International Journal
of
Integrated Sciences & Technology (IJIST)
http://www.cuet.ac.bd/IJIST/index.html

International Journal of Integrated Sciences & Technology 2 (2016) 45-54

Simulation of a Tornado Event on 26 April 1989 over Saturia, Manikgonj, Bangladesh using a Complete Environmental Modeling System (EMS)

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Abstract

An attempt has been made to simulate a Tornado Event on 26 April 1989 over Saturia, Manikgonj, Bangladesh using EMS which incorporates both the NOAA and WRF systems. The simulation was conducted using WRF-ARW for twenty four hours. This was an extraordinary tornado event. The EMS was run on a single domain of 2 km horizontal resolutions using Kain-Fritsch cumulus scheme. The model performance was evaluated by examining the different predicted parameters like mean sea level pressure, rainfall pattern, wind pattern, upper and lower level circulations, moisture, wind shear, vorticity, gust, CAPE and radar reflectivity. The results indicate that the WRF model with the right combination of the domain, horizontal resolution and cumulus scheme was able to simulate reasonably well the potential tornado event and its associated dynamical and thermo-dynamical features. The WRF model suggested that the highly localized tornado over Saturia was the result of the confluence of southwesterly wind flow which transported high magnitude of moisture from the Bay of Bengal towards central part of Bangladesh and adjoining areas. The analysis shows that the tornado formed near the right side of the dry line. It also shows that the CAPE, reflectivity factor and strong vertical wind shear are also supporting to form the tornado.

Keywords: EMS, WRF-ARW Model, Dry line

1. Introduction

Tornadoes are the rotating columns of rising air that create a low pressure area close to the ground, either pendant from a cumuliform cloud or underneath a cumuliform cloud, and it is often (but not always) visible as a funnel type cloud. In practice, for a vortex to be classified as a tornado, it must be in contact with both the ground and the cloud base. They are very complex flows due to their unsteady, three-dimensional and turbulent nature. On an average, tornadoes are 150 m wide and travel on the ground for 8.0 km [1] with a translational speed of 9 m/s to 18 m/s [2]. The intensity of a tornado is measured by Fujita Scale (F-Scale) which was introduced by Tetsuya Theodore Fujita in 1971. This is a forensic scale for which each damage level is associated with a wind speed (V) calculated as V=6.3(F+2)3/2 [3]. This relationship has been derived by smoothly connecting the Beaufort scale and the Mach number scale (see Appendix A for detail). The Beaufort scale is an empirical measure that relates wind speed to observed conditions at sea or on land and Mach number is the ratio of the speed of an object moving through a fluid to the speed of sound. Tornado flow studies began in 1882 with simple one-dimensional analytical models which represented the flow using only the tangential velocity component; the Rankine Vortex model. This early work was followed by more elaborated analytical models such as the Burgers-Rott vortex [4-5]. As the knowledge of tornado vortex dynamics broadened and as the measurement techniques and technology advanced, experimental and numerical simulations of tornado-like vortices widely increased. Experimental simulations of tornado-like flows are began by reproducing the observed features of tornado vortices. These features include: 1) a columnar vortex that touches the ground, 2) updraft at the center

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ISSN : 2411-9997

of the vortex with a surface pressure drop, 3) spiraling flow with radial convergence to the vortex core, and 4) turbulent flow regime [2]. In laboratory simulations, the effects of buoyancy are neglected and therefore the vortex is purely momentum driven. In 1969, Ying and Chang [2] designed and built a tornado simulator that fulfilled the above mentioned features. Later, the Ward-type Tornado Vortex Chamber (TVC) was introduced [6] which was an improved version of the Ying and Chang apparatus. Ward's simulator provided more realistic boundary conditions for the vortex. Hereafter, substantial effort has been made to better represent the tornado flow structure and boundary conditions in the lab [7-11] and to better characterize the flow characteristics [10, 12-18]. This was followed by numerical simulations of tornado-like vortices [19-22]. Numerical simulations can be divided into two general categories: thunderstorm scale simulations which are meteorological models and tornado scale simulations which are essentially engineering models. Thunderstorm scale models reproduce the supercell storm and can be used to study tornado genesis. On the other hand, the tornado scale models focus on the interaction between the tornado vortex and the ground surface. So far, numerical simulations of tornadic flows with engineering applications have been mainly limited to simulating laboratory models or simple axisymmetric flows. Collecting full-scale velocity data from tornadoes has been always challenging for researchers. Technological developments of Doppler radars and the introduction of Doppler on Wheels (DOW) in 1995 [23- 24] are important recent developments enabling scientists to obtain full-scale data from a safe distance. However, these measurements mainly focus on tornado genesis. In addition, the Doppler radar data are mostly collected from heights on the order of tens of meters above the surface [25-31], which is significantly higher than the majority of buildings of interest. Obtaining surface pressure data from real tornadoes is an even more difficult task and only on very rare events have measurements been successfully collected [32]. Despite the significant number of analytical, experimental and numerical studies and advances in measurement methods, investigation of the wind loading effects on structures and buildings has been very limited. This is attributed to an unidentified relationship (i.e. geometric and velocity scales) between simulated and real tornadoes. Once this relationship is identified, modeling structures and buildings and testing them in tornado simulators to measure the wind loading is possible. Different thunder storm simulations [33-40] have been done over West Bengal and Bangledesh using numerical weather prediction model.

