A comparative study on performance of MM5 and WRF models in simulation of tropical cyclones over Indian seas

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Tropical cyclone is one of the most devastating and deadly weather phenomenon worldwide. It is a result of organized intense convective activities over warm tropical oceans. In recent years mesoscale models are extensively used for simulation of genesis, intensification and movement of tropical cyclones. In this study, the recent three very severe cyclonic storms generated over Indian seas (Bay of Bengal and Arabian Sea) are considered. During 26–29 April 2006, a very severe tropical cyclone, known as Mala, developed over the Bay of Bengal and crossed the Arakan coast of Myanmar on 29 April 2006. During 2–7 June 2007, a super cyclonic storm, known as Gonu, developed over the Arabian sea and crossed the Makran coast on 7 June 2007. During 11–16 November 2007, a very severe cyclonic storm, known as Sidr, developed over the Bay of Bengal and crossed the Khulna–Barisal coast of Bangladesh on 15 November 2007. In the present study, two state-of-the-art mesoscale models, MM5 and WRF, developed at the National Center for Atmospheric Research (NCAR), USA, have been used to evaluate the performances of both the models in the simulation of the above-mentioned tropical cyclones. The performances of both the models have been calculated by integrating with 15 different initial conditions, i.e. each case with five different initial conditions. A number of meteorological fields, viz. central pressure, wind and precipitation have been verified against observations/verification analyses. The vector displacement error in track forecast has also been calculated using the best track provided by the India Meteorological Department. The results indicate that the WRF model has better performance in respect of track and intensity prediction than the MM5 model.

Keywords: Tropical cyclone, mesoscale models, track, intensity, precipitation.

TROPICAL cyclones are among nature's most violent manifestations and potentially a deadly meteorological phenomenon. The Bay of Bengal is a potentially energetic region for the development of cyclonic storms and about 7% of the global annual tropical storms forms over this region. Moreover, the Bay of Bengal storms are exceptionally devastating, especially when they cross the land[1]. Thus the Bay of Bengal tropical cyclone is the deadliest natural hazard in the Indian sub-continent. It has significant socio-economic impact on countries bordering the Bay of Bengal, especially India, Bangladesh and Myanmar. At the same time, Arabian Sea contributes 2% of the global annual tropical storms. Therefore, reasonably accurate prediction of these storms is important to avoid the loss of lives.

In last two decades, there have been considerable improvements in the field of weather prediction by numerical models. The PSU (Pennsylvania State University)/NCAR (National Center for Atmospheric Sciences) meso-scale model MM5 has been used in a number of studies for the simulation of tropical cyclones[2–6]. Mohanty *et al.*[7] used the MM5 model to simulate the 1999 Orissa super cyclone. The recently developed NCAR mesoscale model Weather Research Forecasting (WRF) system has improved model physics, cumulus parameterization schemes, planetary boundary layer physics, etc. There are a number of comparative studies on the performance of the mesoscale models for severe weather events triggered by convection. Sousounis *et al.*[8] made a comparative study on the performance of WRF, MM5, RUC and ETA models for heavy precipitation event. They have has taken more than 100 different model configurations of the four different models. Along with those model configurations, 39 different initialization times have been taken to get a combined result from nearly 4000 simulations. This study suggests 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. Real-time WRF and MM5 modelling systems are used by the US Navy to forecast at five test ranges[9]. This shows that the WRF model has better forecast skill in the upper tropospheric circulations, whereas the MM5 model produces more accurate forecasts at the surface and in the lower troposphere. Otkin *et al.*[10] made a comparative study on the performance of the WRF and MM5 models for the simulation of tornadoes over the Northern plains during the evening of 24 June 2003. Qualitative evaluation of the outputs of the models suggested that the WRF model has superior performance in generating fine-scale atmospheric structures. Cheng *et al.*[11] made a comparative study bet-

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Table 1. Brief description of the MM5 model

Model	PSU/NCAR mesoscale model MM5
Dynamics	Non-hydrostatic with 3D Coriolis force
Map projection	Mercator
Domain	Lat. (10°S–30°N), long. (57°–110°E)
Resolution	27 km
No. of vertical levels	31
Horizontal grid scheme	Arakawa B grid
Time integration scheme	Leapfrog scheme with time splitting technique with Δt = 45 s
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
Soil model	Multi-layer soil model
SST and surface parameters	NCEP/NCAR GFS

ween WRF and ETA models on the surface sensible weather forecast over western United States. They found that the WRF has better forecast skill. All the above-mentioned studies clearly indicate the performance of the WRF model in the Atlantic region. A few comparative studies have been carried out for Indian region. Patra *et al.*[12] made a comparative study on the performance of MM5 and RAMS models in simulating the Bay of Bengal cyclones. There is a need to carry out comparative study of the recently developed state-of-the-art WRF system with extensively used MM5 in the simulation of tropical cyclones over the Indian seas.

In the present study, models MM5 and WRF, developed by the Mesoscale and Microscale Meteorology (MMM) Division of NCAR, USA, have been used to simulate the recent tropical cyclones (Mala, Gonu and Sidr) generated over the Indian seas. The performances of both the models have been evaluated and compared with observations and verification analyses.

A brief description of both the mesoscale models along with the numerical experiments and data used for the present study are given below. The synoptic situation for the above-mentioned three cyclones, i.e. Mala, Gonu and Sidr used in the present study is then described. Then results are presented to evaluate the performance of both the models, followed by the conclusion.

Model description

In the present study, two mesoscale models MM5 and WRF have been integrated for a period of 96 h for each case as mentioned above.

MM5 model description

The non-hydrostatic mesoscale model MM5 is widely used for simulation/prediction of severe weather events such as tropical cyclones, heavy rainfall, thunderstorms, etc. MM5 is a primitive equation 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 coordinate are used in surface flux form and solved in Arakawa B grid. Leapfrog time integration scheme with time-splitting technique is used in model integration. In the time-splitting technique, the slowly varying terms are integrated with longer time-steps and the terms giving rise to the first moving waves are integrated with shorter time-steps. The most useful feature of the MM5 model is its flexibility in terms of many options that are user-specified, and by setting these parameters to appropriate values, the model can be used for a wide range of applications. These include number of nests, type of convection, boundary layer and radiation parameterization schemes. With a number of sensitivity tests, it has been demonstrated that the combination of Grell cumulus parameterization scheme with MRF PBL, in general, provides better results for simulation of tropical cyclones[13]. A detailed description of the model is provided by Dudhia[14] and Grell *et al.*[15]. Table 1 summarizes the model configuration and various options used in the present study.

WRF model description

The WRF modelling system 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 numerical weather prediction (NWP), etc. WRF is a fully compressible, non-hydrostatic system of equations with complete Coriolis and curvature terms. Model equations are in the mass-based terrain following coordinate system and solved in Arakawa-C grid. Runge–Kutta second and third-order time integration technique is used for model integration. A new generation of the MRF PBL scheme is introduced here as Yonsei University (YSU)-PBL, that has an explicit representation of entrain-

Table 2. Brief description of the WRF model

Model	NCAR mesoscale model WRF
Dynamics	Non-hydrostatic with 3D Coriolis force
Map projection	Mercator
Domain	Lat. (10°S–30°N), long. (57°–110°E)
Resolution	27 km
No. of vertical levels	31
Horizontal grid scheme	Arakawa C grid
Time integration scheme	Runge–Kutta Second and third-order time splitting technique with $\Delta t = 45$ s.
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
Soil model	Thermal diffusion scheme
SST and surface parameters	NCEP/NCAR GFS

ment at the PBL top which is derived[16] from large eddy modelling. This scheme also adds non-local momentum mixing to provide a better wind profile in the PBL. It has the capability to remove the influence of convective velocity on the surface stress, which will alleviate a daytime low-wind speed bias. Grell and Devenyi (GD)[17] have introduced a new ensemble approach to cumulus parameterization into WRF. It is an ensemble average of typically more than 100 types of clouds, which includes different closures such as CAPE removal, quasi-equilibrium and moisture convergence, and variants of cumulus parameterization, which include changes in the parameters for entrainment, cloud radius, maximum cap and precipitation efficiency. After a number of sensitivity experiments, the best combination of the cumulus parameterization scheme and planetary boundary layer physic is obtained. The combination of GD cumulus parameterization scheme and YSU-PBL gives better result in the simulation of the Bay of Bengal cyclones. Table 2 summarizes the model configuration and various options used in the present study.

