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# Simulation of the Structure and Track of the Tropical Cyclone Sidr using Numerical Models

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### Abstract

Tropical cyclone (TC), one of the most devastating and deadly weather phenomena,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 09-16 November, 2007, a severe cyclonic storm named, Sidr was active in the Bay of Bengal part of the Indian Ocean. At 16 UTC on 15 November 2007, the system crossed Bangladesh coast near at long. 89.8 °E. In the present study, two state-of-the-art mesoscale models, MM5 and WRF, have been used to simulate the structure and track of TC Sidr. Horizontal resolution of 90 km and 30 km respectively for mother and nested domain were used in both the models. Various meteorological fields' viz. central pressure, winds, vorticity, temperature anomaly etc. obtained from the simulations are verified against those observed to test their performance. The simulated tracks are also compared with those obtained from JTWC. The results indicate that MM5 model has better forecast skill in terms of intensity prediction but WRF model has better forecast skill in terms of track prediction of the cyclonic storm.

*Keywords*: Tropical cyclone; Mesoscale models; Intensity; Structure and track.

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## 1. Introduction

The Bay of Bengal tropical cyclone disaster is the 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, it is very important to predict these cyclones with high accuracy to save the valuable

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lives and wealth. Recently, 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 [1]. Mohanty *et al.* [2] used MM5 model to simulate the Orissa super cyclone (1999). Again, WRF model has also been used in a number of studies for the simulation of tropical cyclones [3,4]. There are a number of comparative studies on the performance of the mesoscale models for severe weather events triggered by convection. Sousounis *et al.* [5] 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. Forecast skill of WRF model has been found better in the comparative study between WRF and ETA on the surface sensible weather forecast over Western United States [6]. On the other hand, better forecast skill of MM5 model has been demonstrated in the comparative study on the performance of MM5 and RAMS models in simulating the Bay of Bengal cyclone [7]. Again, Pattanayak *et al.* [8] made a comparative study on the performance of MM5 and WRF models in simulating tropical cyclones over Indian seas. The intensity of the tropical cyclones Mala, Gunu and Sidr in terms of MSLP and maximum sustainable wind illustrates that MM5 simulates the intensity of the system fairly, whereas WRF gives reasonably good results, similar to the observations. Rayhun *et al.* simulated the structure, track and landfall of tropical cyclone Bijli using WRF-ARW model [9]. One of the important findings of the study is that the model has successfully predicted the tracks, recurvature and probable areas and time of landfall of the selected tropical cyclone Bijli with high accuracy even in the 72 h predictions.

In the present study, MM5 version 3.7 and WRF-ARW version 3.1 are used to simulate the TC Sidr formed over Bay of Bengal. The performances of the models have been evaluated and compared with observations and verifying analyses.

## 2. Model Description and Methodology

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 Kain–Fritisch cumulus parameterization scheme with MRF PBL, in general, provides better result for simulation of tropical cyclones [10]. Table 1 summarizes the model configuration and various options used by MM5 in the present study.

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 coordinate system and solved on Arakawa-C grid. Runge-Kutta 2nd and 3rd 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 from large eddy simulation [11]. Table 1 summarizes the model configuration and various options used by WRF-ARW in the present study are partly chosen from the study carried out by Pattanayak *et al.* [8].

Table 1. Brief description of the MM5 and WRF models.

| Parameters | Used for MM5 V 3.7 model | Used for WRF version 3.1 model |
|---|---|---|
| Dynamics | Non-hydrostatic with 3-D Coriolis force | Non-hydrostatic with 3-D Coriolis force |
| Mother Domain | 0.22 °S - 37.94 °N, 67.36 °E-108.64 °E | 1.58 °S–38.94 °N, 66.10 °E-110.02 °E |
| Inner Domain | 5.36 °N -28.71 °N, 81.66 °E - 99.20 °E | 4.19 °N -28.50 °N, 81.25 °E - 99.17 °E |
| Resolution | 90 and 30 km | 90 and 30 km |
| Map projection | Mercator | Mercator |
| No of vertical levels | 28 | 28 |
| Horizontal grid scheme | Arakawa B grid | Arakawa C grid |
| Time integration scheme | Leap-frog scheme with time splitting technique | Runge-Kutta 2nd & 3$^{rd}$order time splitting technique |
| Radiation scheme | Dudhia's shortwave/longwave simple cloud | Dudhia's shortwave /RRTM longwave |
| PBL scheme | MRF | YSU |
| Cumulus parameterization scheme | Kain Fritsch | Kain Fritsch |
| Microphysics | Simple ice | Ferrier |

To analyze the intensity, structure and track of TC Sidr, the MM5 and WRF models were run for 96 h with the initial field on at 13 November, 2007 and the models simulated data were compared with those obtained from Joint Typhoon Warning Centre (JTWC). The National Center for Environmental Prediction (NCEP) FNL reanalysis data (1º X 1º horizontal resolution) are used to provide the initial and lateral boundary conditions respectively to all the models.

## 3. Synoptic situation of Tropical Cyclone Sidr (09-16 November 2007)

A low pressure area formed over southeast of the Andaman Islands with a weak low-level circulation near the Nicobar Islands on 9 November, 2007 moved to north-northwesterly direction initially and intensified into a well-marked low over the same area. Depression over the southeast Bay of Bengal and adjoining Andaman Sea and lay centered at 0900 UTC on 11 November, 2007 near 10.0 °N and 92.0 °E about 200 km south–southwest of Port Blair and the system is likely to intensify further and moved in a west north westerly direction. The depression moved further north northwest and transformed to deep depression (DD) and lay centered 10.5 °N and 91.5 °E at 1800 UTC on the same day. The system further intensified into cyclonic storm as on 0300 UTC on 12 November and severe cyclonic storm (SCS) as on 1200 UTC on the same day and lay centered at 11.5 °N and 90 °E and moved northerly direction. The system attained into a very severe cyclonic storm (VSCS) with the central MSLP of 986 hPa, the MWS of 33 m/s and the central location at about 11.5 °N and 90.0 °E at around 1800 UTC on 12 November. The VSCS 'Sidr' moved in the same direction and intensified further and at 0300 UTC on 15 November its central MSLP lowered to 944.0 hPa, the MWS increased to 58.8 m/s when its central location was at about 18.0 °N and 89.0 °E. Then, the VSCS 'Sidr' moved continuously north wards finally crossed Bangladesh coast at around 1600 UTC on 15 November, 2007. The observed track is depicted in Fig. 1.