In the present study, an attempt has been made to simulate the Tornado event that occurred on 26 April 1989 at Saturia, Manikgonj (23.6°N 90.0°E) using Non-hydrostatic Mesoscale Model (NMM) core of the Weather Research and Forecasting (WRF) system with 25 April 1200 UTC initial condition. This model was developed by the National Oceanic and Atmospheric Administration (NOAA)/National Centers for Environment Prediction (NCEP). Saturia-Manikganj Sadar tornado is a catastrophic tornado that struck the Manikganj district of Bangladesh causing approximately 1,300 fatalities. It was likely the deadliest tornado in recorded history. The tornado struck at around 6:30 pm local time and moved east from the Daulatpur area into the areas of Saturia and Manikganj Sadar. The storm spanned a path that was about 16 km long and about 1.6 km wide (Source BMD). Though confined to a relatively small geographic region (like most other tornadoes) and brief in duration, it completely destroyed all buildings.

2. Experimental Data, Model Setup and Methodology

The National Weather Service (NWS) Science and Training Resource Center's (STRC) Environmental Modeling System (EMS) is a complete, full-physics, state-of-the-science numerical weather prediction (NWP) package that incorporates both the NOAA (NEMS) and WRF systems into a single user friendly, end-to-end forecasting system. All the capability of the NCEP NEMS and NCAR WRF models are retained within the EMS; however, the installation, configuration, and execution of each has been greatly simplified to encourage their use within the operational, private, and University forecasting and research communities. Weather Research and Forecasting (WRF) is a next generation mesoscale numerical weather forecasting community model, which has the potentiality to simulate meteorological phenomena ranging from meters to thousands of kilometers. Advance Research WRF (ARW) is a dynamic solver, which is compatible with the WRF system to simulate broad spectrum of meteorological phenomena. The WRF mesoscale model version 3.4.1 has been adopted for the mesoscale weather research and simulation at Bangladesh Meteorological Department (BMD), Dhaka, Bangladesh.

2.1. Experimental Data

The NCEP 50 km-resolution GFS data covering the entire globe every 6-h were taken as the initial and lateral boundary condition. 30 sec United States Geological Survey (USGS) data (Interpolated depending on resolution) GTOPO30 were used as Topography and 25 Categories United States Geological Survey (USGS) data were taken as vegetation/land use (Modis and Hi-Def Lakes) coverage.

2.2. Model Setup and Methodology

The experiment was performed on a single domain of 2 km resolution. The domain configuration in WRF model has 120×93 grid points in the north-south and east-west directions, respectively. The domain was configured to have the vertical structure of 38 unequally spaced sigma (non-dimensional pressure) levels. Bangladesh is the main focus point of this study. As such, the D_1 is focused on Bangladesh only to observe the small spatial and temporal variability. The physical parameterization schemes used in this study are Kain-Fritsch scheme for cumulus parameterization scheme and Lin et al. scheme for microphysics, MRF for planetary boundary layer, Simple ice for an explicit moisture scheme, simple cooling for radiation scheme and Five layer soil model for land surface processes. The model was run for 24 hours based on the initial condition on 1200 UTC of 26 April 1989. The model performance was evaluated by examining the different predicted parameters like mean sea level pressure, rainfall pattern, wind pattern, upper and lower level circulations, relative humidity, wind shear, vorticity, Gust, CAPE , lifted index(LI) and dBZ.

3. Results and Discussion

In this section, many simulated characteristics of the Saturia tornadic event such as the sea level pressure, wind patterns, temperature, relative humidity, lower level divergence and convergence, mean vertical wind speed, the convective available potential energy (CAPE), Gust, radar reflectivity factor, LI, vertical wind shear and rainfall were investigated. Hourly variations of these parameters were studied over Bangladesh. The diagrams shown below correspond to the hours when model indicated favorable signals for the occurrence of the tornado.

3.1.1. Mean Sea Level Pressure Analysis

The mean sea level pressure simulated by the WRF model valid for 1100 UTC, 1200 UTC and 1300 UTC of 26 April 1989 are presented in Fig.2 (a-c) respectively. The mean sea level pressure over Saturia (23.6°N and 90.0°E) at 1200 UTC is found 1008 hPa which is higher than surrounding area. Sudden pressure rise during a storm is a characteristic feature of a thunderstorm[24], which is captured well by the WRF-NMM. It is also found that the sudden mean sea level pressure drop of 02 hPa observed at 1100 UTC and 1200 UTC which is the indication of thunderstorm.