In the MM5 model, there are no conservation properties, whereas in the WRF model the conservation of mass, momentum and entropy exists in the prognostic equations. Some of the problems may be attributed to the dynamical framework of MM5, especially the second-order advection scheme, which tends to produce spurious oscillations and requires numerical smoothing. The WRF model has a choice of a third or fifth-order advection scheme and is able to run without numerical smoothing to give improved results. Details of the main differences between MM5 and WRF are presented in Table 3.

Numerical experiments and data used

The mesoscale models described above are integrated up to 96 h in a single domain with a horizontal resolution of 27 km for all the cases. The MM5 model has 31 levels up to a height of 30 km in the vertical and the model is integrated with a time-step of 45 s. The WRF model has 31 levels up to a height of 30 km in the vertical and the model is integrated with a time-step of 45 s. Due to the robust dynamics of the WRF model, it has the capability to run with a larger time-step, i.e. nearly sixth time of the model horizontal resolution. However, in order to have a concrete comparison of the two models, it has been integrated with the same time-step as in MM5. The performance of a model cannot give any concrete conclusion from a single run or from a single case. Keeping this view in mind, both the models have been integrated for three cases with five different initial conditions for each case and a total of 15 different initial conditions, to conclude a tangible result on the performance of both the models. For the Mala case, starting from 00 UTC 25 April 2006 and in every 12 h interval, both the models have been integrated for 96 h for each simulation. Thus, five simulations have been carried out from the initial conditions of 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. For the second case, i.e. Gonu, starting from 00 UTC 02 June 2007 and in every 12 h interval, both the models have been integrated for 96 h for each simulation. Thus, five simulations have been carried out from the initial conditions of 00 UTC 2 June 2007, 12 UTC 2 June 2007, 00 UTC 3 June 2007, 12 UTC 3 June 2007 and 00 UTC 4 June 2007. Similarly, for the third case, i.e. Sidr, starting from 00 UTC 13 November 2007 and in every 12 h interval, both the models have been integrated for 96 h for each simulation. Thus, five simulations have been carried out from the initial conditions of 00 UTC 13 November 2007, 12 UTC 13 November 2007, 00 UTC 14 November 2007, 12 UTC 14 November 2007 and 00 UTC 15 November 2007. The initial and lateral boundary conditions to a limited area model are usually provided from the large-scale analysis available at different NWP centres in the world. The National Center for Environmental Prediction (NCEP) Global Forecast system (GFS) analysis and forecasts (1° × 1° horizontal resolution) have been

Table 3. Differences between MM5 and WRF models

MM5	WRF
Terrain following height (sigma-*z*) vertical coordinate	Terrain following hydrostatic pressure vertical coordinate
Arakawa B-grid	Arakawa C-grid
First-order (time-filtering) leapfrog time integration scheme	Second order Runge–Kutta split-explicit time integration
Advection formulation (no conservation properties)	Conserves mass, momentum, entropy and scalar using flux from prognostic equations
Second order centre differencing for advection	Fifth-order upwind or sixth-order centred differencing for advection

used to provide the initial and lateral boundary conditions respectively, for both the models.

System description

Case I (Mala)

The cyclone Mala had developed over the warm tropical ocean, near 9.5°N, 90.5°E, around 3 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 h, i.e. up to 09 UTC 25 April 2006. By 09 UTC 25 April 2006, it turned into a deep depression. Then the system became a cyclonic storm after 12 UTC 25 April 2006. At 00 UTC 26 April 2006, a clear-cut cyclonic storm with its centre at 10.5°N and 89.0°E, central pressure of 994 hPa and maximum surface wind of 45 kts was observed. The system remained in the cyclonic stage up to 00 UTC 27 April 2006. Then around 03 UTC 27 April 2006, it became a severe cyclonic storm with central pressure of 990 hPa and maximum sustainable wind of 55 kts. The system became a very severe cyclonic storm (VSCS) by 12 UTC 27 April 2006, with the central mean sea-level pressure of 984 hPa and maximum surface wind of 65 kts. The storm remained a VSCS for 42 h, 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 VSCS crossed the Arakan coast at about 100 km south of Sandoway around 07 UTC 29 April 2006. The system remained on land for further 12 h and caused a lot of devastation in the underlying coastal areas.

Case II (Gonu)

The tropical storm Gonu had developed as a depression over the east central Arabian Sea with centre near lat. 15.0°N, long. 68.0°E at 18 UTC 1 June 2007. It moved westwards and intensified into a cyclonic storm at 09 UTC 2 June 2007 near lat. 15.0°N, long. 67.0°E. It remained in that stage for 15 h, i.e. up to 00 UTC 3 June 2007. By 00 UTC 3 June 2007, it intensified into a severe cyclonic storm with central pressure of 988 hPa, centred at lat. 15.5°N, long. 66.5°E. The storm remained in that stage for the next 18 h, i.e. up to 18 UTC 3 June 2007. Continuing its northwestward movement, it further intensified into a VSCS by 18 UTC 3 June 2007 and lay centred at lat. 18.0°N, long. 66.0°E, with central pressure of 980 hPa. It remained in that stage for the next 21 h, i.e. up to 15 UTC 4 June 2007. By 15 UTC 04 June 2007, the system moved west-northwestwards and further intensified as a super cyclonic storm and lay centred at lat. 20.0°N, long. 64.0°E, with minimum central pressure of 920 hPa. It remained in the super cyclonic storm stage for the next 6 h, i.e. up to 21 UTC 4 June 2007. Then the storm moved further in the northwestward direction and weakened into a VSCS by 21 UTC 4 June 2007 and lay centred over northwest Arabian Sea at lat. 20.5°N, long. 63.5°E, with minimum central pressure of 935 hPa. The storm remained in that stage for the next 48 h, i.e. up to 21 UTC 6 June 2007. Then it gradually weakened, moved northwestward and crossed the Makran coast near lat. 25.0°N, long. 58.0°E between 03 and 04 UTC 7 June 2007 as a cyclonic storm.

Case III (Sidr)

The cyclone Sidr developed over southeast Bay near lat. 10.5°N, long. 91.5°E as a depression at 00 UTC 12 November 2007. As the storm picked up speed, the sea became turbulent with the gale force winds blowing even harder. On 13 November, Sidr moved over the southeast Bay and adjoining areas and moved northwestwards, becoming a severe cyclonic storm with minimum central pressure of 968 hPa and with a core of hurricane wind. It further intensified and reached the minimum central pressure of 944 hPa on 15 November with a core of winds in the east central Bay. This is an estimated 655 km south-southwest of Chittagong port, 580 km south-southwest of Cox's Bazar port and 595 km south of Mongla port (near lat. 17.0°N and long. 89.2°E). Then it further moved in a northerly direction and crossed the Khulna–Barisal coast, Bangladesh in the evening of 15 November 2007.

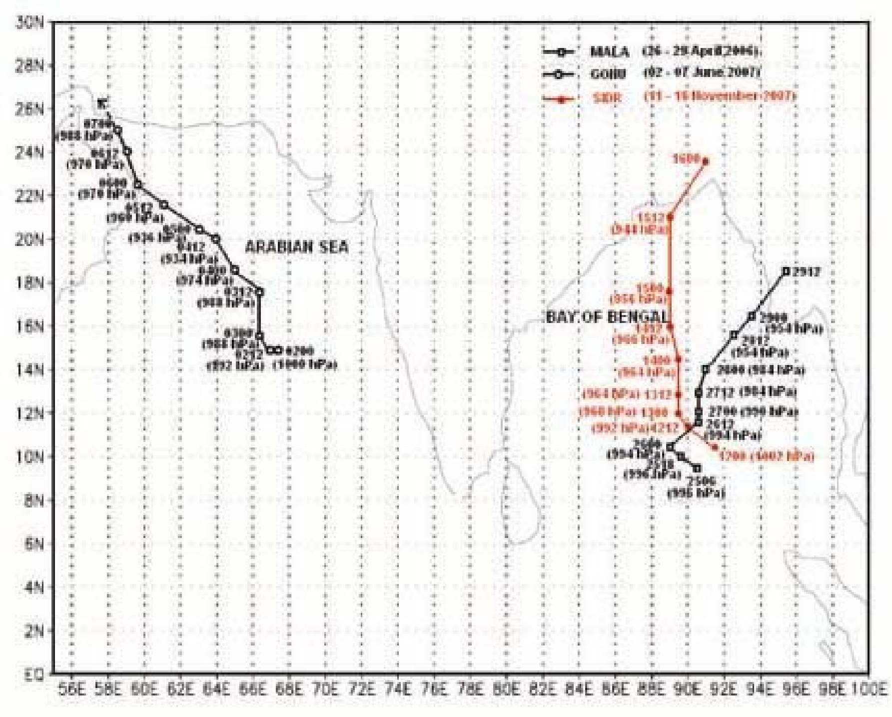

Figure 1. Best-fit track of cyclones Mala, Gonu and Sidr as estimated by India Meteorological Department[18].