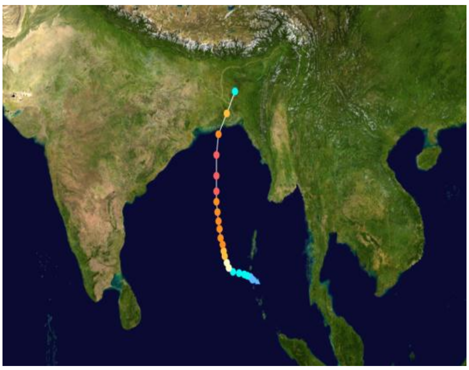

Fig. 1. Observed track of TC Sidr.

## 4. Results and Discussion

To analyze the evolution and structure of TC Sidr, the MM5 and WRF model were run for 96 h with the initial field at 00 UTC on 13 November, 2007. Different meteorological parameters obtained from both the models are discussed for the evolution and structure of the TC Sidr in the following sub-section. Model simulated results are compared with available data obtained from Joint Typhoon Warning Centre

(JTWC). Models output are taken at 3 h intervals and plotted by Grid Analysis and Display System (GrADS) software.

### 4.1. *Pressure field*

Minimum seal level pressure (MSLP) of a TC is of great importance as it helps to measure the intensity of a TC. Fig. 2a shows the observed and model simulated MSLP of TC Sidr. It appears from the Fig. 2a that the MM5 model simulated MSLP gradually drops (without any oscillation) with time and attains peak intensity with minimum pressure 961 hPa at 00 UTC on 15 November, 2007 and thereafter MSLP increases gradually. Finally just before the landfall the MSLP is 966 hPa at 12 UTC on 15 November, 2007. Again, WRF model simulated MSLP gradually drops (having little bit oscillation) with time and attains peak intensity with minimum pressure 977 hPa at 03, 15 and 18 UTC on 15 November, 2007 and thereafter MSLP increases gradually. Finally just before the landfall the MSLP is 987 hPa at 00 UTC on 16 November, 2007. On the other hand, the observed MSLP 918 hPa is obtained at 18 UTC on 14 November and remain same up to 06 UTC on 15 November, 2007 and thereafter MSLP increases gradually. Landfall of the system occurs at 12 UTC on 15 November with observed value of MSLP 926 hPa. It is noted that landfall time obtained from MM5 model simulation is same to that of observed but landfall time obtained from WRF model is different from that of observed. Again, at the landfall position, MSLPs are different for model simulated and observed cases. The variation of model simulated MSLP compare to that of observed with time shows that both the models simulate realistic temporal variation of MSLP but simulated values are higher than observed values.

The distribution of sea level pressures (SLP) for the TC Sidr at 00 UTC on 13-15 November and 12 UTC on 15 November, 2007 (i.e. before landfall) for MM5 model and at 00 UTC on 13, 14, 15 and 16 November, 2007 (i.e. before landfall) for WRF model have been shown in Figs. 2b and 2c respectfully. Figure demonstrate that the intensity of the TC increases as the MSLP drops with time up to its peak intensity and TC changes its position with time. The isobar has circular arrangement around the TC centre with some asymmetric features in the outer periphery. The contour interval is different in magnitude for different position because of different intensity of the system. At mature stage the contour intervals are 5 and 3 hPa obtained from MM5 and WRF model respectively. Using MM5 model, the lowest simulated MSLP (961 hPa) is obtained at 00 UTC on 15 November (Fig. 2a). But just before the landfall at 12 UTC on 15 November, 2007 simulated MSLPs is 966 hPa. At this stage, considering the outermost closed isobar, the system's horizontal size is estimated as 8.0° in the east-west and 9.5° in the north-south direction demonstrating a little bit spatial asymmetry in its horizontal structure (Fig. 2b). Again, using WRF model, the lowest simulated MSLP (977 hPa) at the centre of the eye of the TC Sidr is found at 03 UTC on 15 November, 2007 (Fig. 2a). But at 00 UTC on 16 November, 2007 the simulated MSLP of the centre is 987 hPa. At this stage, considering the outermost closed isobar, the system's horizontal size is estimated as 5.0° in the east-west direction and 7.5° in the north-south demonstrating a spatial asymmetry in its horizontal structure (Fig. 2c).

The distribution of the SLP of the TC Sidr along east-west cross section passing through its centre at (20.541 °N and 90.734 °E) at time 12 UTC on 15 November, 2007 for MM5 and through its centre at (21.462 $^{o}$N and 89.453 °E) at time 00 UTC on 16 November, 2007 have been shown in Figs. 2d and 2e respectively. The figures demonstrate the moderate pressure gradient around the centre with maximum gradient at around 15-20 km from the centre for both the models. Thus the radius of the TC eye is found to be below 15 km according to the simulation from both the models.

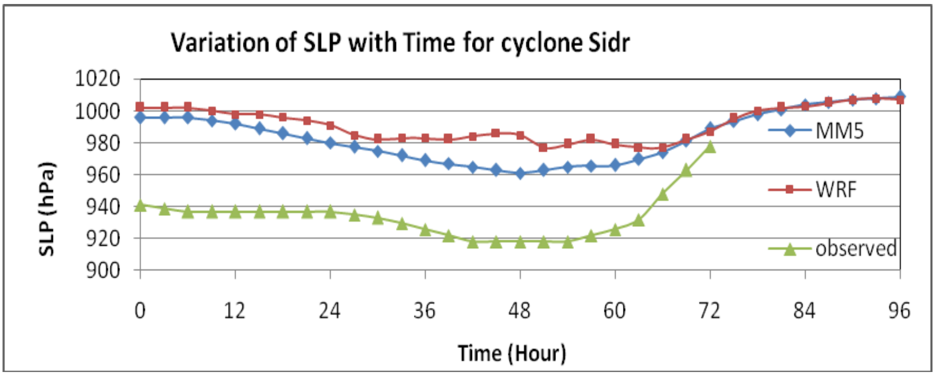


Fig. 2a. MM5 model simulated and observed central pressure of TC Sidr.