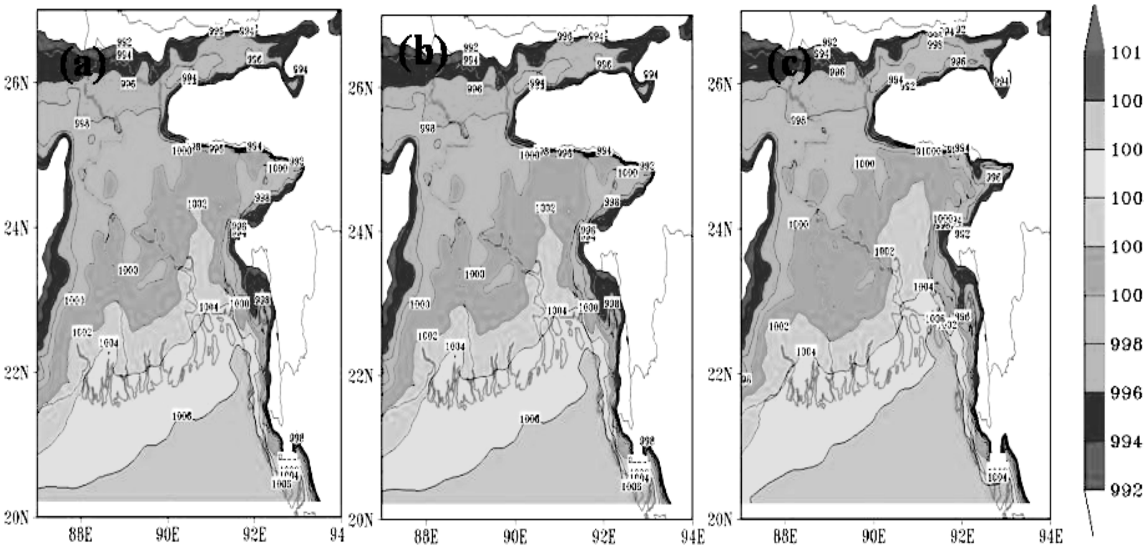


Fig.2 (a-c). Simulated mean sea level pressure (hPa) by the model for 1100 UTC, 1200 UTC and 1300 UTC on 26 April 1989

3.1.2. Surface Wind Flow Patterns

The wind pattern at 10 meters above the ground level simulated by the WRF model valid for 1100 UTC, 1200 UTC and 1300UTC of 26 April 1989 are presented in Fig.3 (a-c). The prominent feature is a strong southwesterly confluence line transporting high magnitude of moisture from the Bay of Bengal into central part of Bangladesh at 1100 UTC of 26 April 1989 [Fig.3 (a)]. The area of convergence i.e., zone of high convective activity (circle marked) observed over Saturia and neighborhood valid for 1100 UTC, 1200 UTC and 1300 UTC [Fig.3 (b-c)]. The southwesterly wind is prevailed over North Bay of Bengal and central part of Bangladesh.

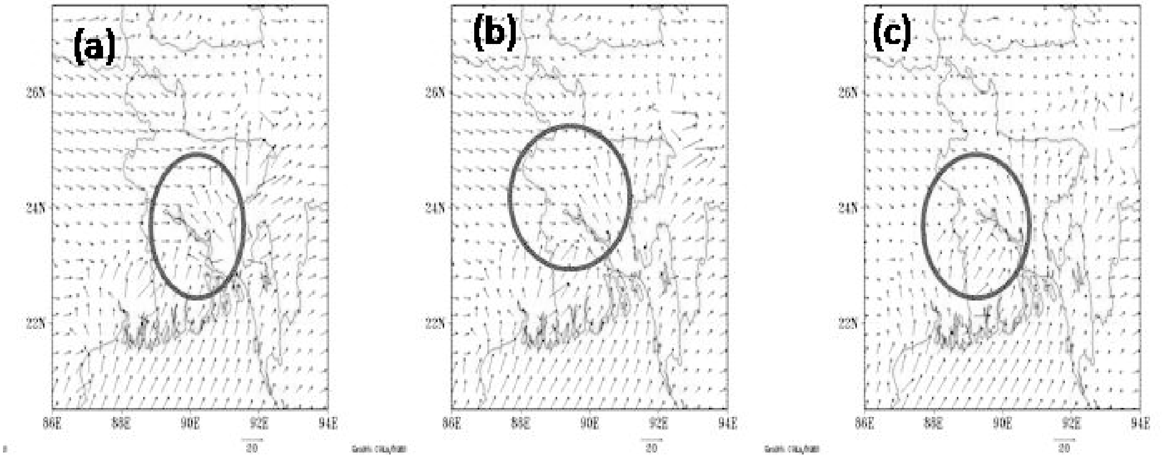


Fig.3 (a-c): Simulated 10m wind pattern (ms^{-1}) by the model for at 1100 UTC [Fig.(a)], 1200 UTC [Fig.(b)] and 1300 UTC [Fig.(c)] on 26 April 1989

3.1.3. Temperature Analysis

The temperature at 2 meters above the ground level simulated by the WRF model valid for 1100 UTC, 1200 UTC and 1300 UTC of 26 April 1989 are presented in [Fig.4 (a-c)]. The surface temperature [Fig.4 (a)] was captured at 1100 UTC 33℃ to 39℃ and at 1200 UTC 33℃ to 39℃ over Saturia and neighborhood and it is found that the temperature was higher (> 39℃) at the western part of Saturia and adjoining area. So the tornado was formed by the interaction of moist and humid air with hot and dry air. Temperature at 1300 UTC from 39℃ to 27℃, 1h after the time of the tornado initiation, which could be attributed to the cooling of the surface temperature due to precipitation by the tornado system.

