A COMPARATIVE STUDY ON PERFORMANCE OF MM5 AND WRF (ARW & NMM) MODELS IN SIMULATION OF TROPICAL CYCLONE OVER BAY OF BENGAL

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KEY WORDS: Tropical cyclone, Mesoscale models, Track, Intensity, Precipitation

ABSTRACT:

Tropical cyclone is one of the most devastating and deadly weather phenomena worldwide. It is a result of organized intense convective activities over warm tropical oceans. In the recent years mesoscale models are extensively used for simulation of genesis, intensification and movement of tropical cyclones. During 26-29 April 2006, a very severe tropical cyclone (Mala) developed over Indian Seas (Bay of Bengal) and crossed the Arakan coast of Myanmar on 29 April 2006. In the present study, three state-of-the-art mesoscale models MM5 and WRF-ARW and WRF-NMM have been used to evaluate the performances of both the models in the simulation of Mala cyclone. The performance of the models has been evaluated with five different initial conditions. A number of various meteorological fields' viz. central pressure, winds, precipitation etc. are verified against observations / verification analysis to compare the results for different experiments. The vector displacement error in track forecast will also calculated using the best track provided by the India Meteorological Department (IMD). The results indicate that, WRF-ARW model has better forecast skill in terms of intensity prediction, but WRF-NMM has better forecast skill in terms of track prediction of the cyclonic storm.

1. INTRODUCTION:

Tropical cyclones are one of the nature's most violent manifestations and potentially the deadly meteorological phenomena. The Bay of Bengal tropical cyclone disaster is the costliest and deadliest natural hazard in the Indian sub-continent. It has a significant socio-economic impact on the countries bordering the Bay of Bengal, especially India, Bangladesh and Myanmar. Therefore, reasonably accurate prediction of these storms has great importance to avoid the loss of valuable lives.

There have been considerable improvements in the field of weather prediction by numerical models. The Pennsylvania State University (PSU)/ National Center for Atmospheric Research (NCAR) mesoscale model MM5 has been used in a number of studies for the simulation of tropical cyclones (Zhang, 2003). Mohanty et al (2003) used MM5 model to simulate the Orissa super cyclone (1999). There are a number of comparative studies on the performance of the mesoscale models for severe weather events triggered by convection. Sousounis et al. (2004) made a comparative study on the performance of WRF, MM5, RUC and ETA models for heavy precipitation event and suggested that, WRF model has the capability to generate physically realistic fine-scale structure which is not seen in the standard output resolution of other operational forecast models. Cheng et al (2005) made a comparison study between WRF and ETA on the surface sensible weather forecast over Western United States and found that, the WRF has better forecast skill. Patra et al (2000) made a comparative study on the performance of MM5 and RAMS models in simulating the Bay of Bengal cyclones and demonstrate better forecast skill of MM5 model.

In the present study, MM5, WRF-ARW and WRF-NMM are used to simulate the tropical cyclone Mala generated over Bay of Bengal. The performances of the models have been evaluated and compared with observations and verifying analyses. A brief description of the mesoscale models along with the numerical experiments and data used for the present study are given in section 2. The synoptic situation for the above mentioned cyclone used in the present study is described in section 3. The results are presented in section 4 in order to evaluate the performance of the models and the conclusions are in section 5.

2. MODEL DESCRIPTION:

MM5 has been widely used for simulation / prediction of severe weather events such as tropical cyclones, heavy rainfall, thunderstorms etc. MM5 is a nonhydrostatic mesoscale model with pressure perturbation p', three velocity components (u, v, w), temperature T and specific humidity q as the prognostic variables. Model equations in the terrain following sigma co-ordinate are used in surface flux form and solved on Arakawa B grid. Leapfrog time integration scheme with time splitting technique is used in model integration. With a number of sensitivity tests, it has demonstrated that the combination of Grell cumulus parameterization scheme with MRF PBL, in general, provides better result for simulation of tropical cyclones (Mandal et al, 2004). Table 1(a) summarizes the model configuration and various options used by MM5 in the present study.