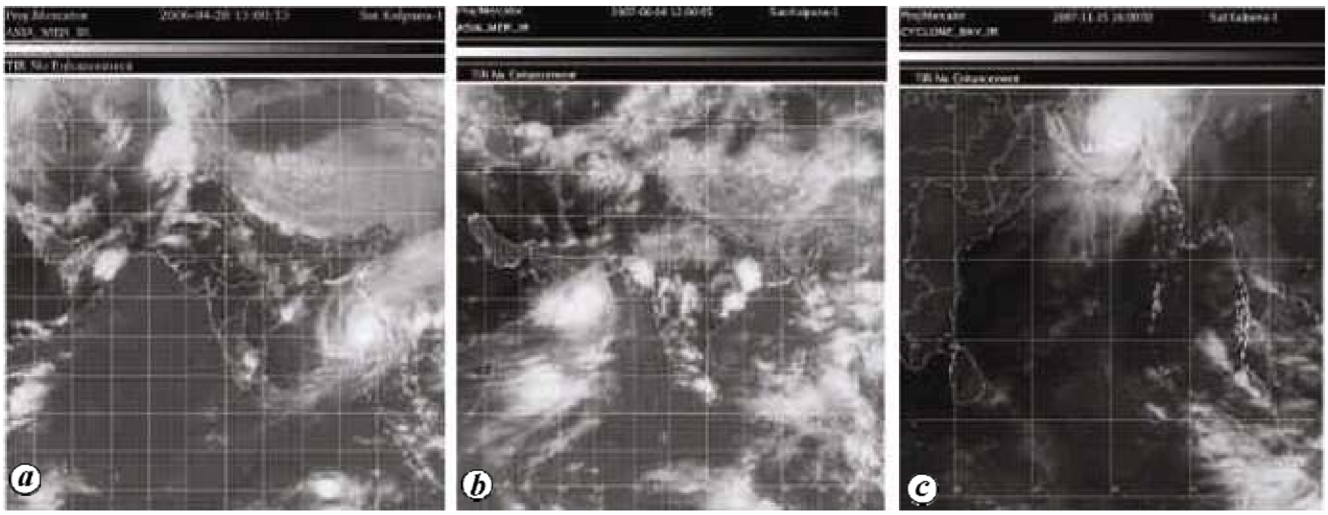

Figure 2. Satellite imageries as obtained from INSAT (Kalpana-1). Valid at (***a***) 13 UTC 28 April 2006 (Mala), (***b***) 12 UTC 4 June 2007 (Gonu) and (***c***) 16 UTC 15 November 2007 (Sidr).

The observed best-fit track as well as the central mean sea-level pressure in every 12 h interval for all the three cyclones as described above is provided in Figure 1. The INSAT satellite imageries for all the three cyclones are provided in Figure 2 (all figures are not shown). Figure 2 *a* shows the satellite imagery for Mala, valid at 13 UTC 28 April 2006, during which the minimum central mean sea-level pressure of 954 hPa with maximum sustainable wind of 100 kts was observed. Figure 2 *b* shows the satellite imagery for valid at 12 UTC 4 June 2007, while Figure 2 *c* shows the satellite imagery for Sidr.

Results and discussion

The results from both the model simulations for all the three cases as mentioned above are presented in this section. In order to avoid duplication of results (if all the results will be provided), the results as obtained from the initial condition of 00 UTC 26 April 2006 have been provided for Mala, those from the initial condition of 00 UTC 3 June 2007 have been provided for Gonu and from the initial condition of 00 UTC 13 November 2007 provided for Sidr for large-scale fields. Comparative results of the mean sea-level pressure (MSLP), wind at 850 hPa, precipitation and track of the cyclones have also been described. Also, taking the 15 different initial conditions as 15 different cases, statistical evaluation of the performances of both the models MM5 and WRF was made in terms of RMSE and mean. RMSE for the MSLP, 10 m wind and mean of the vector displacement error and mean landfall error (in displacement) are evaluated for the above-mentioned 15 cases.

Mean sea-level pressure and wind at 850 hPa

Case I (Mala): Figure 3 shows day-1 and day-3 forecasts of the MSLP and maximum sustained wind as obtained from both the model simulations. Figures 3 *a* and *b* shows the day-1 forecast of MSLP from MM5 and WRF model simulations respectively, valid at 00 UTC 27 April 2006. At the day-1 forecast, MM5 simulation shows that the storm moved northeastward from (11.3°N/89.5°E) to (11.8°N/89.7°E) with a pressure drop of 17 hPa. The WRF

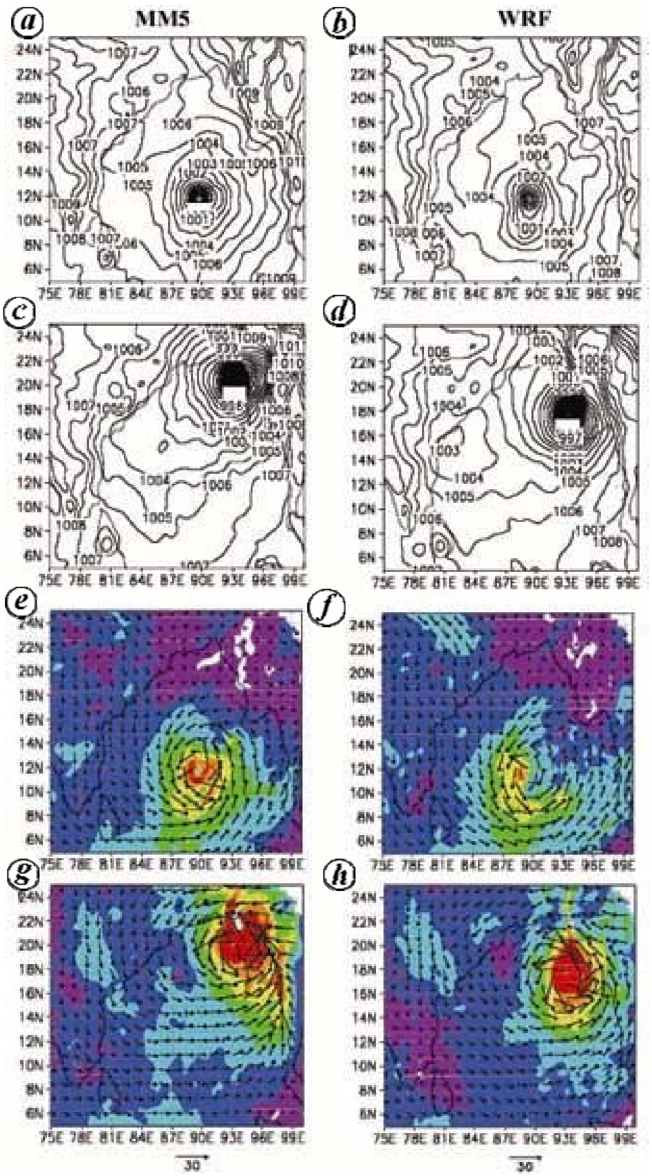

Figure 3. Simulation of mean sea-level pressure (MSLP) and wind at 850 hPa for case-I (Mala) from initial condition of 00 UTC 26 April 2006. ***a***, MSLP for day-1 with MM5; ***b***, MSLP for day-1 with WRF; ***c***, MSLP for day-3 with MM5; ***d***, MSLP for day-3 with WRF; ***e***, Wind for day-1 with MM5; ***f***, Wind for Day-1 with WRF; ***g***, Wind for day-3 with MM5, and ***h***, Wind for day-3 with WRF.