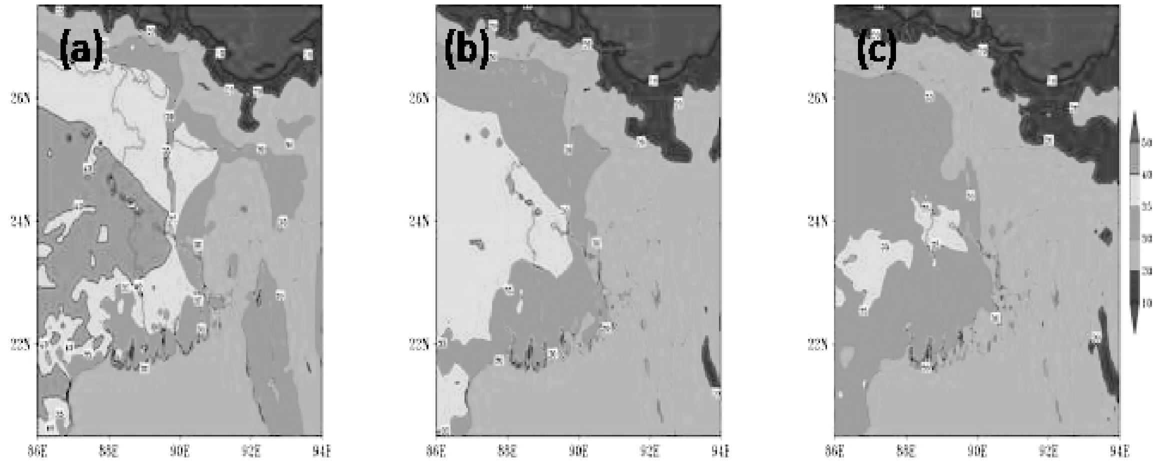


Fig.4 (a-c): Simulated temperature analysis by the model for 1100 UTC, 1200 UTC and 1300 UTC on 26 April 1989

3.1.4. Relative Humidity Analysis

Relative humidity at the surface level has also been taken into account, as it is an essential factor for intense convection. Storm days require a sufficiently humid and deep layer in the lower and middle atmosphere. The model simulated lower level relative humidity at 1100 UTC, 1200 UTC and 1300 UTC of 26 April 1989 was depicted in [Fig.5 (a-c)] and it is found that the relative humidity is 50- 60% over Saturia and adjoining area and at the right side of the tornado relative humidity is more than 70%. The tornado was actually formed over Saturia (23.6°N 90.0°E) at the right side of the dry Line.

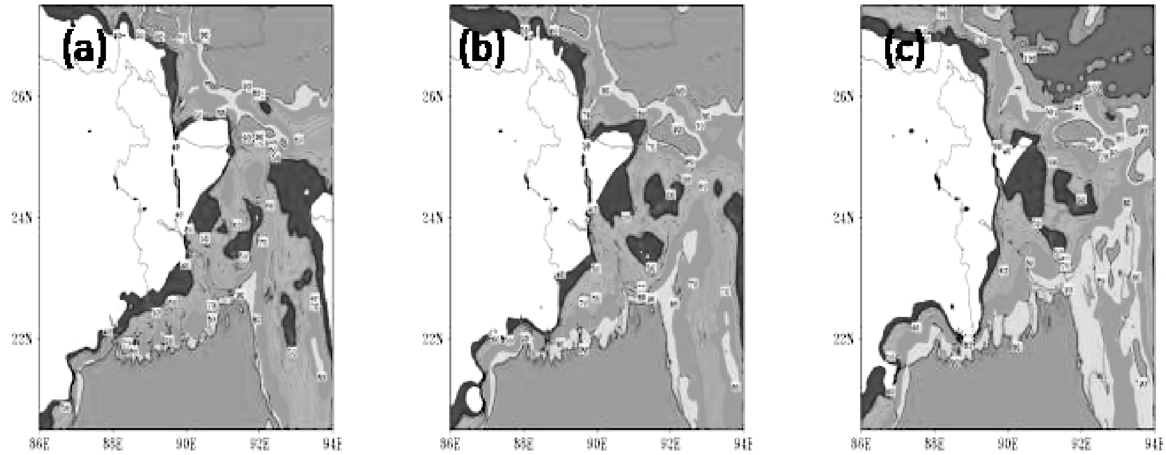


Fig.5: Simulated relative humidity analysis by the model for 1100UTC, 1200 UTC and 1300UTC on 26 April 1989

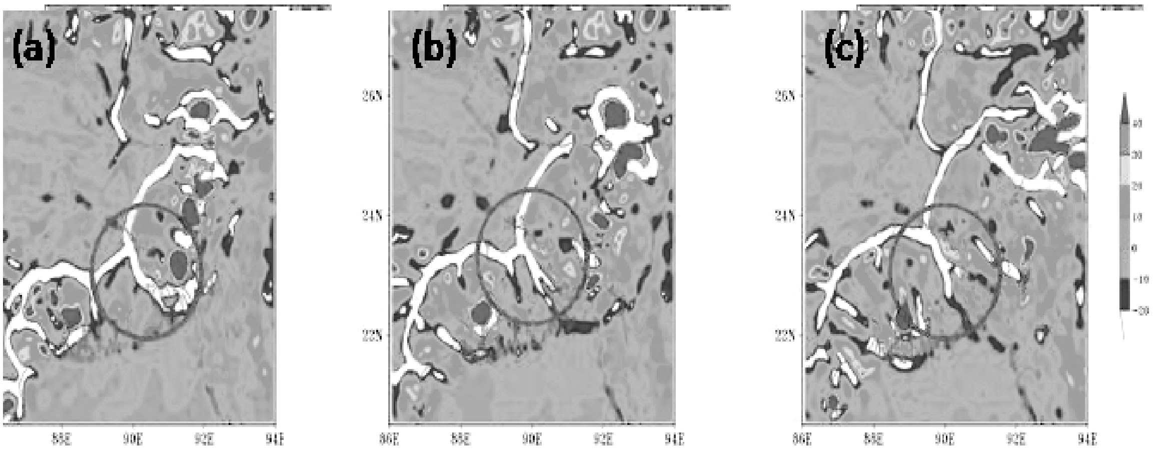


Fig.6 (a-c): Simulated lower level divergence (× s^{-1}) analysis by the model for 1100 UTC, 1200 UTC and 1300 UTC on 26 April 1989