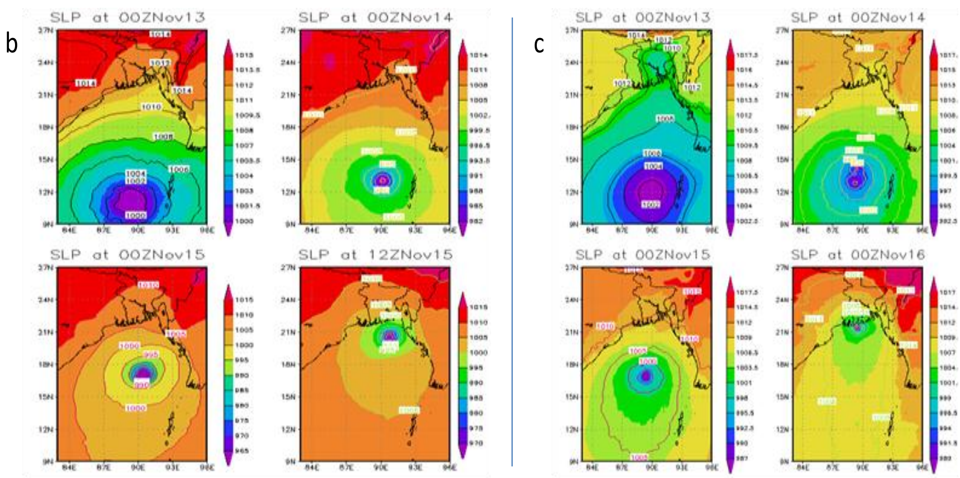


Fig. 2. (b) MM5 and (c) WRF Models simulated SLP of TC Sidr.

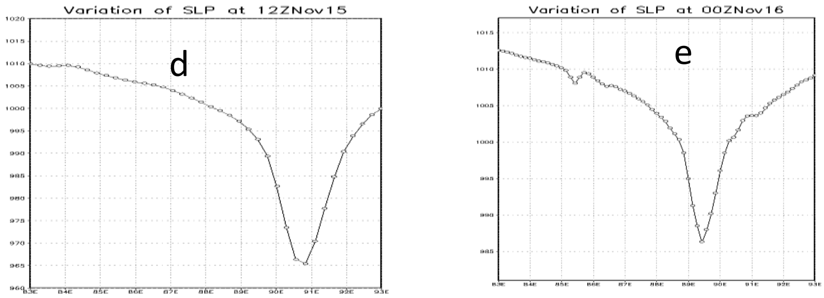


Fig. 2. East West cross sectional view of simulated SLP of TC Sidr obtained from (d) MM5 and (e) WRF models through the centre.

### 4.2. *Wind field*

Maximum wind speed (MWS) directly devastates the affected area at the time of landfall. Fig. 3a shows the temporal variations of MM5 and WRF model simulated MWS and observed winds of TC Sidr. The model simulated MWS are obtained at the standard meteorological height of 10 m. The model simulated MWSs obtained from MM5 are lower than the observed values all through the simulated time except for the landfall time when the simulated values are almost matched with that observed value. Again, the model simulated MWSs obtained from WRF are higher than the observed values all through the simulated time. The simulated highest MWS is obtained at 00 UTC on 15 November for MM5 model and at 18 UTC on15 November for WRF where as that for observed is obtained at 18 UTC on 14 November, 2007 retains this value up to 18 UTC on 15 November, 2007.

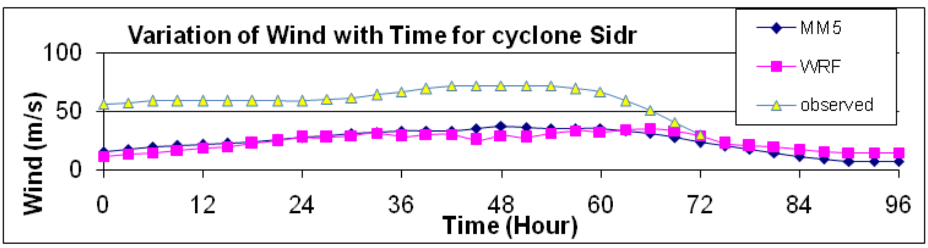


Fig. 3a. Observed and MM5 and WRF model simulated wind speed (m/s) of TC Sidr with time.

The distribution of surface (10 m) wind for the TC Sidr at different times for MM5 and WRF models are shown in Figs. 3b and 3c. Figures show that the wind field of the TC is highly asymmetric in the horizontal distribution. At 00 UTC on 13 November, 2007 (i.e. at the initial time of simulation), when the TC was in the sea according to the simulated results from both the models, the pattern has an asymmetric wind distribution with strong wind bands in the front left and right sides, close to the centre of north directed moving storm. The wind flow in the core region shows a near circular feature with minimum wind speed at the centre. Maximum speed at this time is 16 and 12 m/s for the MM5 and WRF models respectively. At 00 UTC on 14 and 15 November, 2007, TC is organized with strong wind band around and the wind flow in the core region shows asymmetric feature with minimum wind at the centre. Maximum winds at these stages are 27 and 35 m/s for MM5 model and 27 and 30 m/s for WRF model. For MM5 model, at 12 UTC on 15 November, 2007 (i.e. just before the landfall), a strong wind band (wind speed > 30 m/s) having strongest wind exceeding 35 m/s is found around the system centre. It may be noted that the model has generated lower winds of 36 m/s (130 km/h) than the observed winds of around 140 km/h but just before landfall (i.e. at 12 UTC on 15 November, 2007) both simulated and observed winds are close to each other (Fig. 3b). Fig. 3b shows the landfall feature of surface wind distribution where the winds is much less in the front side compared to other of the cyclonic system. It is due to frictional force of landmass. Similar feature is seen for WRF model at 00 UTC on 16 November, 2007 but the maximum wind speed obtained from WRF model is smaller to that of MM5 model (Fig. 3c).

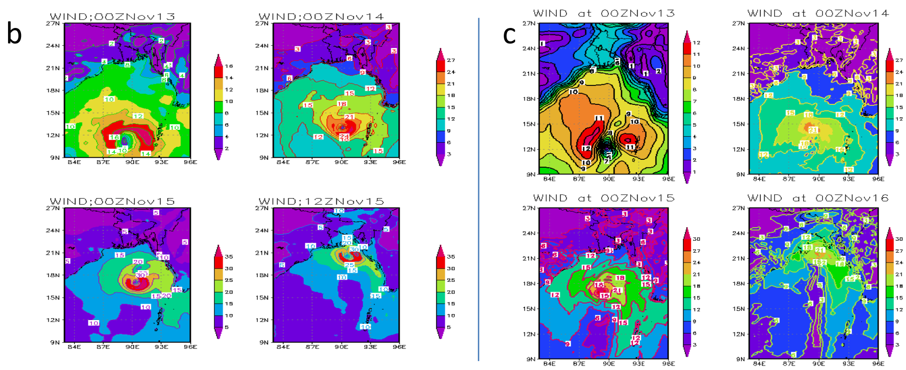


Fig. 3. (b) MM5 and (c) WRF models simulated Wind speed (m/s) TC Sidr at 10 m.