Table 1 (a) Brief description of the MM5 model

Model	PSU / NCAR Mesoscale model MM5
Dynamics	Non-hydrostatic with 3-D Coriolis force
Resolution	27 km
No of vertical levels	51
Horizontal grid scheme	Arakawa B grid
Time integration scheme	Leap-frog scheme with time splitting technique
Lateral boundary condition	NCEP / NCAR GFS forecast
Radiation scheme	Dudhia's shortwave/longwave simple cloud
PBL scheme	MRF (Hong-Pan, 1996)
Cumulus parameterization scheme	Grell (Grell, 1993)
microphysics	Simple ice

The WRF-ARW modeling system developed by the Mesoscale and Microscale Meteorology (MMM) Division of NCAR is designed to be a flexible, state-of-the-art atmospheric simulation system which is suitable for a broad range of applications such as idealized simulations, parameterization research, data assimilation research, real-time NWP etc. Model equations are in the mass-based terrain following co-ordinate system and solved on Arakawa-C grid. Runge-Kutta 2^{nd} and 3^{rd} order time integration technique is used for model integration. The new generation of the MRF PBL scheme is introduced here as Yonsei University (YSU) PBL. It has an explicit representation of entrainment at the PBL top, which is derived (Noh, 2003) from large eddy simulation.

Table 1 (b) Brief description of the WRF-ARW model

Model	NCAR Mesoscale model WRF
Dynamics	Non-hydrostatic with 3-D Coriolis force
Resolution	27 km
No of vertical levels	51
Horizontal grid scheme	Arakawa C grid
Time integration scheme	Runge-Kutta 2^{nd} & 3^{rd} order time splitting technique
Lateral boundary condition	NCEP / NCAR GFS forecast
Radiation scheme	Dudhia's shortwave / RRTM longwave
PBL scheme	YSU
Cumulus parameterization scheme	Grell – Devenyi Ensemble scheme
Microphysics	Ferrier

Grell and Devenyi (GD) have introduced a new ensemble approach to cumulus parameterization into WRF (Grell, 2002). After a number of sensitivity experiments, the best combination of the cumulus parameterization scheme and planetary boundary layer physic are obtained. The combination of GD cumulus parameterization scheme and YSU-PBL gives better result in the simulation of the Bay of Bengal cyclones. Table 1 b) summarizes the model configuration and various options used by WRF-ARW in the present study.

The Nonhydrostatic Mesoscale Model (NMM) core of the Weather Research and Forecasting (WRF) system was developed by the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP). The WRF- NMM is designed to be a flexible, state-of-the-art atmospheric simulation system that is efficient on available parallel computing platforms. The WRF-NMM model is a fully compressible, non-hydrostatic model with a hydrostatic option (Janjic et al. 2001; Janjic 2003a, Janjic 2003b). The horizontal Arakawa – E grid staggering is used for computational efficiency. The model uses a terrain following hybrid sigma-pressure vertical coordinate. The dynamics conserve a number of first and second order quantities including energy and enstrophy (Janjic 1984). Forward-backward schemes are used for the horizontally propagating fast-waves and implicit scheme is used for the vertically propagating sound waves. Adams-Bashforth scheme and Crank-Nicholson scheme are used for horizontally and vertically propagating waves. The Geophysical Fluid Dynamics Laboratory (GFDL) long wave and short wave radiation schemes are incorporated in the model. Table 1(c) summarizes the model configuration and various options used by WRF-NMM in the present study.

Table 1 (c) Brief description of the WRF-NMM model

Model	WRF-NMM
Dynamics	Non-hydrostatic with terrain following hybrid pressure sigma vertical co-ordinate
Resolution	27 km
No of vertical levels	51
Horizontal grid scheme	Arakawa E grid
Time integration scheme	Horizontally: Forward-backward scheme Vertical: Implicit scheme
Lateral boundary condition	NCEP / NCAR GFS forecast
Radiation scheme	Dudhia's shortwave / RRTM longwave
PBL scheme	YSU
Cumulus parameterization scheme	Grell – Devenyi Ensemble scheme
Microphysics	Ferrier

The mesoscale models described in above sections are integrated up to 96 hrs in a single domain with the horizontal resolution of 27 km along with 51 levels up to a height of 30 km in the vertical for five different initial conditions i.e. 00 UTC 25 April 2006, 12 UTC 25 April 2006, 00 UTC 26 April 2006, 12 UTC 26 April 2006 and 00 UTC 27 April 2006. The initial and lateral boundary conditions to a limited area model are usually provided from the large-scale analysis available at different NWP centers in the world. The National Center for Environmental Prediction (NCEP) Global Forecast system (GFS) analyses and forecasts (1º X 1º horizontal resolution) are used to provide the initial and lateral boundary conditions respectively to all the models.