3.1.5. Lower Level Divergence Analysis

Low level convergence is one of the important parameters to analysis the convection systems. The distribution of low level divergence (×s^{-1}) at 850mb valid for 1100 UTC, 1200 UTC and 1300 UTC of 26 April 1989 is shown in [Fig.6 (a-c)]. Negative and positive divergence is found over Saturia and adjoining area. Negative divergence is related to updraft and positive divergence is related to downdraft which is the indication of severe thunderstorm like tornado event.

3.1.6. Lower Level Convergence Analysis

The WRF model simulated low level horizontal relative vorticity (×s^{-1}) at 850mb, valid for 1100 UTC, 1200 UTC and 1300UTC of 26 April 1989 are presented in [Fig.7 (a-c)] respectively. A prominent feature is a positive vorticity maxima over Saturia and adjoining area. It is related to convergence and an essential parameter for deep convection.

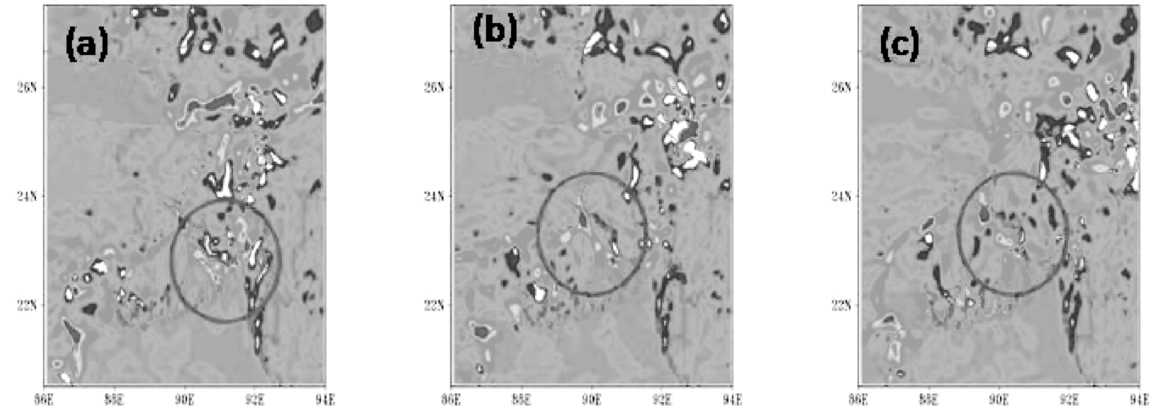


Fig.7 (a-c): Simulated lower level convergence (×s^{-1}) analysis by the model for 1100 UTC, 1200 UTC and 1300 UTC on 26 April 1989

3.1.7. Mean Vertical Wind Speed Analysis

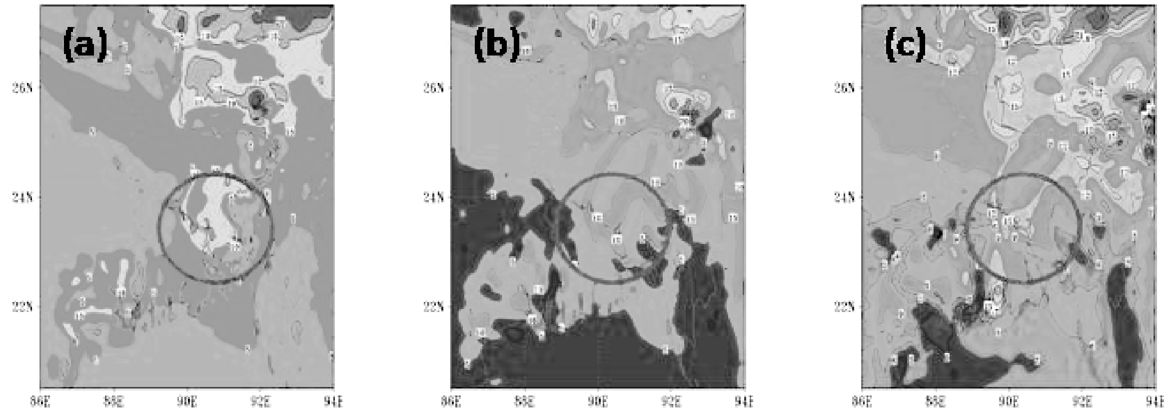


Fig.8 (a-c): Simulated vertical mean wind (m/sec) by the model for 1100 UTC, 1200 UTC and 1300 UTC on 26 April 1989

The mean vertical wind speed is simulated by the model, valid for 1100 UTC, 1200 UTC and 1300 UTC of 26 April 1989 are depicted in [Fig.8 (a-c)] for Saturia tornado event. The vertical mean wind speed is found positive which is related to updraft and a positive sign of deep convection.