The distribution of the surface wind of the TC Sidr along east-west cross section passing through its centre (20.54 °N and 89.453 °E) at 12 UTC on 15 November, 2007 for MM5 model and at centre (21.462 °N and 89.453 °E) at 00 UTC on 16 November, 2007 for WRF model are shown in Figs. 3d and 3e respectively. Figures demonstrate that a calm region is found inside the eye of the system and maximum wind is found in the eye wall. The radius of maximum wind of the TC Sidr is found to be just lower than 70 km according to the simulations.

The horizontal distribution of vector and magnitude of the wind field for 850, 500, 300 and 200 hPa at 12 UTC on 15 November, 2007 (i.e. before landfall) for MM5 and 00 UTC on 16 November, 2007 (i.e. before landfall) for WRF model have been shown in Figs. 3f and 3g respectively. Figures show that a well organized cyclonic circulation with strong winds encircling the centre is found at 850 and 500 hPa levels. At 300 hPa wind shows little bit cyclonic circulation in the right side of the TC and weak outflow in the left side. At 200 hPa level strong outflow is evident from the central part of the TC except at 00 UTC on 13 November, 2007 (i.e. at initial time not shown in Fgure). Model derived maximum winds obtained from MM5 and WRF models for different times are tabulated in Table 2. MM5 model derived maximum winds obtained just before landfall (12 UTC on 15 November, 2007) are about 60, 50, 50 and 25 m/s at 850, 500, 300 and 200 hPa levels respectively. Again, WRF model derived maximum winds just before landfall (00 UTC on 16 November, 2007) are about 50, 40, 30 and 20 m/s at 850, 500, 300 and 100 hPa levels respectively. Magnitude of wind obtained from WRF model is higher than that obtained from MM5 model. It is noted that the strong wind is confined to the right of the direction of the movement of the system. So, model derived results shown in Fig. 3f-g satisfy the inflow in the lower levels and outflow in the upper levels.

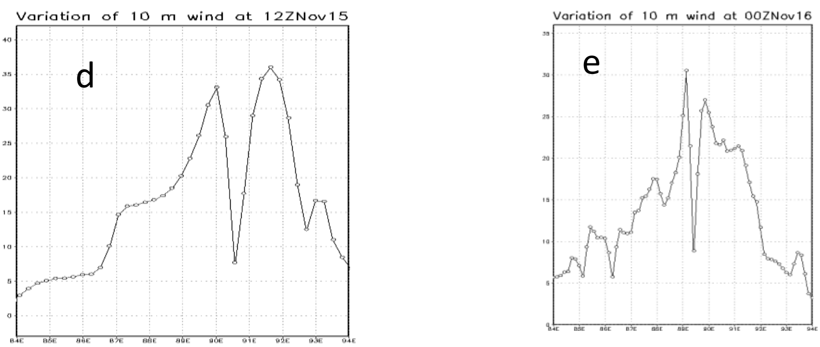


Fig. 3. East West cross sectional view of (d) MM5 and (e) WRF models simulated wind speed (m/s) of TC Sidr along the centres.

Table 2. MM5and WRFmodels simulated wind speed (m/s) at different pressure levels of TC Sidr.

| Model | Pressure level | Wind Speed (m/s) at | | | | |
|---|---|---|---|---|---|---|
| | | 00 UTC 13 November | 00 UTC 14 November | 00 UTC 15 November | 12 UTC 15 November | 00 UTC 16 November |
| MM5 | 850 | 20 | 40 | 60 | 60 | -------- |
| | 500 | 20 | 30 | 50 | 50 | -------- |
| | 300 | 40 | 40 | 40 | 50 | -------- |
| | 200 | 50 | 60 | 50 | 50 | -------- |
| WRF | 850 | 20 | 40 | 50 | -------- | 50 |
| | 500 | 20 | 40 | 50 | -------- | 40 |
| | 300 | 40 | 40 | 40 | -------- | 30 |
| | 200 | 50 | 50 | 50 | -------- | 40 |

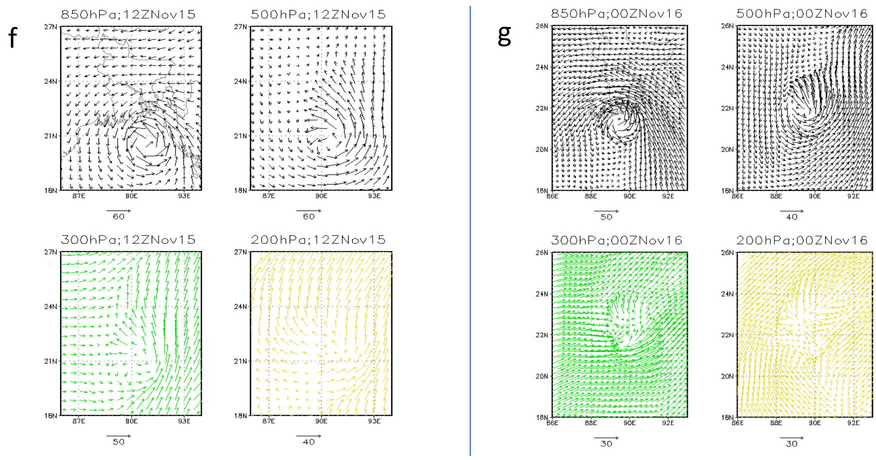


Fig. 3. (f) MM5 and (g) WRF models simulated wind vector at 850, 500, 300 and 200 hPa levels.

Figs. 3h and 3i show the vertical profile of radial wind, tangential wind, vertical velocity and horizontal wind of the system at 12 UTC on 15 November, 2007 (i.e. just before landfall) for MM5 model and 00 UTC on 16 November, 2007 (i.e. just before landfall) for WRF model respectively. MM5 and WRF model simulated radial wind, tangential wind, vertical velocity and horizontal wind (cm/s) of TC Sidr at different times are tabulated in the in the Table 3.