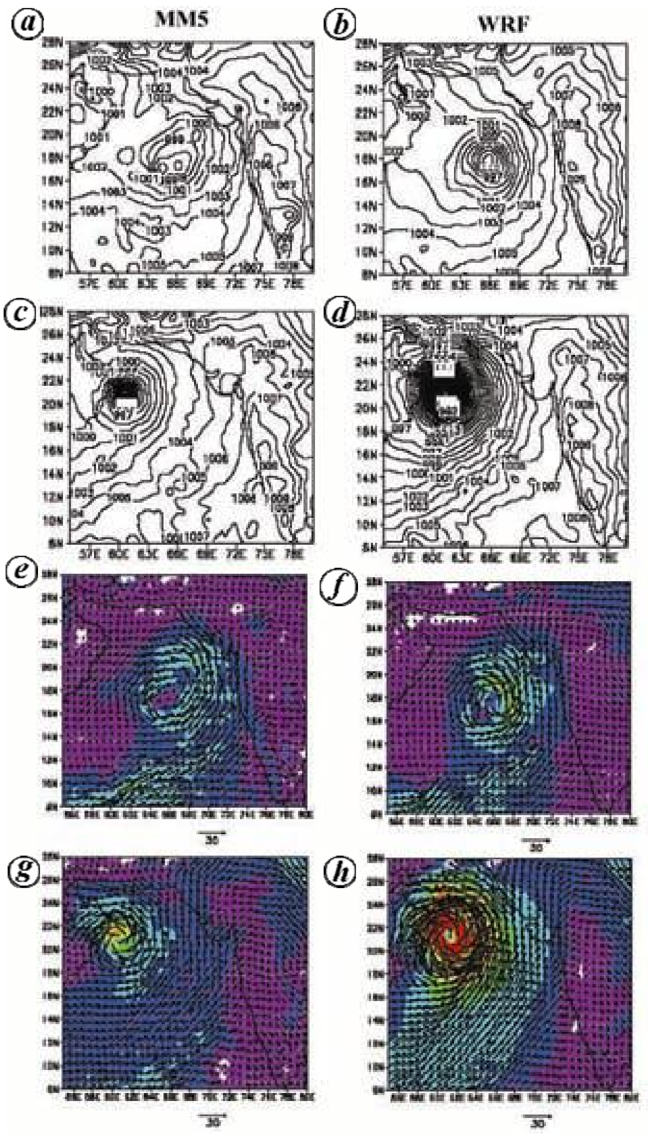

Figure 4. Simulation of MSLP and wind at 850 hPa for case-II (Gonu) from initial condition of 00 UTC 3 June 2007. ***a***, MSLP for day-1 with MM5; ***b***, MSLP for day-1 with WRF; ***c***, MSLP for day-3 with MM5; ***d***, MSLP for day-3 with WRF; ***e***, Wind for day-1 with MM5; ***f***, Wind for day-1 with WRF; ***g***, Wind for day-3 with MM5, and ***h***, Wind for day-3 with WRF.

model simulation shows that the storm moved northwestward from (10.8°N/89.5°E) to (11.9°N/89.1°E) in the first 24 h during which central MSLP changed from 1003 to 991 hPa. The direction of movement of the storm with the WRF model simulation matched that of the observed movement. Figure 3 *c* and *d* shows the day-3 forecast of the MSLP from MM5 and WRF model simulations respectively, valid at 00 UTC 29 April 2006. At the day-3 forecast, MM5 simulation shows that the storm moved northeastward from (14.4°N/90.9°E) to (20.1°N/93.0°E) in the last 24 h, with a pressure drop of 45 hPa. The WRF model simulation shows that the storm moved northeastward from (13.7°N/91.2°E) to (17.7°N/93.2°E) in the last 24 h with MSLP of 954 hPa, which exactly matched that of the observation. The maximum observed MSLP was 954 hPa with the pressure drop of 52 hPa. The WRF model simulated a maximum MSLP of 954 hPa with a pressure drop of 49 hPa, whereas with the MM5 model a maximum MSLP of 944 hPa and pressure drop of 58 hPa have been simulated.

Figure 3 *e* and *f* represents the day-1 forecast of the wind at 850 hPa as obtained from MM5 and WRF models respectively, valid at 00 UTC 27 April 2006. The day-1 forecast of wind at 850 hPa shows that the system is being elongated in the north–south direction in both the simulations, but MM5 simulation shows stronger wind in the southern sector than the WRF simulation. The WRF simulation shows stronger wind in the southwest sector. Figure 3 *g* and *h* represents the wind at 850 hPa from the MM5 and WRF models respectively, valid at 00 UTC 29 April 2006. The system is found to be stronger in the

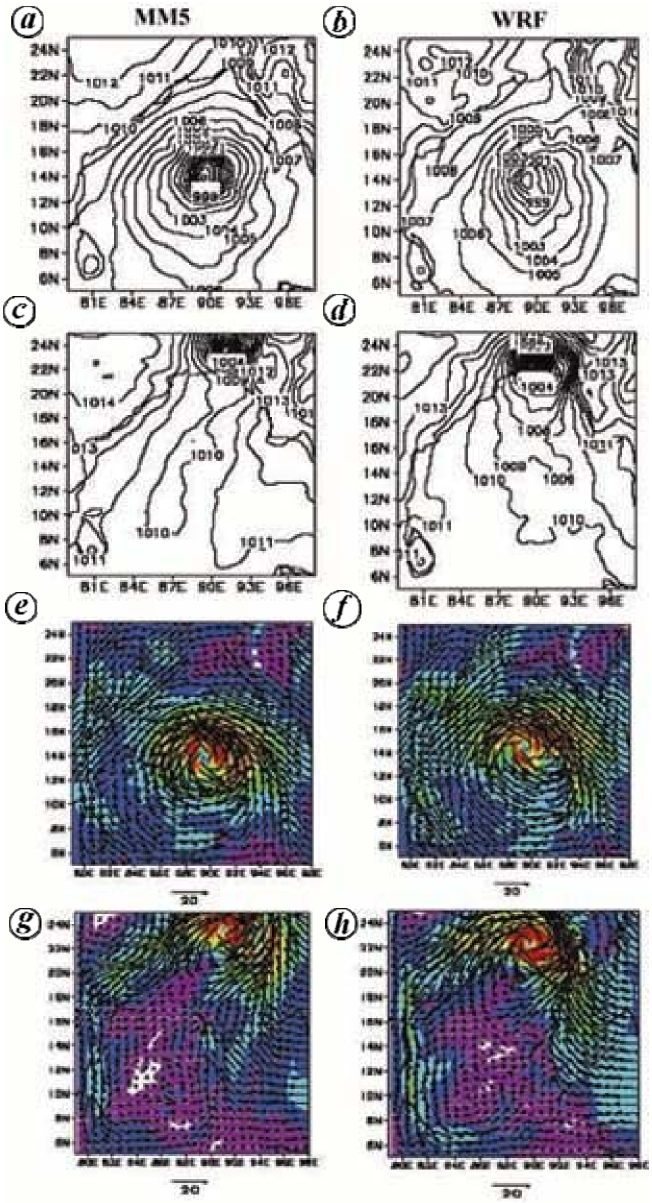

Figure 5. Simulation of MSLP and wind at 850 hPa for case-III (Sidr) from initial condition of 00 UTC 13 November 2007. ***a***, MSLP for day-1 with MM5; ***b***, MSLP for day-1 with WRF; ***c***, MSLP for day-3 with MM5; ***d***, MSLP for day-3 with WRF; ***e***, Wind for day-1 with MM5; ***f***, Wind for day-1 with WRF; ***g***, Wind for day-3 with MM5, and ***h***, Wind for day-3 with WRF.

