west directions respectively. The domain is centered at 23.95°N , 91.12°E over Brahmanbaria, Bangladesh to represent the regional-scale circulations and to extract the complex meteorological features. The domain was configured to have the same vertical structure of 35 unequally spaced nondimensional pressure levels in the sigma coordinate. The other physical parameterization schemes used in this study are the Yonsei University (YSU) scheme (Hong *et al.* 2006) for the boundary layer parameterization, WSM 6 class Simple Ice schemes (Hong and Lim 2006) for microphysics, Rapid Radiative Transfer Model (RRTM) scheme (Mlawer *et al.* 1997) for longwave radiation and Dudhia scheme (Dudhia 1989) for shortwave radiation for the selected case. The configuration of the WRF model domain for the present study along with the topography of the region in the background is shown in figure 2.

2.3 Data used

The United States Geological Survey (USGS) Global datasets with 30 s horizontal resolution were used to create topography/terrain and vegetation/land-use field. The FNL Operational Model Global Tropospheric Analyses of NCEP with the $1^\circ \times 1^\circ$ horizontal and 6-hr temporal resolution were used as the initial and lateral boundary condition.

The daily $0.25^\circ \times 0.25^\circ$ resolution TRMM 3B42RT rainfall data have been downloaded from the website of NASA (<ftp://disc2.nascom.nasa.gov/data/TRMM/>) to justify the model simulated rainfall structure, development time, and location. The daily observed rainfall data have been

Figure 2. WRF Model domain for the NWP study. Shaded areas are the topography (m) of the region.

collected from the archive of Bangladesh Meteorological Department (BMD) to compare or validate the model output. The Meteosat cloud images are also used to see the signature of cloud activities and moisture presence over the study area.

The NCEP ADP Global Upper Air and Surface Weather Observations (satellite radiance data) in PREPBUFR format of 0000 UTC on 22 March, 2013 were downloaded from the website of NCEP (<http://rda.ucar.edu/datasets/ds337.0/>) and used for 3DVar data assimilation in WRF model.

2.4 Methodology

The WRF Model has been used for the study of the tornado that occurred on 22 March, 2013 over Bangladesh with 3 Dimensional Variational (3DVar) Data Assimilation (DA) techniques. Model was run using six hourly NCEP-FNL datasets from 0000 UTC on 22 March to 0000UTC on 23 March, 2013 as initial and boundary condition for Control (CNTL) run. The satellite radiance data of 0000 UTC on 22 March, 2013 were assimilated in WRF Model with the first guess for Data Assimilation (DA) run. All model-derived outputs for Data Assimilation (DA) have been prepared to investigate the common synoptic conditions for the occurrence of the tornado. The tornado reaches mature stage at about 1100 UTC as per post-storm

report of SAARC Meteorological Research Centre (SMRC). Thus all model parameters are prepared for 1100 UTC (mature time of tornado event) on 22 March, 2013. The model simulated parameters are compared with that of a ‘no severe thunderstorm observed day’ (the day on which no severe thunderstorm is observed throughout the country by BMD) on 22 March, 2012. Thus, the model also run in the same domain at same resolution for 24 hrs, starting at 0000 UTC on 22 March, 2012. The model outputs help to investigate the synoptic and environmental characteristics responsible for the formation of the tornado event on 22 March, 2013 over Brahmanbaria, Bangladesh.

The mean sea level pressure; low level and upper level wind flow; horizontal and vertical profile of relative humidity; low level vertical wind shear of the ‘u’ component of wind; convective available potential energy, low level and upper level temperature advection; convective inhibition energy and rainfall, etc., fields have been investigated. Model simulated above-mentioned parameters are compared with the same as on 22 March, 2012 on which there is no thunderstorm observed (i.e., thunderstorm inactive day) over Bangladesh. Model simulated total convective (Cumulus scheme) and non-convective (Grid scale) precipitation at surface level has been considered as rainfall throughout the study. Observed daily rainfall data of BMD and daily TRMM 3B42RT rainfall data have been

used to validate/compare the model simulated rainfall.