3.1.8. Convective Available Potential Energy (Cape)

The simulated CAPE (Jkg^{-1}) by the model over Saturia, Bangladesh, valid for 1100 UTC, 1200 UTC and 1300UTC of 26 April 1989 is shown in [Fig.9 (a-c)]. On 26 April, 1989 the tornado was reported around 1230 UTC in Saturia. Analysis showed that CAPE started building up southeast of the area since morning 1100 UTC and was maximum (1500-3000 J kg^{-1}) at 1300 UTC and it decreased afterwards. This CAPE value is very supporting to form severe Thunderstorm like tornado.

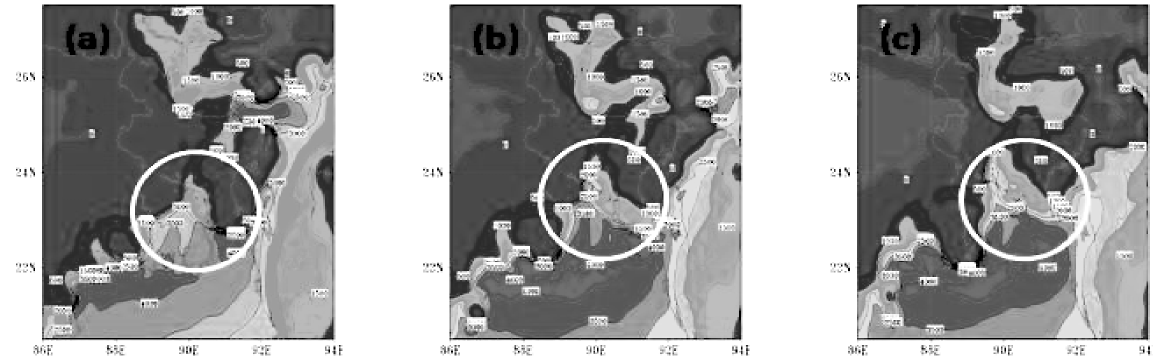


Fig.9 (a-c): Simulated convective available potential energy (Jkg^{-1}) by the model for 1100 UTC, 1200 UTC and 1300UTC on 26 April 1989

3.1.9. Gusty Wind Analysis

The 10 m above ground gust is simulated by the model, valid for 1100 UTC, 1200 UTC and 1300 UTC of 26 April 1989 are shown in [Fig.10 (a-c)] for Saturia tornado event. It is clear that the gust of 10-15 ms^{-1} is simulated over Saturia and adjoining area validated at 1300UTC in fig. 10 (c) which is the indication of horizontal movement of the system.

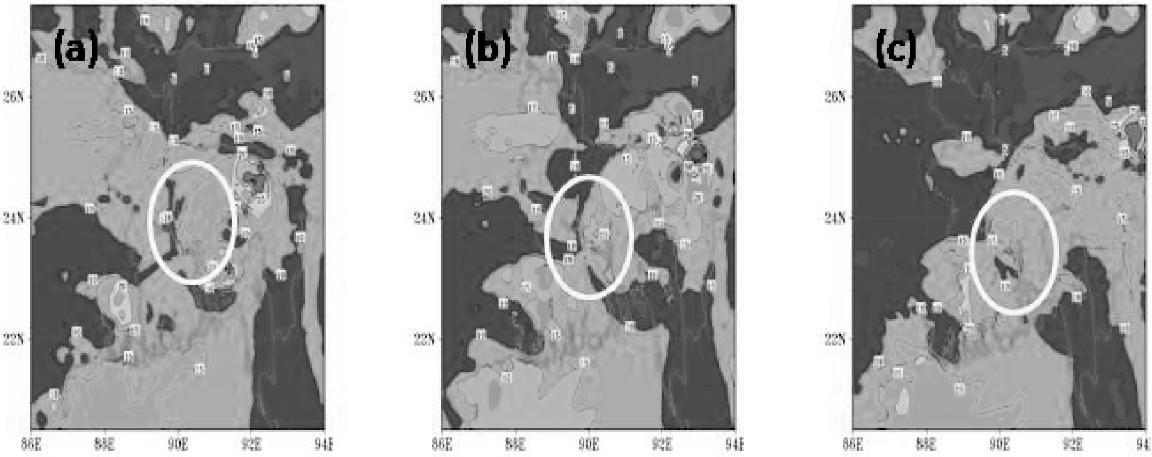


Fig.10 (a-c): Simulated gusty wind (m/sec) by the model for 1100 UTC, 1200 UTC and 1300UTC on 26 April 1989.