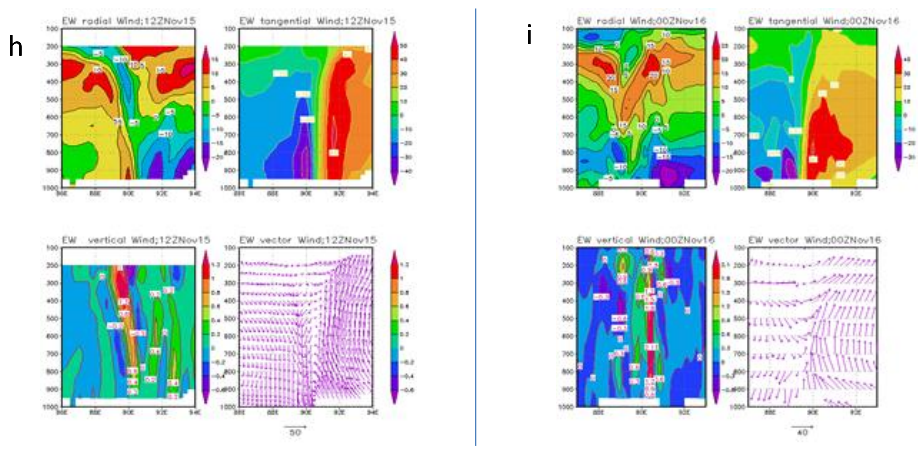


Fig. 3. (h) MM5 and (i) WRF models simulated east-west cross section of vertical structure of radial wind, tangential wind, vertical velocity and horizontal wind of TC Sidr along the centre.

The system is much more organized except at 00 UTC on 13 November, 2007 (i.e. at initial time; not shown in Figure) and it is also clearly showed that the system has strong inflow in the lower level which brings the air to the system through the boundary level and lower level and outflow in the upper level.

Figs. 3h and 3i demonstrate that the tangential wind flows towards northerly direction at the eastern side of the system and southerly direction at the western side. The strong wind with different speed (tabulated in Tables 3) is confined to the different levels in the lower troposphere and extended up to 200 hPa level at right and left side of the system.

From the Table 3, it is seen that the values of vertical motion are different in magnitude for different time and it reveals that strong upward motion of about 120 cm/s at 12 UTC on 15 November, 2007 for MM5 model and about 200 cm/s at 00 UTC on 15 November, 2007 for WRF model exists along the eye wall and other parts of the system which feed moisture into the system. It is noted that Sidr has very strong updraft motion at the eye wall throughout mid and upper troposphere. In general downward motion is not strong. The downward motion is visible in the central parts of the TC and other areas of small pockets, which could be due to subsidence associated with convection.

Table 3. MM5 and WRF models simulated radial wind, tangential wind, vertical velocity and horizontal wind (cm/s) of TC Sidr.

| Model | Component of wind | Simulated wind speed (cm/s) at | | | | |
|---|---|---|---|---|---|---|
| | | 00 UTC 13 November | 00 UTC 14 November | 00 UTC 15 November | 12 UTC 15 November | 00 UTC 16 November |
| MM5 | Radial wind | 1200 | 1200 | 1500 | 2000 | -------- |
| | Tangential wind | 1500 | 3000 | 5000 | 5000 | -------- |
| | Vertical velocity | 50 | 60 | 80 | 120 | -------- |
| | Horizontal wind | 2000 | 4000 | 5000 | 5000 | -------- |
| WRF | Radial wind | 800 | 12 | 2500 | -------- | 2500 |
| | Tangential wind | 18 | 2500 | 3000 | -------- | 3000 |
| | Vertical velocity | 0.40 | 70 | 200 | -------- | 140 |
| | Horizontal wind | 2000 | 2000 | 4000 | -------- | 4000 |

From the Table 3, it is seen that the values of horizontal wind at different times are different. Fig. 3h-i show the distribution of strong winds up to 200 hPa around the centre of TC at 12 UTC on 15 November, 2007 for MM5 and 00 UTC on 16 November, 2007 for WRF model along the centre of the system. It further confirms that the maximum winds are confined to the right quadrant of the direction of movement of the system. This value decreases with the radial distance from both sides of the eye. Calm wind zone is sharp and narrow and little bit tilted to the west and get expanded towards upper levels. Cyclonic circulation is generally seen up to about 300 hPa level and anticyclonic circulation with divergence fields aloft. This is in agreement with the previous studies studies [12,13]. In this case cyclonic circulation is also seen up to about 350 hPa level for MM5 model and up to 300 hPa for WRF model and anticyclonic circulation with divergence fields aloft.

### 4.3. *Vorticity field*

To know the evolution, the plot of MM5 and WRF models simulated low level relative vorticity at 850 hPa as a function of time is shown in Fig. 4a.The analysis reveals that there is a gradual rise in the vorticity value in the first 60 h of the simulation of MM5 model and thereafter the value shows a falling tendency up to 96 h of model run. Again output from WRF model reveals that there is a gradual rise of vorticity in the first 24 h of simulation of the model and then sustains the maximum value with little bit lower value by making several oscillations for next 42 h duration (24-66 h of forecast). Thereafter the value shows a rapid fall.

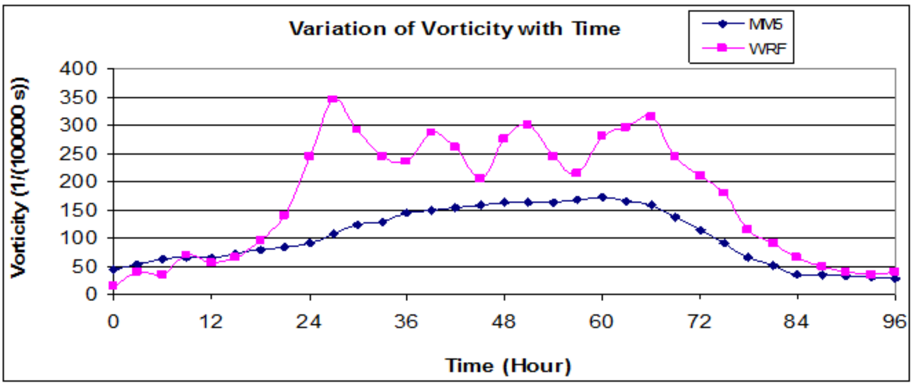


Fig. 4a. Evolution of MM5 and WRF models simulated vorticity with time of TC Sidr.