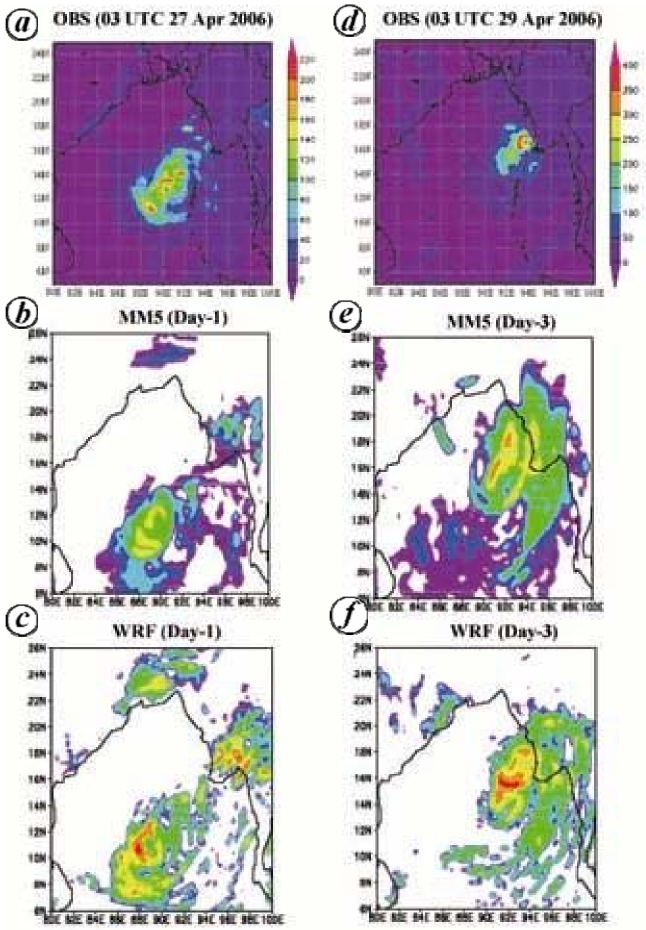

Figure 6. The 24 h accumulated precipitation for case-I (Mala) from initial condition of 00 UTC 26 April 2006. ***a***, Observed at 03 UTC 27 April 2006; ***b***, Simulated with MM5 (day-1); ***c***, simulated with WRF (day-1); ***d***, Observed at 3 UTC 29 April 2006; ***e***, Simulated with MM5 (day-3), and ***f***, Simulated with WRF (day-3).

northeastern sector in the MM5 model, but in the WRF model, the wind is stronger in the eastern sector of the system. In the MM5 simulation, 10 m wind is maximum at 12 UTC 28 April 2006 and a strong wind of 138 kts has been simulated. The observed wind is 100 kts and the WRF model could simulate the 10 m wind of 88 kts.

Case II (Gonu): Figure 4 shows the day-1 and day-3 forecasts of the MSLP and maximum sustained wind as obtained from the model simulations. Figure 4 *a* and *b* shows the day-1 forecast of the MSLP from MM5 and WRF model simulation respectively, valid at 00 UTC 4 June 2007. At the day-1 forecast, MM5 simulation shows that the storm moved northwestward, but there was the formation of two centres with the minimum central pressure of 997 hPa. The WRF simulation shows that the storm moved northwestward with the minimum central pressure of 994 hPa. The observed central pressure at this time was 988 hPa. Figure 4 *c* and *d* shows the day-3 forecast of the MSLP from MM5 and WRF model simulations respectively, valid at 00 UTC 6 June 2007. At the day-3 forecast, MM5 simulation shows that the storm moved northwestward with the minimum central pressure of 981 hPa. The WRF model simulation shows that the storm moved northwestward with a minimum central pressure of 955 hPa. The observed central pressure at that time was 970 hPa.

Figure 4 *e* and *f* represents the day-1 forecast of the wind at 850 hPa as obtained from MM5 and WRF model simulations respectively, valid at 00 UTC 4 June 2007. The day-1 MM5 forecast of wind at 850 hPa shows that the system elongated in the northeast and southwest direction, but the WRF model simulation shows more concentric wind pattern. Figure 4 *g* and *h* represents wind at 850 hPa from MM5 and WRF model simulations respectively, valid at 00 UTC 6 June 2007. The WRF model simulation shows much stronger wind than that of the MM5 model simulation. The observed maximum sustained surface wind at that time was 77 kts, whereas the MM5 and WRF models could simulate maximum 10 m wind as of 46.5 kts and 66 kts respectively.

Case III (Sidr): Figure 5 shows the day-1 and day-3 forecasts of the MSLP and maximum sustained wind as obtained from both the model simulations. Figure 5 *a* and *b* shows the day-1 forecast of the MSLP from MM5 and

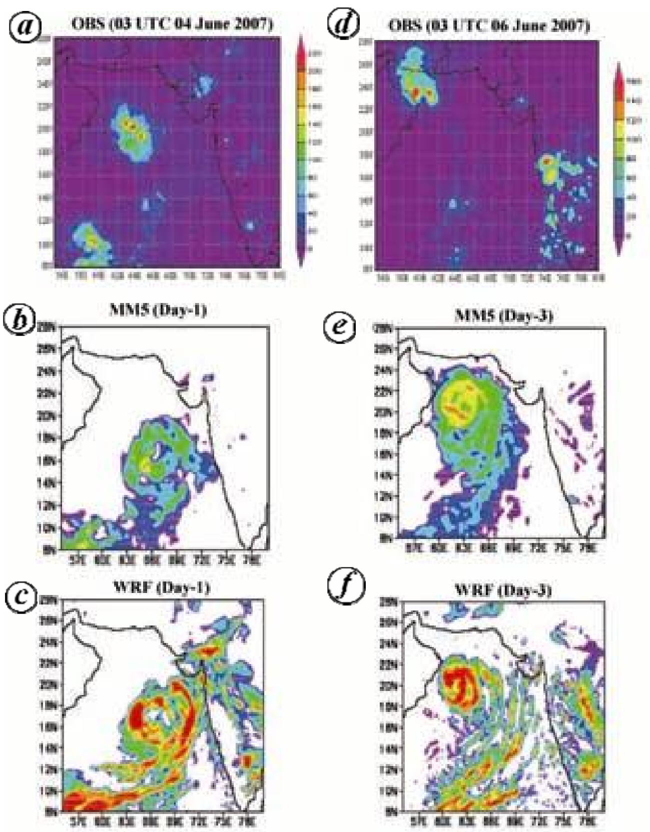

Figure 7. The 24 h accumulated precipitation for case-II (Gonu) from initial condition of 00 UTC 3 June 2007. ***a***, Observed at 03 UTC 4 June 2007; ***b***, Simulated with MM5 (day-1); ***c***, Simulated with WRF (day-1); ***d***, Observed at 03 UTC 6 June 2007; ***e***, Simulated with MM5 (day-3), and ***f***, Simulated with WRF (day-3).

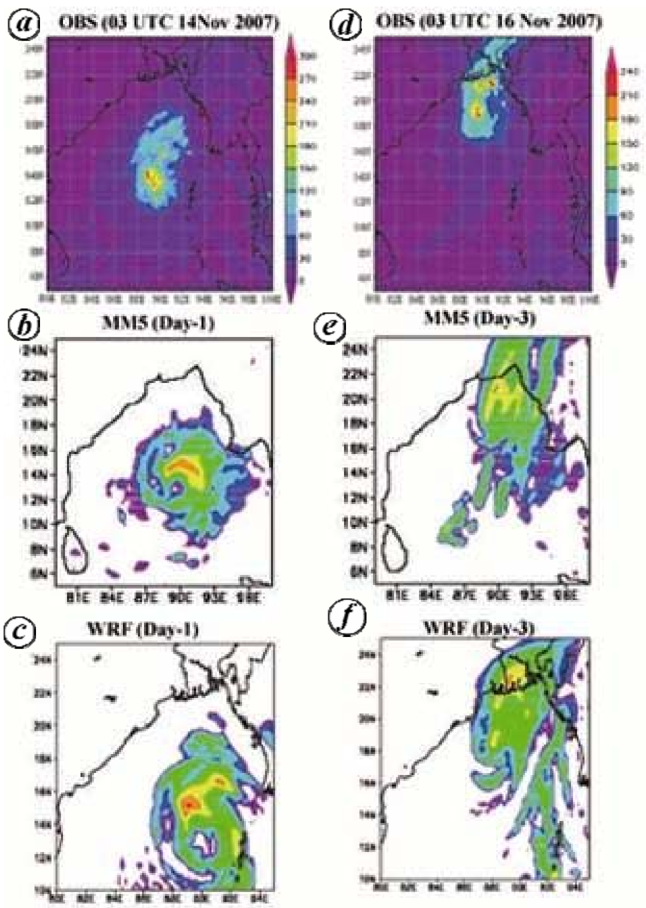

Figure 8. The 24 h accumulated precipitation for case-III (Sidr) from initial condition of 00 UTC 13 November 2007. ***a***, Observed at 03 UTC 14 November 2007; ***b***, Simulated with MM5 (day-1); ***c***, simulated with WRF (day-1); ***d***, Observed at 03 UTC 16 November 2007; ***e***, Simulated with MM5 (day-3), and ***f***, Simulated with WRF (day-3).