3. Results and discussion

The results and discussion of the common synoptic and environmental conditions responsible for the formation of the tornado on 22 March, 2013 over Brahmanbaria, Bangladesh based on WRF model output are outlined below:

3.1 Simulated meteorological conditions

The WRF model simulated meteorological conditions (various synoptic maps of the flow variables and some derived parameters) valid at 1100 UTC 22 March, 2013 (tornado event observed day) and on 22 March, 2012 (no severe thunderstorm observed day) are presented in figures 3–9(a–b).

The distribution of mean sea level pressure valid at 1100 UTC on 22 March, 2013 and 22 March, 2012 are shown in figure 3(a–b) respectively. The prominent feature is an elongated trough of low pressure running across the Gangetic plains over north India which intrudes Bangladesh through the middle of the country. The low pressure area covered the western vicinity of Bangladesh (figure 3a–b). The lowest surface pressure at the centre of the low pressure area at 1100 UTC is about 1004 hPa on 22 March, 2013 (figure 3a) which is very high (~ 1010 hPa) on 22 March, 2012 (figure 3b). This is one of the favourable conditions for the formation of severe thunderstorms including tornadoes over Bangladesh.

The distribution of low level (950 hPa) wind flow (ms^{-1}) at 1100 UTC on 22 March, 2013 and 22 March, 2012 are presented in figure 4(a–b). It is found that the strong southerly low level jet (LLJ) of the order of $15\text{--}20 \text{ ms}^{-1}$ may be seen over north Bay of Bengal and eastern part of the country at 1100 UTC on 22 March, 2013 (figure 4a) which is observed very less in figure 4(b). These southerly LLJ may help transporting moisture from the Bay of Bengal into south, south-east and eastern parts of Bangladesh. The position of the dry line (a line where cold-dry air and warm-moist air meet together) is indicated by a zigzag line and the position of the tornado occurrence on 22 March, 2013 is indicated by the circle. Prominent dry line is not observed in figure 4(b).

The distribution of upper level (300 hPa) wind flow (ms^{-1}) at 1100 UTC on 22 March, 2013 and 22 March, 2012 representing the subtropical jet stream over the region are shown in figure 5(a–b). A jet stream of the order of $30\text{--}40 \text{ ms}^{-1}$ may be seen over Bangladesh and its north neighbourhood at 1100 UTC on 22 March, 2013, marking a strong vertical wind shear in the environment (figure 5a–b). An upper air trough in westerlies is also seen over Bangladesh and its axis passed just over the middle of the country (figure 5a) which is not observed in figure 5(b). The presence of STJ provides a mechanism for strong vertical wind shear, thus favouring development of severe convection. The speed of STJ has been found to contribute to the severity of the thunderstorms.

The spatial distribution of vertical wind shear (ms^{-1}) of the ‘u’ component of wind in the lowest 6 km of the atmosphere 500–925 hPa at 1100 UTC on 22 March, 2013 and 22 March, 2012 is presented in

Figure 3. Distribution of model simulated mean sea level pressure (hPa) valid at 1100 UTC on (a) 22 March, 2013 and (b) 22 March, 2012.

Figure 4. Distribution of model simulated low level (950 hPa) wind flow (ms^{-1}) valid at 1100 UTC on (a) 22 March, 2013 and (b) 22 March, 2012. The position of the dry line is indicated by a zigzag line and the position of the tornado occurrence is indicated by the circle (a).

Figure 5. Distribution of model simulated upper level (300 hPa) wind flow (ms^{-1}) analysis valid at 1100 UTC on (a) 22 March, 2013 and (b) 22 March, 2012.

figure 6(a–b). In figure 6(a), the prominent feature, which is the core of strong vertical wind shear of the order of 20 ms^{-1} (38 knots), may be seen over east neighbourhood of Bangladesh, which is not observed in figure 6(b). The vertical wind shear is an important dynamical factor in the development of severe thunderstorms and tornadoes, and this windshear (20 ms^{-1}) is capable of forming a supercell thunderstorm (Holton 2004).