The horizontal distribution of the relative vorticity obtained from MM5 model at 12 UTC on 15 November, 2007 (i.e. before landfall) and obtained from WRF model at 00 UTC on 16 November, 2007 (i.e. before landfall) of TC Sidr at 850, 500, 300 and 200 hPa levels are shown in Figs. 4b and 4c respectively

It is seen from the Figs. 4b and 4c that the vorticity obtained from MM5 and WRF models is distributed with maximum value at the centre and these values are tabulated in Table 4 for MM5 and WRF model. From Table 4, it is clear that these values increased with the advance of time except at 12 UTC on 15 November, 2007 (i.e. before landfall) for MM5 model and 00 UTC on 16 November, 2007 (i.e. just before landfall) for WRF model at different levels. This is due to landmass effect before landfall. The distribution maintains circular pattern with some asymmetric features in the outer periphery except at 00 UTC on 13 November, 2007 (i.e. initial time) for both models where symmetrical circular pattern is available at all levels.

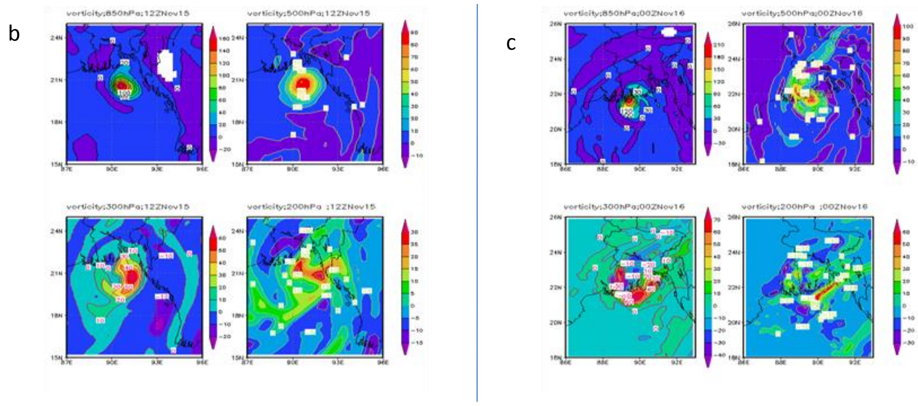


Fig. 4. (b) MM5 and (c) WRF models simulated vorticity field associated with Sidr at 850, 500, 300 and 200hPa levels.

At 850 hPa level, (Figs. 4b and 4c) negative vorticity fields are found almost in all sides of the centre of the TC which is followed by a positive and negative vorticity fields at 12 UTC on 15 November, 2007 (i.e. just before the landfall). Similar phenomena of negative vorticity are found at 00 UTC on 13-15 November, 2007 (not shown in Fig.). The distance of the negative vorticity from the centre increased due to the intensification of the intensity of TC (not shown). Low level relative vorticity fields confirm the strong cyclonic circulation with different values of the radius at different time in feeding moisture into the system to sustain its intensity.

At 500 and 300 hPa levels the distribution of relative vorticity shows a symmetric character in the horizontal direction. The values of relative vorticity increased with the intensification of the intensity of the cyclone and then decreased before landfall at time 12 UTC on 15 November for MM5 model and after landfall at 00 UTC on 16 November, 2007 at 500 hPa level. But the values of relative vorticity increased with the development of TC at all stages at 300 hPa level. At 200 hPa level, the weak positive vorticity embedded with negative vorticity field is visible at 200 hPa level. Negative vorticity is found at or near the centre.

Vertical distribution of relative vorticity through the centre in the east-west direction is shown in Figs. 4d and 4e for models MM5 and WRF and values are tabulated in the Table 4.

According to the output obtained from MM5 model at 00 UTC on 13 November (i.e. the initial time), the positive vorticity is spread over a horizontal distance with strong vorticity at slightly western side of the centre (11.042 °N and 89.588 °E). This pattern of distribution extends from surface to around 200 hPa level with the exception that the magnitude of the vorticity decreases with height. Similar pattern with higher positive value of vorticity is found at the centre after 24 h of simulation at 00 UTC on

14 November, 2007 along the centre (13.044 °N). At 00 UTC on 15 November, 2007, the system has the positive vorticity along the centre (17.134 °N) up to 200 hPa with highest positive value of vorticity. At 12 UTC on 15 November, 2007, the system has the same value of positive vorticity as the previous time at 00 UTC on 15 November, 2007 along the centre (20.541 °N) up to 200 hPa.

Table 4. MM5 and WRF Models simulated maximum vorticity ($x10^{-5}$ $s^{-1}$) of TC Sidr.

| Model | Pressure level | Wind Speed (m/s) at 00 UTC 13 November | 00 UTC 14 November | 00 UTC 15 November | 12 UTC 15 November | 00 UTC 16 November |
|---|---|---|---|---|---|---|
| MM5 | 850 | 45 | 90 | 160 | 160 | -------- |
| | 500 | 35 | 55 | 100 | 90 | -------- |
| | 300 | 20 | 40 | 60 | 60 | -------- |
| | 200 | 15 | 20 | 50 | 30 | -------- |
| | Vertical distribution | 35 | 60 | 160 | 160 | |
| WRF | 850 | 18 | 240 | 270 | -------- | 210 |
| | 500 | 15 | 240 | 140 | -------- | 100 |
| | 300 | 12 | 180 | 120 | -------- | 70 |
| | 200 | 10 | 80 | 70 | -------- | 60 |
| | Vertical distribution | 18 | 80 | 270 | | 210 |

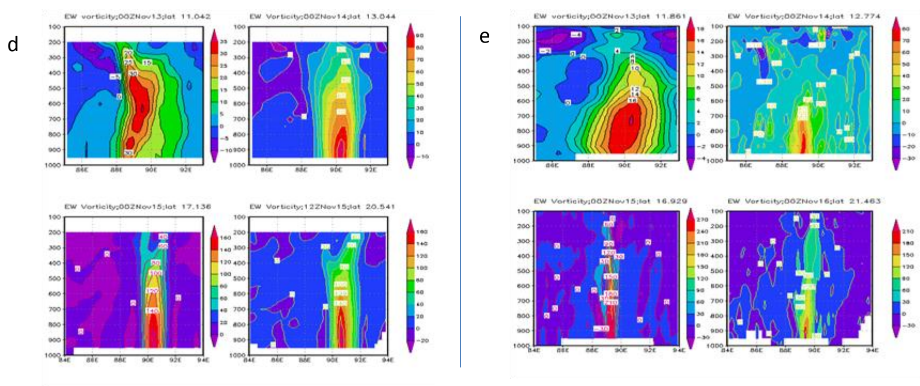

Fig. 4. (d) MM5 and (e) WRF models simulated vertical distribution of relative vorticity field in the east-west direction of TC Sidr.