WRF model simulations respectively, valid at 00 UTC 14 November 2007. At the day-1 forecast MM5 simulation shows that the storm moved northward with minimum central pressure of 990 hPa. The WRF simulation shows that the system moved northward with minimum central pressure of 998 hPa. The observed minimum central pressure at that time was 964 hPa. Figure 5 *c* and *d* shows the day-3 forecast of the MM5 and WRF model simulations respectively, valid at 00 UTC 16 November 2007. At the day-3 forecast, both the simulations clearly show the landfall of the system, but in the MM5 model simulation the system moved much faster than that of the WRF model simulation.

Figure 5 *e* and *f* represents the day-1 forecast of the wind at 850 hPa as obtained from the MM5 and WRF model simulations respectively. The day-1 forecast of the MM5 model has much stronger wind than that of the WRF model simulation. Figure 5 *g* and *h* shows the day-3 forecast from MM5 and WRF model simulations respectively, valid at 00 UTC 16 November 2007. In both the simulations, the system is already over land. The observed maximum sustained surface wind is 115 kts, whereas

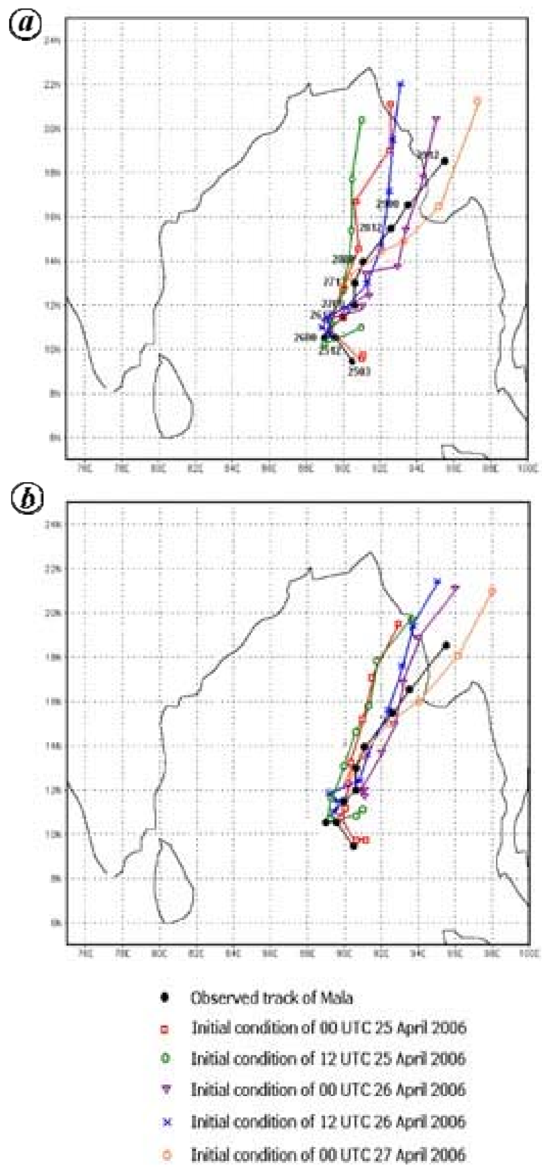

Figure 9. Observed best-fit track and track simulations for five different initial conditions for Mala. Simulation with MM5 (***a***) and WRF (***b***).

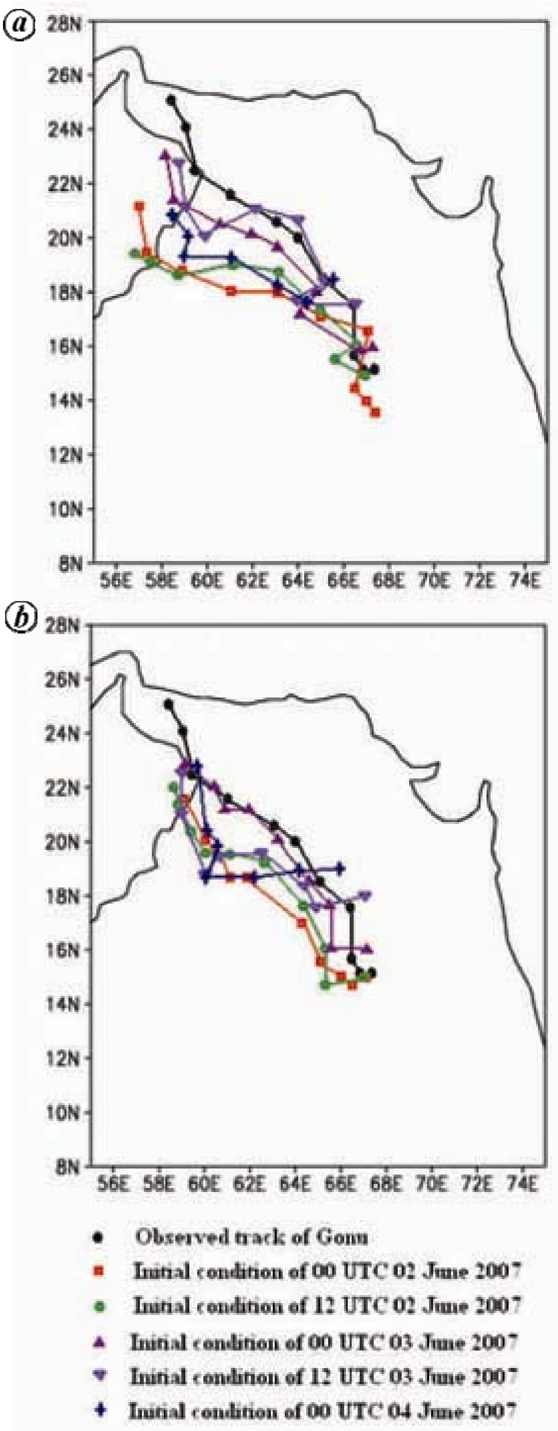

Figure 10. Observed best-fit track and track simulations for five different initial conditions for Gonu. Simulation with MM5 (***a***) and WRF (***b***).

MM5 and WRF could simulate the 10 m maximum winds as 76 and 62 kts respectively.

From these results, it may be inferred that simulation with the MM5 model gives a much faster storm movement whereas WRF simulation results show reasonable accuracy with that of the observation. However, it may be noticed that in some cases the MM5 model could simulate the maximum sustained wind better than the WRF simulation.

Precipitation

Case I (Mala): Figure 6 *a* and *d* represents 24 h accumulated precipitation as a merged analysis of Tropical Rainfall Measuring Mission (TRMM), TMI and rain gauge observations carried out by National Aeronautics and Space Administration (NASA), USA valid for 03 UTC 27 April 2006 and 03 UTC 29 April 2006 respectively. The precipitation data as well as the figures have been obtained from the NASA website (http://disc2.nascom.nasa.gov/Giovanni/tovas). Figure 6 *b* and *c* represents day-1 forecast of 24 h accumulated precipitation valid at 03 UTC 27 April 2006 from both MM5 and WRF model simulations respectively. The observed precipitation is about 22 cm in day-1, whereas MM5 and WRF models simulate the precipitation of 18 and 25 cm respectively. Figure 6 *e* and *f* represents the day-3 forecast of accumulated precipitation valid at 03 UTC 29 April 2006 from MM5 and WRF respectively. The observed precipitation is about 40 cm in day-3, whereas MM5 and WRF models simulate the precipitation of 22 and 40 cm respectively.

Case II (Gonu): Figure 7 *a* and *d* represents the 24 h accumulated precipitation as a merged analysis of TRMM, TMI and rain gauge observations carried out by NASA valid at 03 UTC 4 June 2007 and 03 UTC 6 June 2007 respectively. Figure 7 *b* and *c* represents day-1 forecast of 24 h accumulated precipitation valid at 03 UTC 4 June 2007 from both MM5 and WRF model simulations respectively. The observed precipitation is about 22 cm, whereas MM5 and WRF could simulate the precipitation of 15 and 28 cm respectively. Figure 7 *e* and *f* represents the day-3 forecast of 24 h accumulated precipitation valid at 03 UTC 6 June 2007 from MM5 and WRF respectively. The observed precipitation was about 16 cm, whereas MM5 and WRF models could simulate the precipitation of 12 and 22 cm respectively.