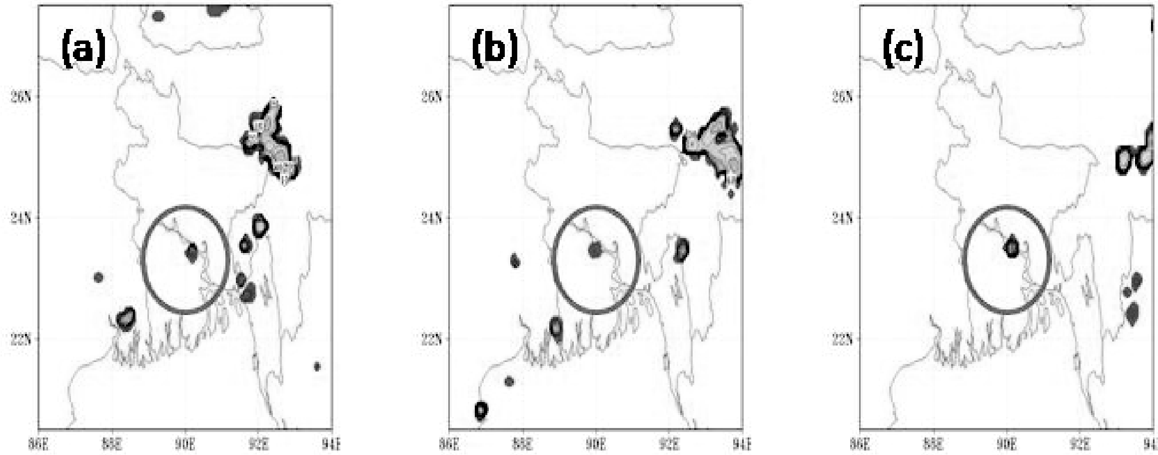


Fig.11 (a-c): Simulated radar reflectivity factor, Z (dBZ) by the model for 1100 UTC, 1200UTC and 1300UTC on 26 April 1989.

3.2.0. Radar Reflectivity Factor Analysis

Radar Reflectivity Factor is an important factor for intense convection. The model simulated Radar Reflectivity Factor at 1100 UTC, 1200 UTC and 1300 UTC of 26 April 1989 was illustrated in [Fig.11 (a-c)] and it is found that the Reflectivity Factor (dBZ) is above 50 over Saturia and adjoining area. This value is very much supporting to form severe thunderstorm like tornado with associated hails.

3.2.1: Lifted Index Analysis

The Lifted Index (LI) measures the difference between a parcel's temperatures compared with the environmental temperature at 500 hPa after the parcel has been lifted from the Lifting Condensation Level (Air Weather Service, 1990). LI has proved useful for indicating the likelihood of severe thunderstorms. The chances of a severe thunderstorm are best when the LI is less than or equal to -6. This is because air rising in these situations is much warmer than its surroundings and can accelerate rapidly and create tall and violent thunderstorms. Values less than -9 reflect intense instability. The WRF model is able to capture a low value which is -6 at 1100 UTC, 1200 UTC and 1300 UTC and LI value started increasing at 1300 UTC shown in fig.12 (a-c).

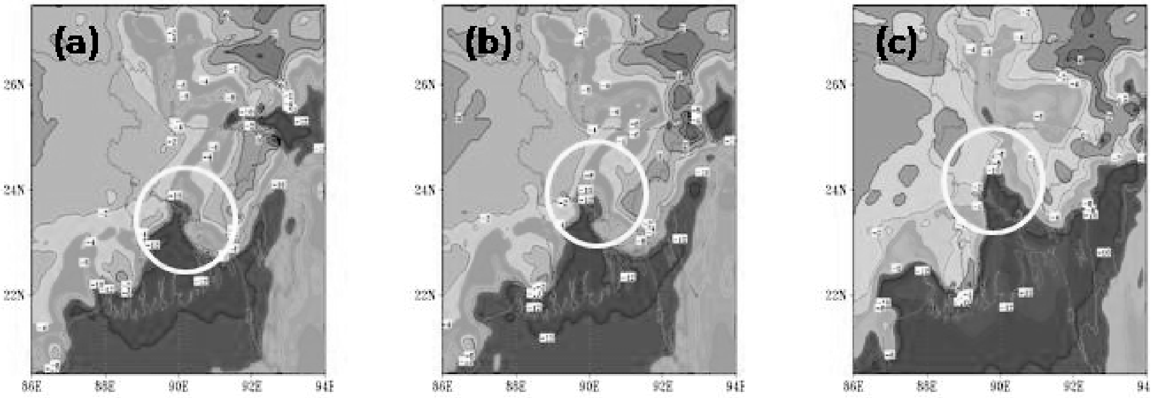


Fig.12 (a-c): Simulated lifted index by the model for 1100 UTC, 1200 UTC and 1300 UTC on 26 April 1989.

3.2.2: Vertical Wind Shear Analysis

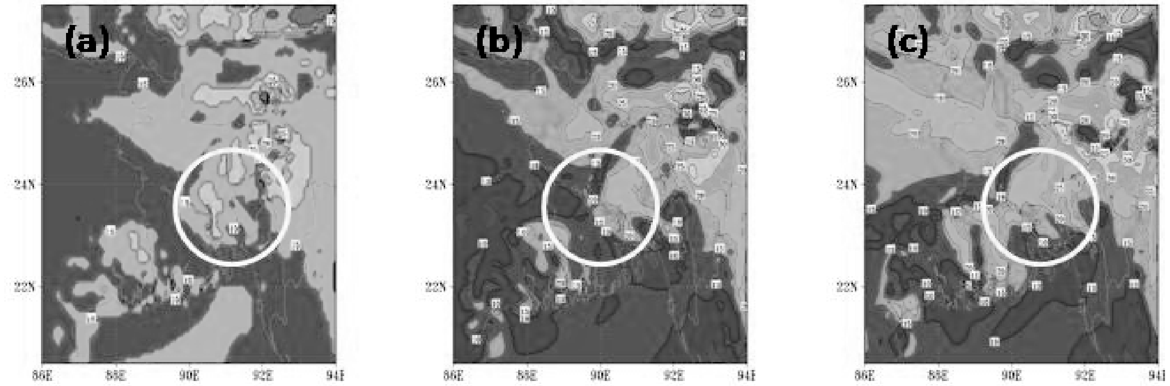


Fig.13 (a-c): Simulated vertical wind shear (m/sec) by the model for 1100 UTC, 1200 UTC and 1300 UTC on 26 April 1989.