Again, according to the output obtained from WRF model at 00 UTC on 13 November (i.e. the initial time), the positive vorticity is spread over a horizontal distance with strong vorticity at slightly eastern side of the centre (11.861 °N and 89.868 °E). This pattern of distribution extends from surface to around 150 hPa level with the exception that the magnitude of the vorticity decreases with height. Similar pattern with higher positive vorticity is found at the centre after 24 h of simulation at 00 UTC on 14 November, 2007 along the centre (12.774 °N). At 00 UTC on 15

November, 2007, the system has the positive vorticity along the centre (16.929 °N) up to 200 hPa level with highest positive value. At 00 UTC on 16 November, 2007, the system has less positive vorticity than the previous time at 00 UTC on 15 November, 2007 along the centre (21.463 °N) up to 150 hPa with low magnitude. It may be effect of landmass before landfall.

### 4.4. *Temperature anomaly*

The MM5 model simulated temperature anomaly of TC Sidr at 00 UTC on 13-15 November and 12 UTC on 15 November, 2007 (i.e. before landfall) from surface to 100 hPa level is shown in Fig. 5a and temperature anomaly is tabulated in Table 5. At 00 UTC on 13 November, 2007, warm core of 10°C is simulated at 950-200 hPa layer. It is noted that the warm core region is slightly expanded outward at 800-300 hPa level. The greatest anomaly has occurred around 450 hPa level. Negative temperature anomalies are also shown in the upper levels. At 00 UTC of 14 November, 2007, warm core of 12°C is simulated at 950-200 hPa layer. It is noted that the warm core region is expanded outward at 700-350 hPa level. The greatest anomaly is simulated by the MM5 model around 500 hPalevel. At 00 UTC on 15 November, 2007, 14°C warm core is observed at 950-200 hPa layer. It is noted that the warm core region is expanded outward at 600-350 hPa level. The greatest anomaly is simulated around 400 hPalevel. At 12 UTC on 15 November, 2007, warm core 11°C is observed in 950-200 hPa layer. It is noted that the warm core region is expanded outward at 650-300 hPa level. The greatest anomaly is simulated around 500 hPa level. The simulated temperature anomaly demonstrates that the warm core is visible mainly in the upper troposphere during 13 -15 November, 2007. Negative temperature anomalies at lower levels are due to contamination by heavy precipitation at 00 UTC and 12 UTC of 15 November, 2007.

Table 5. MM5 and WRF Models simulated temperature anomaly (°C) associated with TC Sidr.

| Model | Temperature anomaly (°C) at | | | | |
|---|---|---|---|---|---|
| | 00 UTC on 13 November | 00 UTC on 14 November | 00 UTC on 15 November | 12 UTC on 15 November | 00 UTC on 16 November |
| MM5 | 10 | 12 | 14 | 11 | ------------ |
| WRF | 10 | 8 | 10 | ------------ | 8 |

Again, the WRF model simulated temperature anomaly of TC Sidr at 00 UTC on 13-16 November, 2007 from surface to 100 hPa level are shown in Fig. 5b and values are tabulated in Table 5. At 00 UTC on 13 November, 2007, 10°C warm core is observed in the layer between 950-350 hPa. It is noted that the warm core region is slightly expanded outward at 750-350 hPa level. The greatest anomaly is found around 450 hPa level. The simulated temperature anomaly demonstrates that the warm core is visible mainly in the upper troposphere. Negative temperature anomalies are seen at the upper levels. At 00 UTC on 14 November, 2007, 8°C warm core is observed in the layer between 950-300 hPa. It is noted that the warm core region is expanded outward at 700-300 hPa level. The greatest anomaly is found around 450 hPa level. The simulated temperature anomaly demonstrates that the warm core is visible mainly in the upper troposphere. At 00 UTC on 15 November, 2007, 10°C warm core is observed in the layer between 950-200 hPa. It is noted that the warm core region is expanded outward at 850-200 hPa level. The greatest anomaly is found around 450 hPa level. The simulated temperature anomaly demonstrates that the warm core is visible mainly at upper troposphere. At 00 UTC on 16 November, 2007, 8°C warm core is observed in the layer between 950-300 hPa. The warm core region is expanded outward at 700-300 hPa level. The greatest anomaly is seen around 550 hPa level. The simulated temperature anomaly demonstrates that the warm core is visible mainly at upper troposphere. Negative temperature anomalies at lower levels are due to effect of heavy precipitation.

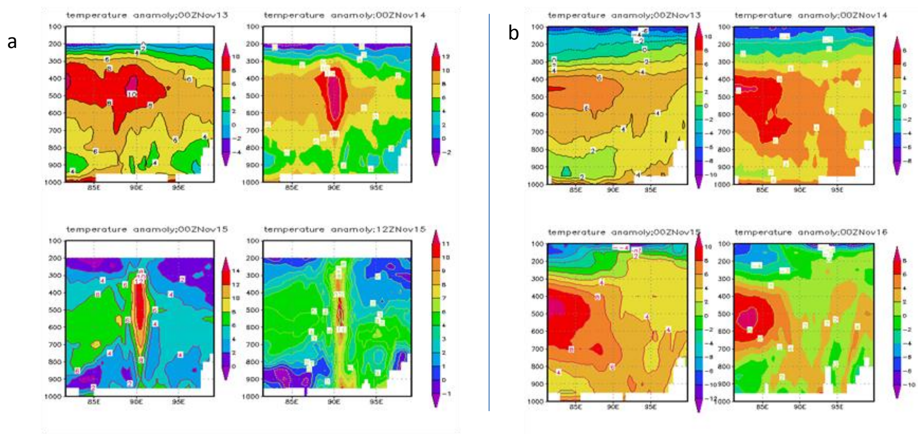


Fig. 5. (a) MM5 and (b) WRF models simulated vertical distribution of temperature anomaly in the east-west cross section of TC Sidr through the centre.

### 4.5. ***Track pattern and landfall time and position***

MM5 and WRF models simulated track of TC Sidr along with observed track are plotted in the Fig. 6a-b. The track forecasts of TC Sidr for 96, 72 48 and 24 h are based on the initial fields of 00 UTC on 13 November, 00 UTC on 14 November, 00 UTC on 15 November and 12 UTC of 15 November, 2007 respectively.