Case III (Sidr): Figure 8 *a* and *b* represents the 24 h accumulated precipitation as a merged analysis of TRMM, TMI and rain gauge observations carried out by NASA valid at 03 UTC 14 November 2007. Figure 8 *b* and *c* represents day-1 forecast of 24 h accumulated precipitation valid at 03 UTC 14 November 2007 from both MM5 and WRF model simulations respectively. The observed precipitation was 30 cm, whereas MM5 and WRF could simulate the precipitation of 15 and 22 cm. Figure 8 *e* and *f* represents the day-3 forecast of 24 h accumulated precipitation valid at 03 UTC 16 November 2007 from MM5 and WRF model simulations respectively. The observed precipitation was about 24 cm, whereas MM5 and WRF could simulate the precipitation of 12 and 20 cm respectively.

It may be noticed that though MM5 overestimates with respect to MSLP and maximum sustainable wind com-

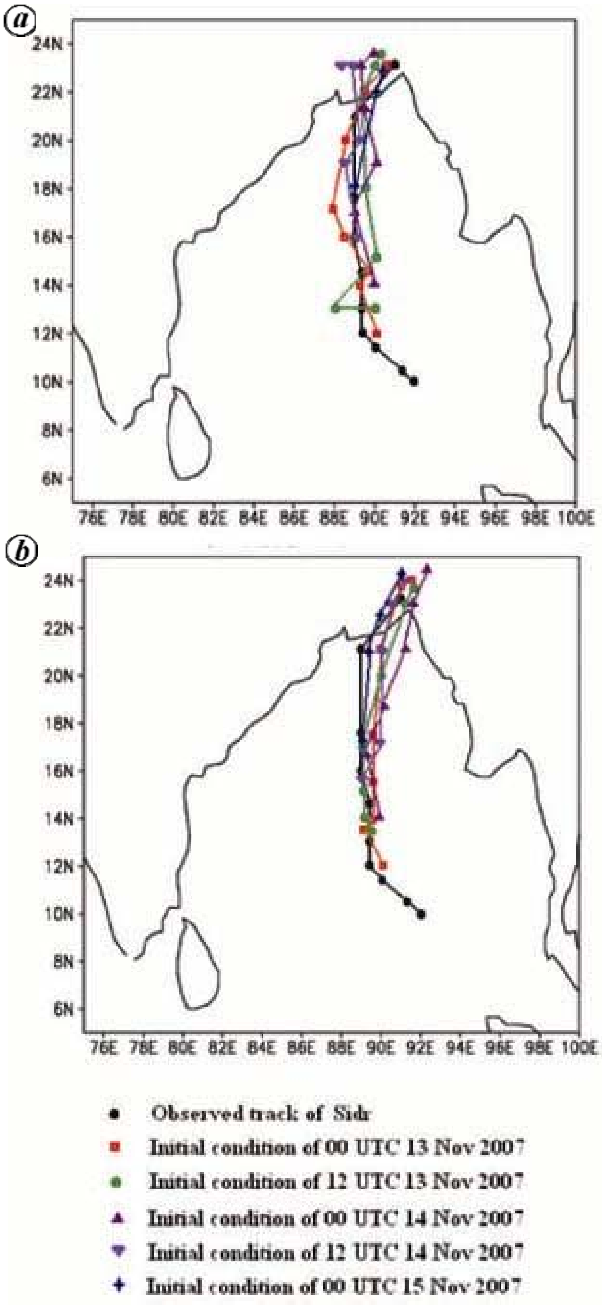

Figure 11. Observed best-fit track and track simulations for five different initial conditions for Sidr. Simulation with MM5 (***a***) and WRF (***b***).

Table 4. Statistical evaluation of the central pressure with MM5 and WRF simulation

	Model	00	12	24	36	48	60	72
Case-1 (2500)	MM5	–10	–6	3	18	38	38	43
Case-2 (2512)	MM5	–7	–7	1	15	28	36	17
Case-3 (2600)	MM5	–9	–5	5	17	35	24	31
Case-4 (2612)	MM5	–8	–9	–12	–6	–21	3	10
Case-5 (2700)	MM5	–9	–14	–8	–17	–9	–16	
Case-6 (0200)	MM5	0	4	10	1	1	24	13
Case-7 (0212)	MM5	–3	–9	0	6	–23	–20	8
Case-8 (0300)	MM5	–10	–9	–20	–52	–32	3	18
Case-9 (0312)	MM5	–8	–25	–65	–61	–33	–15	–2
Case-10 (0400)	MM5	–24	–65	–63	–37	–22	–11	13
Case-11 (1300)	MM5	34	35	28	12	6	15	13
Case-12 (1312)	MM5	37	34	29	29	30	9	5
Case-13 (1400)	MM5	36	35	40	48	26	9	1
Case-14 (1412)	MM5	36	48	54	22	10		
Case-15 (1500)	MM5	46	60	24	10	2		
RMSE		23.6	31.5	32.3	29.3	24.3	20.2	18.5
Case-1 (2500)	WRF	–8	–3	0	5	6	9	7
Case-2 (2512)	WRF	–7	–4	3	10	5	6	–9
Case-3 (2600)	WRF	–9	0	3	3	10	–8	–2
Case-4 (2612)	WRF	–8	–3	–10	–5	–18	–6	–12
Case-5 (2700)	WRF	–8	–7	–1	–29	–31	–31	
Case-6 (0200)	WRF	1	4	6	0	4	6	9
Case-7 (0212)	WRF	–4	–5	–2	–5	–25	–15	–8
Case-8 (0300)	WRF	–11	–10	–18	–45	–30	–15	–11
Case-9 (0312)	WRF	–9	–25	–60	–50	–32	–22	–25
Case-10 (0400)	WRF	–24	–65	–55	–33	–22	–20	–8
Case-11 (1300)	WRF	33	34	28	20	32	40	10
Case-12 (1312)	WRF	36	33	31	36	45	22	7
Case-13 (1400)	WRF	35	33	39	53	23	5	–3
Case-14 (1412)	WRF	33	43	57	23	7	–1	
Case-15 (1500)	WRF	45	57	23	9	–1		
RMSE		22.8	29.3	30.7	27.9	23.2	18.2	10.7
Percentage of improvement in WRF model		3.5	7.5	5.2	5.0	4.7	10.9	72.9

pared to the observations, it underestimates the simulation of maximum precipitation. In respect of the pattern of distribution of precipitation around the centre of the cyclone, both the models simulate reasonably well. Thus, the result confirms that the performance of the WRF model is reasonably better than that of MM5.

Track

The track of the cyclone as obtained with both the model simulations from different initial conditions has been evaluated and compared with the best-fit track as estimated by IMD. Figure 9 *a* and *b* represents the track of the cyclone Mala as obtained with MM5 and WRF model simulations respectively, from different initial conditions. Both the models show that in each case the cyclone moves to the Arakan coast, irrespective of the initial condition chosen. But with MM5 simulation, at the landfall location the track spreads about 700 km, whereas it is confined within 400 km with the WRF model simulation. Figure 10 *a* and *b* represents the track of the cyclone Gonu as obtained with MM5 and WRF model simulations respectively, from different initial conditions. Both the model simulations show that in each case the cyclone moves to the Oman coast, irrespective of the initial condition chosen. Figure 11 *a* and *b* represents the track of the cyclone Sidr as obtained with MM5 and WRF model simulations respectively, from different initial conditions. Both the model simulations shows that in each case the cyclone moves to the Bangladesh coast, irrespective of the initial condition chosen. Details of the track error are given in the next section.

Evaluation of the performance of MM5 and WRF models

The MM5 and WRF models are integrated with 15 different initial conditions as described above and these as 15 different cases, a statistical evaluation of the performances of the models has been made. For this, the root mean