3. SYSTEM DESCRIPTION:

The cyclone Mala has developed over the warm tropical ocean, near 9.5º N, 90.5º E, around 03 UTC 25 April 2006 with the central mean sea level pressure of 996 hPa and the maximum sustainable wind of 25 kts. The system remained at that stage for further 6 hours i.e. up to 09 UTC 25 April 2006. By 09 UTC 25 April 2006, it was turned into deep depression stage. Then the system became cyclonic storm after 12 UTC 25 April 2006. At 00 UTC 26 April 2006, the clear-cut cyclonic storm with the center of the storm at 10.5º N and 89.0º E with the central pressure of 994 hPa and maximum surface wind of 45 kts was observed. The system remained in cyclonic stage up to 00 UTC 27 April 2006. Then around 03 UTC 27 April 2006, it became severe cyclonic storm with central pressure of 990 hPa and the maximum sustainable wind of 55 kts. The system became very severe cyclonic storm (VSCS) by 12 UTC 27 April 2006 with the central mean sea level pressure of 984 hPa and the maximum surface wind of 65 kts. The storm remained in VSCS for a period of 42 hours i.e up to 06 UTC 29 April 2006. The maximum observed central pressure was 954 hPa with the pressure drop of 52 hPa. The observed maximum sustainable surface wind was 100 kts. The very severe cyclonic storm crossed the Arakan coast at about 100 km south to Sandoway around 07 UTC 29 April 2006. The system remained on the land for further 12 hours and caused a lot of devastation in the underlying coastal areas.

4. RESULTS AND DISCUSSION:

The results from the above mentioned three models are presented in this section. In order to avoid duplication of the results (if all the results will be provided), the results as obtained from the initial condition of 00 UTC 26 April 2006 are provided for the large scale fields.

4.1 Mean sea level pressure and wind at 850 hPa

Figure 1(a) and (b) represents the day-3 forecast of the mean sea level pressure (MSLP) and wind at 850 hPa from MM5 model simulation valid at 00 UTC 29 April 2006. The central MSLP of 944 hPa with the maximum sustainable wind of 128 kts is simulated. Figure 2(a) and (b) represents the day-3 forecast of the MSLP and wind at 850 hPa from WRF-ARW model valid at 00 UTC 29 April 2006. The central MSLP of 956 hPa with the maximum sustainable wind of 72 kts is simulated.

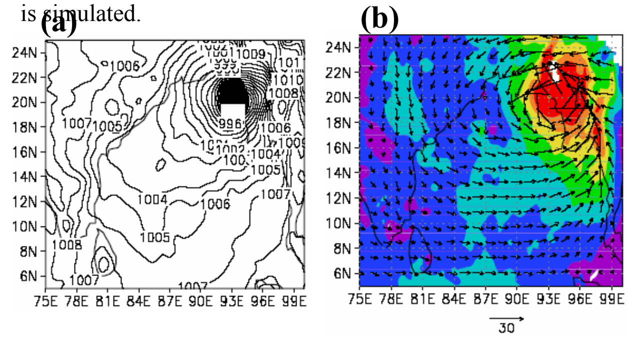

Figure 1(a) MSLP, (b) wind at 850 hPa with MM5 simulation.