It is seen from Fig. 6a that MM5 model simulated track for 96, 72, 48 and 24 h are parallel to the observed track but it is deviated to east and west side of the observed track. It may be because of initial data error. This Figure shows that model is able to generate northwest, north and northeast movement of the system very well. It reveals that 24, 48 and 72 h tracks are more close to the JTWC best track compared to 96 h tracks. However, there are some errors in the positions with respect to time which shows some lag in landfall. The track from 24 h simulation track is better than that of any others simulation. The landfall position for 24 h simulation track is much closer to any other simulation. So, by changing initial data, the simulated track becomes close to the observed track.

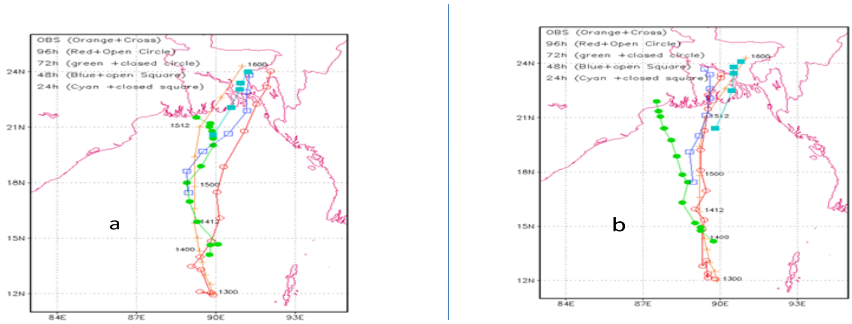


Fig. 6. (a) MM5 and (b) WRF Model simulated and observed tracks of TC Sidr.

It is seen from Fig. 6b that WRF model simulated track for 96, 72, 48 and 24 h are parallel to observed track but it is deviated east and west side of the observed track. It may be because of initial data error. It shows that model is able to generate northwest, north and northeast movement of the system very well. The track obtained from 96 h simulation are more close to the JTWC best track compared to the track obtained from 24, 48 and 72 h simulation. However, there are some errors in the positions with respect to time which shows some lag in landfall. Simulated landfall time is 00 UTC of 16 November compared to observed landfall time 18 UTC of 15 November using 96 h simulation of WRF model based on the initial condition 00 UTC of 13 November, 2007. The track from 96 h simulation is better than that of any other simulations. The landfall position for 96 h simulation track is matched with observed position. So, by changing initial data, the simulated track became close to the observed track.

Table 6a. Landfall point and time error during cyclone Sidr.

| Forecast Hours | obs/ models | initial condition date/Time (UTC) | landfall time date/Time (UTC) | landfall position lat°N | lon°E | Error Distance (km) | Time (hours) |
|---|---|---|---|---|---|---|---|
| | Obs | | 200711151600 | 21.83 | 89.80 | | |
| 96 | MM5 | 200711130000 | 200711152000 | 22.54 | 91.65 | 203e | 4D |
| 72 | | 200711140000 | 200711170000 | 21.53 | 89.26 | 60w | 33D |
| 48 | | 200711150000 | 200711160100 | 22.20 | 91.20 | 155e | 10D |
| 24 | | 200711151200 | 200711151800 | 22.07 | 90.58 | 87e | 2D |
| 96 | WRF | 200711130000 | 200711160200 | 21.80 | 89.52 | 31w | 11D |
| 72 | | 200711140000 | 200711161900 | 21.60 | 87.60 | 244w | 27D |
| 48 | | 200711150000 | 200711152215 | 21.75 | 89.60 | 22w | 6.25D |
| 24 | | 200711151200 | 200711151545 | 21.80 | 90.25 | 50e | 0.25E |

D indicates forecast landfall time is delayed compared to actual time, W indicates west of the actual landfall position and E indicates forecast landfall time is earlier to actual landfall time.

The landfall times and positions are tabulated in Table 6a. The error of landfall and time are also summaries in Table 6b. Mean position errors for 24, 48, 72 and 96 h are117, 152, 89 and 69 km respectively and respective mean time errors are 8, 30, 8 and 1h.

Table 6b. Mean landfall position and time errors of selected tropical cyclone.

| Forcast Hours | Mean landfall Position Error (km) | Mean landfall Time Error (hrs) |
|---|---|---|
| 96 hrs | 117 | 8 |
| 72 hrs | 152 | 30 |
| 48 hrs | 89 | 8 |
| 24 hrs | 69 | 1 |

## 5. Conclusion

TC Sidr have been selected to simulate the structure, intensity, MSLP, wind (vector, radial, tangential, vertical wind), voticity, temperature anomaly and track by both of the models. Simulated parameters are compared with the data obtained from JTWC.

- Both the models are able to simulate some salient features of TC such as pressure distribution, vertical motion around the centre, vertical and horizontal distribution of wind, vorticity and temperature anomaly. Some of them are very close to the observations.
- Both of the models fail to simulate the SLP. Simulated SLP is higher than that of observed SLP. Spatial and temporal variation of minimum SLP obtained. But in all cases sharp pressure gradient in the vicinity of the centre of the TC are observed by the simulated pressure field at surface level.
- Asymmetric patterns of surface wind distribution with well organized banded structure having the maximum at about 40 to 240 km far from the centre and relatively weak winds at the centre are well simulated. Well organized circulation patterns are simulated at 850 hPa level confirming that maximum winds are confined to the right of the track of the TC movement. Anticyclonic circulation patterns at 200 hPa level or lower are visible in most of the cases. Model simulated MWS is nearly equal to the observed value.
- MM5 model predicts intensity better than WRF model.
- The model has successfully simulated the strong relative vorticity at lower level spreading over the strong convective region of each cyclone. For the very strong systems the positive vorticity is found to extend up to 100 hPa level. Simulated low level vorticity fields at 850 hPa level demonstrate the size of the system with strong convective regions of each cyclone, which are in agreements with the observations.
- The warm core characteristics with maximum temperature anomaly of 8-14°C simulated in the middle and upper troposphere successfully by the models. This

warm core has the vertical extends from the lower level to tropopause for strong system.

- With regard to track predictions of selected TC, models are run for 24, 48, 72 and 48 h forecast. Simulated track for 24 and 96 h forecast are the best among other forecasts for MM5 and WRF models respectively. Performance of WRF model for track prediction is better than MM5 model.

Considering the above, it can be mentioned that both the models simulate the cyclonic feature well. MM5 model has better forecast skill in terms of intensity prediction but WRF model has better forecast skill in terms of track prediction of the cyclonic storm. So, both of the models may be used as operational model by using the suitable microphysics and cumulus parameterization schemes.

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