The spatial distribution of relative humidity at 1100 UTC on 22 March, 2013 and 22 March, 2012 are presented in figure 7(a–b). It is found

that the contents of moisture of the order of 70–80% over the eastern part of Bangladesh at 1100 UTC on 22 March, 2013 (figure 7a), is only of the order of 40–50% over the eastern part of Bangladesh at 1100 UTC on 22 March, 2012 (figure 7b). The circulation of southerly/southwesterly LLJ transports plentiful moisture from the Bay of Bengal to the plains of Bangladesh and the adjoining states of India. This influx of moisture due to southerly/southwesterly LLJ might lead to formation of dryline at the meeting zone of the maritime airmass and the dry continental airmass

Figure 6. Distribution of model simulated vertical wind shear (ms^{-1}) of the 'u' component of wind in the lowest 6 km of the atmosphere 500–925 hPa valid at 1100 UTC on (a) 22 March, 2013 and (b) 22 March, 2012.

Figure 7. Distribution of model simulated relative humidity valid at 1100 UTC on (a) 22 March, 2013 and (b) 22 March, 2012.

(figure 4) which is not observed in figure 7(b). The vertical profile of the relative humidity field at 1100 UTC on 22 March, 2013 and 22 March, 2012 along 23.95°N latitude (latitudinal position of Brahmanbaria) are presented in figure 8(a–b). It is found that the intensity of vertical profile of the relative humidity field, which reached 150 hPa at 1100 UTC on 22 March, 2013 in the mature stage along $90^\circ\text{--}92^\circ\text{E}$ longitude (the position of the tornado) (figure 8a), reached only upto 700 hPa on 22 March, 2012 (figure 8b).

The distribution of low level (850 hPa) temperature valid at 1100 UTC on 22 March,

2013 and 22 March, 2012 are presented in figure 9(a–b). The low level temperature shows a pocket of warm temperature over Brahmanbaria, Bangladesh and neighbourhood. The magnitude of warm temperature was equivalent to about 18°C in figure 9(a) and the same is observed in figure 9(b). The distribution of upper level (300 hPa) temperature valid at 1100 UTC on 22 March, 2013 and 22 March, 2012 are presented in figure 10(a–b). A pocket of cold temperature at 300 hPa, measuring about -43°C , was also seen over Brahmanbaria, Bangladesh in figure 10(a) and the same is observed very low ($\sim -33^\circ\text{C}$) in figure 10(b). Warming of the lower troposphere and cooling

Figure 8. Distribution of model simulated vertical profile of the relative humidity field along 23.95°N latitude (latitudinal position of Brahmanbaria) valid at 1100 UTC on (a) 22 March, 2013 and (b) 22 March, 2012.

Figure 9. Distribution of model simulated low level (850 hPa) valid at 1100 UTC on (a) 22 March, 2013 and (b) 22 March, 2012.

of the upper troposphere would have the effect of steepening the environmental lapse rate and thereby increasing its susceptibility to development of severe convection.

The distribution of Convective Available Potential Energy (CAPE) at 1100 UTC on 22 March, 2013 and 22 March, 2012 is shown in figure 11(a–b). It is found that the area in the eastern part of Bangladesh covering the area of tornado is characterized by high value of CAPE of the order of $2500\text{--}3000 \text{ J Kg}^{-1}$ (figure 11a), which is observed very low ($\sim 500\text{--}1000 \text{ J Kg}^{-1}$) over Bangladesh in figure 11(b). The distribution of Convective Inhibition Energy (CINE) at 1100 UTC on 22 March, 2013 and 22 March, 2012 is shown in figure 12(a–b).

It is found that the area in the eastern part of Bangladesh covering the area of tornado is characterized by low value of CINE of the order of $0\text{--}25 \text{ J Kg}^{-1}$ on 22 March, 2013 (figure 12a), which is observed of the order of $50\text{--}100 \text{ J Kg}^{-1}$ over Bangladesh in figure 12(b). A combination of high CAPE and low CINE would render the environment thermodynamically favourable for convection (figures 13 and 14).