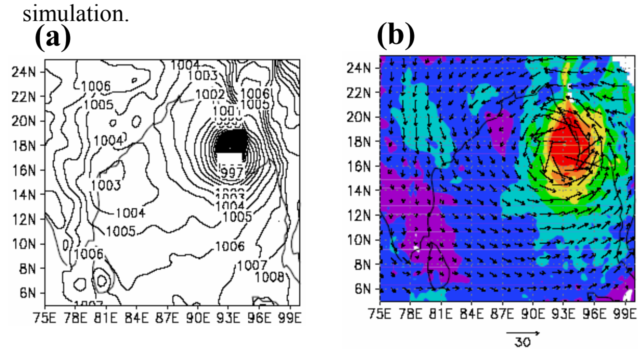

Figure 2(a) MSLP, (b) wind at 850 hPa with WRF-ARW simulation.

Figure 3(a) and (b) represents the day-3 forecast of the MSLP and wind at 850 hPa from WRF-NMM model simulation valid at 00 UTC 29 April 2006. The central MSLP of 999 hPa with the maximum sustainable wind of 40 kts is simulated.

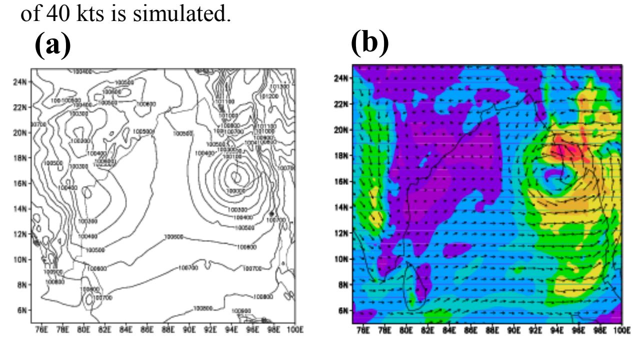

Figure 3(a) MSLP, (b) wind at 850 hPa with WRF-NMM simulation.

From the results (not all figures shown) it may be inferred that, simulation with MM5 model gives the storm movement much faster. However, WRF-ARW and WRF-NMM results shown reasonably accuracy with observation. It may also notice that, MM5 intensify the storm much more, whereas WRF-ARW simulated reasonable accuracy with observation. However, WRF-NMM fails to simulate the intensity of the storm.

4.2 Precipitation

Figure 4 represents the 24 hours accumulated precipitation valid at 03 UTC 29 April 2006. Figure

4(a) represents 24 hr accumulated precipitation as a merged analysis of Tropical Rainfall Measuring Mission (TRMM), TMI and rain gauges observations carried out by National Aeronautics and Space Administration (NASA) valid for 03 UTC 27 April 2006 and 03 UTC 29 April 2006 respectively. The precipitation data as well as the figures are obtained from the NASA web site (http://disc2.nascom.nasa.gov/Giovanni/tovas). Figure 4(b), (c) and (d) represent the 24 hr accumulated precipitation from MM5, WRF-ARW and WRF-NMM respectively. The observed precipitation is about 40 cm, where as MM5, WRF-ARW and WRF-NMM could simulate the precipitation of 20cm, 40 cm and 22 cm respectively.

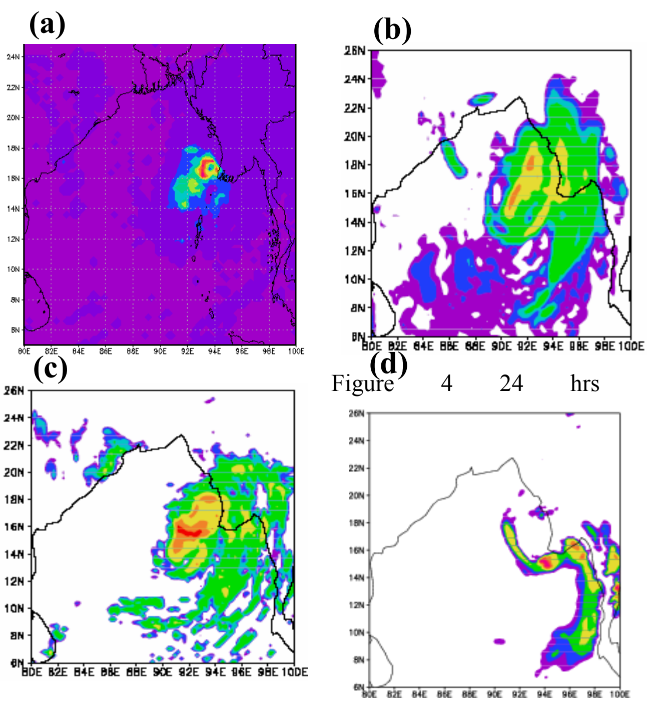

Figure 4 24 hrs accumulated precipitation valid at 03 UTC 29 April 2006.