Table 5. Statistical evaluation of the 10 m wind with MM5 and WRF simulation

Case	Models	00	12	24	36	48	60	72
Case-1 (2500)	MM5	3	22	17	20	65	56	66
Case-2 (2512)	MM5	5	7	5	35	36	50	20
Case-3 (2600)	MM5	–19	–5	17	30	45	28	–12
Case-4 (2612)	MM5	–22	–13	–25	–5	1	44	–
Case-5 (2700)	MM5	–17	–25	7	17	38	–	–
Case-6 (0200)	MM5	3	17	22	35	40	45	58
Case-7 (0212)	MM5	4	10	17	18	28	36	30
Case-8 (0300)	MM5	–15	14	27	30	35	28	22
Case-9 (0312)	MM5	–17	9	28	22	35	25	
Case-10 (0400)	MM5	–25	–8	16	25	30	22	
Case-11 (1300)	MM5	2	12	15	20	35	37	55
Case-12 (1312)	MM5	5	7	5	20	30	35	25
Case-13 (1400)	MM5	–15	–5	12	15	25	20	17
Case-14 (1412)	MM5	–12	–8	17	22	35	40	
Case-15 (1500)	MM5	–16	–10	9	20	38		
RMSE		14.1	12.8	17.5	23.5	36.6	37.4	38.9
Case-1 (2500)	WRF	–2	4	–4	2	11	–1	–7
Case-2 (2512)	WRF	–8	–6	–6	9	–7	–1	–36
Case-3 (2600)	WRF	–22	–8	2	–12	–3	–28	–28
Case-4 (2612)	WRF	–22	–8	–30	–18	–51	–34	–
Case-5 (2700)	WRF	–22	–18	–9	–42	–67	–	–
Case-6 (0200)	WRF	5	12	25	35	45	50	55
Case-7 (0212)	WRF	2	5	18	25	30	30	25
Case-8 (0300)	WRF	–8	–12	–1	15	25	22	20
Case-9 (0312)	WRF	–6	–14	4	22	30	20	
Case-10 (0400)	WRF	–25	–5	12	22	35	18	
Case-11 (1300)	WRF	3	11	15	22	30	35	45
Case-12 (1312)	WRF	7	10	8	22	35	30	22
Case-13 (1400)	WRF	5	7	10	25	20	22	15
Case-14 (1412)	WRF	–15	5	8	20	30	35	
Case-15 (1500)	WRF	–12	–15	2	18	35		
RMSE		13.3	10.1	13.1	22.6	34.2	28.2	31.4
Percentage of improvement in WRF model		6	27	33	4	7	33	24

square error (RMSE) is calculated for MSLP as well as for 10 m wind of the storm from both the model simulations.

The RMSE is given as:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - F_i)^2},$$

where O_i represents the observations, F_i the corresponding forecasts and n the number of cases ($n = 15$).

Also, the percentage of improvement in the WRF model simulation result compared to the MM5 simulation result is evaluated.

The percentage of improvement is given as

$$\text{Percentage of improvement} = \frac{\mathrm{WRF} - \mathrm{MM5}}{\mathrm{WRF}} \times 100.$$

In MSLP, at the initial time (00 h), RMSE of 23.6 and 22.8 hPa is simulated with the MM5 and WRF models respectively. In 24 h forecast, the MM5 model simulation gives RMSE of 32.3 hPa, whereas the WRF model simulation gives RMSE of 30.7 hPa. Thus, 24 h forecast clearly shows an improvement of 5.2% in WRF model simulation than MM5 model. In 48 h forecast, the RMSE is about 24.3 hPa in MM5 simulation, whereas it is 23.2 hPa with the WRF model simulation. An improvement of 4.7% exists in WRF model simulation compared to the MM5 model simulation. Similarly, for the 72 h forecast, the RMSE is 18.5 hPa with the MM5 simulation, whereas it is 10.7 hPa with the WRF model. Thus, in the 72 h forecast there is 72.9% of improvement with the WRF model simulation than the MM5 model simulation. Thus, MM5 has a large RMSE in MSLP than WRF. Also the percentage improvement in the WRF forecasted results demonstrates the efficiency of the model. Details of the statistics are provided in Table 4.

RMSE is also calculated for the 10 m wind. Initially, RMSE of 14.1 and 13.3 m/s was evaluated for MM5 and WRF model simulations respectively. At the day-1 forecast, RMSE of 17.5 and 13.1 m/s was calculated with

Table 6. Statistical evaluation of vector displacement error at the landfall point

	MM5	WRF
Initial time of model integration	Displacement error (km)	Displacement error (km)
Case-1 (2500)	334.1	–
Case-2 (2512)	–	319.7
Case-3 (2600)	338	234.3
Case-4 (2612)	21.5	174.9
Case-5 (2700)	180.2	150.9
Case-6 (1300)	78.2	58.6
Case-7 (1312)	78.5	45.2
Case-8 (1400)	220.5	30.5
Case-9 (1412)	30.5	35.1
Case-10 (1500)	15.8	30
Case-11 (0200)	450.9	125.8
Case-12 (0212)	525.2	126.2
Case-13 (0300)	160.7	12.8
Case-14 (0312)	200	38.9
Case-15 (0400)	232.4	78.2
Mean	204.8	104.3

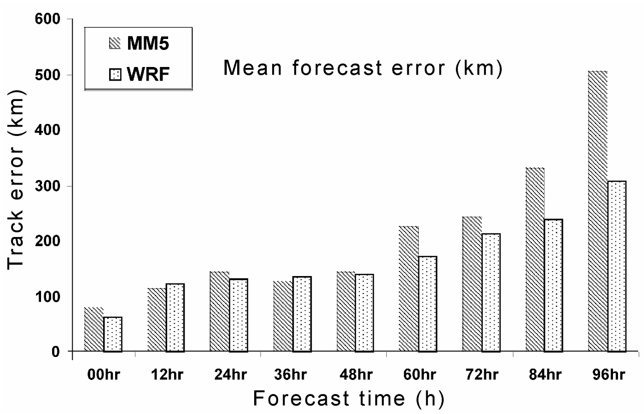

Figure 12. Mean vector displacement error with MM5 and WRF simulations (of the track of the tropical cyclones Mala, Gonu and Sidr) for all the 15 different cases.

MM5 and WRF simulation respectively. Thus, there was the improvement of 33% in the WRF model in the day-1 forecast. At the day-2 forecast, large RMSE of 36.6 and 34.2 m/s was evaluated with MM5 and WRF models respectively. There was 7% improvement in the WRF model simulation result than the MM5 model simulation result. Similarly, in 72 h, i.e. day-3 forecast an improvement of 24% was observed in the WRF model simulation than the MM5 model simulation. Details of the RMSE calculations from both the model simulations are given in Table 5.

From the results, it may be inferred that with the WRF model there is improvement in the intensity prediction in terms of MSLP and 10-m wind.

Vector displacement error (VDE) was also calculated by taking the track position from different initial conditions. Figure 12 represents the mean vector displacement error at every 12 h interval from the 15 different initial conditions. At the initial time of the model integration, mean VDE of 78.7 and 62 km was calculated with MM5 and WRF model simulations respectively. The day-1 forecast shows the mean VDE of 143.3 and 131.9 km in MM5 and WRF simulations respectively. Mean VDE of 145 and 140.4 km was calculated with MM5 and WRF models in 48 h simulations respectively. Again, the mean VDE of 243.2 and 212.8 km was evaluated in 72 h simulations with the MM5 and WRF models respectively. Similarly, in 96 h, mean VDE of 504.5 and 307.8 km was calculated from the MM5 and WRF model simulations respectively.

Also, VDE at the time of landfall has been evaluated. Mean VDE of 204.8 km was evaluated with MM5 model simulation, whereas with WRF model simulation 104.3 km of mean VDE was calculated. The mean VDE clearly shows an improvement of 96% in the WRF model simulation than the MM5 model simulation. Details of the statistical evaluations are given in Table 6.

Conclusion

From a comparative study on the performance of the two state-of-the-art non-hydrostatic meso-scale models in the simulation of tropical cyclones over the Indian seas, the following broad conclusions can be derived.

Both the models could simulate most of the features of the cyclones Mala, Gonu and Sidr with reasonable accuracy. The intensity of the tropical cyclones in terms of MSLP and maximum sustainable wind illustrates that MM5 has a tendency to intensify the system, whereas WRF gives reasonably good results, similar to the observations. However, the MM5 model underestimates the simulation of maximum precipitation compared to the WRF model.

The pattern of distribution of precipitation is reasonably well predicted by both the models.

From all the three cases, it may be noticed that up to 36 h, there is no significant improvement in any model because of the influence of the initial position error as well as intensity error in coarse resolution NCEP analysis. However, after 36 h, as the length of integration increases, performance of WRF was found to be significantly better than MM5.

For all the 15 initial conditions it may be noticed that MM5 with different initial condition gives much more spread in landfall point compared to WRF. Thus the overall performance of the WRF model in simulation of landfall point is close to the actual realization compared to the MM5.

The results of VDE show that in the early hours of prediction (up to 36 h), both the models generate almost similar types of error and in some events better results with MM5. This is mainly attributed to the fact that a large initial positional error contributes to this type of error by both the models. It may be noted that in longer period integration of the models beyond 36 h, track simulation with WRF model shows distinct advantages over that of the MM5 model. Again, at the landfall point the mean VDE was nearly double with MM5 simulation than with WRF simulation. In fact, there was an improvement of 96% in WRF simulation.

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