Maximum value of Vertical wind shear is an important parameter for prediction of thunderstorm. The WRF simulated vertical wind shear at 610 m height is depicted in [Fig. 13(a-c)] validated for 1100 UTC, 1200 UTC and 1300 UTC on 26 April 1989. Simulated vertical wind shear over Saturia is about 20 - 25 ms^{-1} which is very high and related to form severe thunderstorm like Tornado.

3.2.3. Rainfall

During tornadoes the rainfall may be less, but the strength of wind are dangerously high. The simulated rainfall values are shown in [Fig.14 (a-c)] for 1100 UTC, 1200 UTC and 1300 UTC on 26 April 1989. The diagrams correspond to the highest values of rainfall in the vicinity of the tornado event. Results show that the highest values of rainfall were simulated and values were generally less than 90 mm hr^{-1} and the rainfall pattern is hook type. In this case study the direction of movement of the rainfall bands followed according to the direction of movement of the gust winds and high CAPE values as discussed earlier.

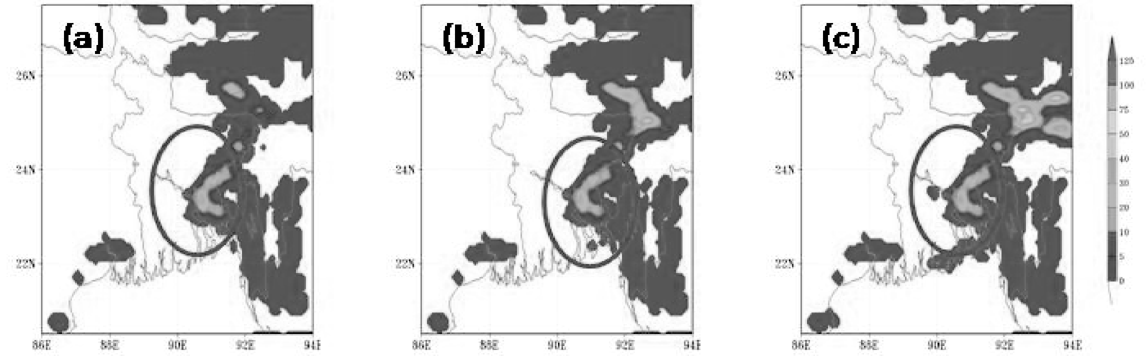


Fig. 14(a-c): Simulated rainfall (mm hr^{-1}) by the model valid for 1100UTC, 1200UTC and 1300UTC on 26 April 1989.

4. Conclusion

The simulation of the tornado event on 26 April 1989 over Saturia, Manikgonj, Bangladesh has been carried out using complete environmental Modeling system. On the basis of the present study, the following conclusions can be drawn:

(1) Simulation of the stability indices like CAPE, LI, Radar Reflectivity and gust were good, with values indicating higher instability for the tornado to occur. The model simulated well the updraft and downdraft during the tornado formation and occurrence.

(2) Sudden mean sea level pressure drop of 2 hPa observed at 0900UTC and 1000 UTC which is the indication of thunderstorm.

(3) The confluence of southwesterly flow was transporting high magnitude of moisture from the Bay of Bengal towards Saturia of Bangladesh and neighbourhood.

(4) The model also simulated high moisture convergence over Saturia during tornado hours and the convergence zone lies over Saturia and adjoining area.

(5) Simulated vertical wind shear and vertical mean wind speed were too supportive for the formation of severe thunderstorm.

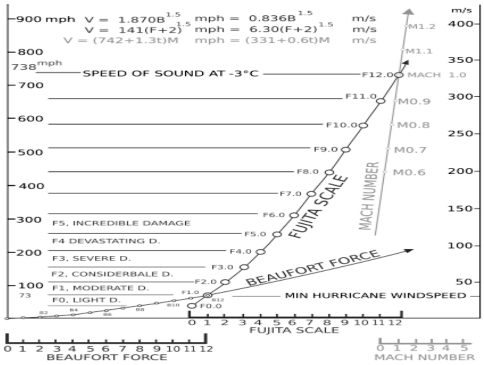
(6) The tornado event on Saturia was formed over the right side of the dry line.

Thus we conclude that the 2 km WRF model performed well in genesis, intensification and decay of severe thunderstorm like tornado. This suggests that high-resolution models have the potential to provide unique and valuable information for severe tornado forecasts.

Acknowledgements

We are indebted to Mr. Md. Shah Alam, Director, Bangladesh Meteorological Department (BMD) for his constant support and constructive suggestions. We are also thankful to Mr. Shamsuddin Ahmed, Deputy Director, Storm Warning Center, BMD for his good advices for the research works.

Appendix-A



Source: www.wikipedia.org/wiki/Fujita_scale

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