3.2 Distribution of rainfall

The distribution of model simulated 24-hr accumulated rainfall on 22 March, 2013 is given in figure 10(a). The model simulated rainfall has

Figure 10. Distribution of model simulated upper level (300 hPa) temperature valid at 1100 UTC on (a) 22 March, 2013 and (b) 22 March, 2012.

Figure 11. Distribution of model simulated CAPE valid at 1100 UTC on (a) 22 March, 2013 and (b) 22 March, 2012.

been compared with the daily TRMM 3B42RT and BMD Observed (BMD Obs) rainfall, which is shown in figure 10(b–c). It is found that model simulated rainfall over the country overestimated the rainfall compared to that of TRMM and BMD Obs. However, the WRF model captured the location and structure of the rainfall over Brahmanbaria and its neighbourhoods reasonably well. It is to be mentioned in this regard that the network of rain-gauge stations of Bangladesh is not dense enough to capture a realistic picture of mesoscale processes unless one or more stations are located in the passage of convective systems. In the case of this tornado, there is no observatory

of BMD in Brahmanbaria. The highest rainfall on 22 March, 2013 is recorded in the nearby observatory in Comilla (23.43°N, 91.18°E). The intensity and structure of TRMM recorded rainfall seems very similar to that of BMD Observatory. Thus, the WRF model-simulated rainfall seems to be more or less realistic, though the model would have generated higher than realistic rainfall throughout the country.

The Meteosat-5 cloud images are shown in figure 11(a–c). The formation, mature and dissipating stage of the tornado on 22 March, 2013 over Brahmanbaria, Bangladesh is clearly seen in the cloud images.

Figure 12. Distribution of model simulated CINE valid at 1100 UTC on (a) 22 March, 2013 and (b) 22 March, 2012.

Figure 13. Distribution of model simulated 24-hr accumulated rainfall valid for 0000 UTC of 23 March, 2013 for (a) Model, (b) TRMM and (c) BMD Obs.

Figure 14. Meteosat cloud images at (a) 0600 UTC, (b) 1200 UTC and (c) 1800 UTC on 22 March, 2013.

4. Conclusions

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

- The WRF model captured the studied case on 22 March, 2013 reasonably well, though there are some spatial and temporal biases in the model simulation. Mean sea level pressure contains an elongated trough of low pressure running across the Gangetic plains over north India which intrudes Bangladesh through the middle of the western part of the country. The lowest pressure at the centre of the low pressure is below 1004 hPa.
- A strong southerly low level jet ($15\text{--}20\text{ ms}^{-1}$) transporting moisture in the order of 70–80% from the Bay of Bengal, which vertically reached up to 150 hPa in the mature stage along 93°E longitude (the position of the tornado). An upper air trough in westerlies is also seen over Bangladesh, its axis passing just over the middle of the country. The systems advected towards east, due to upper level (300 hPa) wind flow (ms^{-1}), representing the subtropical jet stream ($30\text{--}40\text{ ms}^{-1}$), marking a strong vertical wind shear of $10\text{--}20\text{ ms}^{-1}$ (19–38 knots), in the environment. A significant dry line formed over the area of Brahmanbaria due to the meeting of cold-dry air from the landmass of India and warm-moist air from the Bay of Bengal.
- The warm air at low level (850 hPa) and cold air at upper level (300 hPa) which promotes thermal instability due to steepening of the lapse rates become favourable for the formation of the tornado over Bangladesh. The combination of high value of CAPE and low value of CINE makes the eastern area of Bangladesh favourable for the occurrence of the tornado.
- The model simulated 24-hr rainfall over the country overestimated the rainfall compared to that of TRMM and BMD Observatory. However, the WRF model captured the location and structure of the rainfall over Brahmanbaria and its neighbourhoods reasonably well.

Finally, it is concluded that the high resolution WRF model may be adopted in forecasting of tornadoes over Bangladesh, but more case studies need to be done.

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