4.3 Track

The track of the cyclone as obtained from the model simulations using different initial conditions are evaluated and compared with the best-fit track as estimated by from IMD. Figure 5 (a), 5 (b) and 5 (c) represents the track of the cyclone Mala as obtained with MM5 WRF-ARW and WRF-NMM model simulations from different initial conditions.

All the models show that, in each case the cyclone moves to the Arakan coast, what ever the initial condition is being chosen. But with MM5 simulation, at the landfall location the track spreads about 700 km whereas, the tracks are confined within 400 km with WRF-ARW and about 250 km with WRF-NMM model simulation.

The vector displacement error is also calculated at the landfall point. The mean vector displacement error of 232.2 km is evaluated with MM5 model simulation, whereas with WRF-ARW model simulation, 219.95 km of mean vector displacement error and with WRF-NMM model simulation, the mean error of 169.36 is

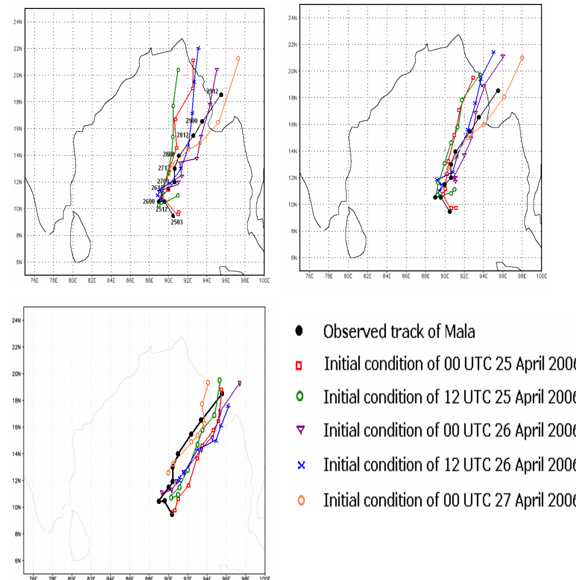

Figure 5 Observed best-fit track and the track simulations from different initial condition with (a) MM5, (b) WRF-ARW and (c) WRF-NMM for cvclone Mala

calculated. The detailed of the displacement error are described in Table 2.

Table 2 Vector displacement error at the landfall point

Initial Condition	MM5	WRF-ARW	WRF-NMM
2500	334.1	-	189
2512	-	319.7	115.8
2600	338	234.3	166.5
2612	71.5	174.9	200
2700	185.2	150.9	175.5
Mean	232.2	219.95	169.36

5. CONCLUSIONS:

From the comparative study on the performance of the mesoscale models, following broad conclusions are derived.

All the models could simulate most of the features of the cyclone Mala with reasonably accuracy. The WRF-ARW could simulate the intensity in terms of minimum central pressure and maximum sustainable wind with more accuracy. However, MM5 intensify the storm rapidly and WRF-NMM fails to simulate the intensity of the storm.

The precipitation forecast with WRF-ARW is found to be more realistic with respect to the observed precipitation, both in terms of amount and pattern of distribution.

The track forecast with WRF-NMM is found to be more accurate than WRF-ARW and MM5. The mean vector displacement error clearly demonstrates the forecast skill of the WRF-NMM in terms of track prediction.

ACKNOWLEGDEMENTS

The authors acknowledge Mesoscale and Microscale Meteorology Division of NCAR for providing MM5 and WRF modeling system and NOAA, NCEP for providing WRF-NMM for the present study. The authors also acknowledge the NCEP for providing the real time large scale analysis as well as forecasts of Global Forecast System (GFS). The authors owe thanks to India Meteorological Department (IMD) for providing observational data sets and best-fit track of the storm and NASA for precipitation data sets.

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