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Simulation of Formation, Intensity, Structure and Track of Tropical Cyclone Sidr using WRF-ARW Model

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Abstract

The formation, intensity, structure and track of Tropical Cyclone Sidr (2007), have been investigated using WRF (Weather Research and Forecasting) – ARW (Advanced Research WRF) model. The model was used at 24 km horizontal resolution with a single domain of size 3.43-30.19^{o}N and 75.35-103.62^{o}E. Kain-Fritch (KF) cumulus parameterization, WRF-single moment (WSM) 3-class microphysics and Yonsei University Planetary Boundary Layer (PBL) schemes have been used. The NCEP FNL data of 1°x1° resolution has been used as initial field and lateral boundary conditions. The ARW model was run for 24, 48, 72 and 96 hrs. The best track JTWC data of Sidr was used for comparing the model results. The results show that ARW model is capable of forecasting the formation of the first low pressure system 36 hrs ahead from its actual genesis. The model successfully simulates the realistic intensification process. But the model underestimates the intensity of tropical cyclone Sidr. The model generates a realistic structure of the tropical cyclone with high spatial details and has successfully predicted the tracks and probable area and time of landfall of the selected tropical cyclone with some errors.

Keywords: Prediction, Evolution, Relative Vorticity, Landfall, SLP, JTWC

Introduction

Tropical cyclones are well known for their destructive character and impact on human activities. The massive destruction caused by strong winds, storm surge and torrential rains associated with a storm.

It has been evident that mortality associated with tropical cyclones is considerably high especially in the Bay of Bengal region mainly due to poor socio-economic conditions of bordering countries. Understanding tropical cyclogenesis and associated characteristic features has been a challenging subject in meteorology over the last several decades.

In the recent decades a good number of studies have been published on tropical cyclone track and intensity forecasting and structure simulation. Krishnamurti and Jha [1] carried out a large number of experimentation programs on the landfall of 1991 cyclone that hit Chittagong using Florida State University (FSU) model. They found that the results were indeed resolution dependent; the high resolution global model provided the best results. Davis and Bosart [2] utilized Mesoscale model version 5 (MM5) model to simulate genesis of hurricane Diana-1984 and documented that physics plays an important role in understanding transformation from marginal storm to hurricane intensity. Barun [3] employed MM5 model to simulate asymmetrical structure of eye and eyewall of BOB-1991 hurricane. Trivedi *et al.* [4] documented some improvement of track prediction of Orissa super cyclone with assimilation of synthetic vortex into the initial analysis. Mohanty *et al.* [5] made simulation of Orissa super cyclone-1999 by using MM5 model with horizontal resolution of 30 km. They reported that model was able to predict intensity of the storm up to 48 hrs and underestimate between 48 hrs and 72 hrs. Prasad [6] made cyclone track prediction experiments with a Quasi-Lagrangian Model (QLM) for 9 cyclonic storms developing during the four year period 1997-2000. Goswami *et al.* [7] made advance forecasting of cyclone track over the north Indian Ocean by using Global Circulation Model (GCM). Pattanayak and Mohanty [8] made a comparative study on the performance of both MM5 and ARW models in the simulation of tropical cyclones over North Indian Ocean and demonstrated the superiority of the ARW model over MM5. Lin *et al.* [9] studied warm ocean anomaly, air sea fluxes, and the rapid intensification of tropical cyclone Nargis-2008. The structure and movement of topical cyclones over the North Indian Ocean simulated by WRF-ARW model were carried out by Basnayake *et al.* [10]. Mohanty *et al.* [11] made a study on high resolution mesoscale modelling systems for simulation of tropical cyclones over the Bay of Bengal and the results indicate that the high resolution mesoscale modelling systems provide better guidance for tropical cyclone forecast up to 72 hours.

In the present study, the formation, intensity, structure, track and landfall for tropical cyclone Sidr (2007) formed in the Bay of Bengal have been investigated using the Advanced Research WRF (ARW) model at grid spacing of 24 km. Here WRF stands for Weather Research and Forecasting which is a fully compressible and nonhydrostatic model (Skamarock *et al.* [12]). Sidr was a super cyclonic storm in category 5 of Saffir-Simpson Hurricane scale, which hit the Sundarbans coast near Patuakhali of Bangladesh on 15 November 2007, killing more than 3,300 people (Choudhury [13]).

Model Setup, Initialization and Methodology

To simulate the above selected tropical cyclone a domain of dimension 3.43-30.19^{o}N and 75.35-103.62^{o}E was selected to cover the Bay of Bengal basin at 24 km horizontal resolution with 27 vertical η levels. Figure 1 shows the horizontal domain of the model. The model domain consists of 127×127 grid points. Marcator map projection has been used. Kain-Fritch (KF) cumulus parameterization scheme and WRF-single moment (WSM) 3-class microphysics scheme have been chosen for simulating the event. Surface layer was treated using Monin-Obukhov scheme with Carslon-Bolan viscous sub-layer option and boundary layer has been treated with Yonsei University scheme. Noah 4-layer Land Surface Model (LSM) has been utilized with the above combination. Long and short wave radiations have been treated with Rapid Radiative Transfer Model (RRTM) and Dudhia schemes, respectively. Time step of integration was set to 120 seconds for maintaining the computational stability as the model uses 3rd order Runga-Kutta time integration scheme.

The present study has been performed using Numerical Weather Prediction (NWP) modelling techniques. ARW model was run for 24, 48, 72 and 96 hrs to simulate formation, intensity, structure, track and landfall of tropical cyclone Sidr. National Centre for Environment Prediction (NCEP) Final Reanalysis (FNL) data (1°x1° resolution) was utilized as initial and lateral boundary conditions (LBCs) which is updated at six hourly interval. The model was initialized with 0000, 0600, 1200 and 1800 UTC initial field of corresponding date. The model outputs have been taken at every 6 hrs interval. The simulated results have been presented in the graphical and tabular forms. Grid Analysis and Display System (GrADS) and WinSurfer software have been employed for visualization of model outputs. Finally the model outputs have been compared with Joint Typhoon Warning Center (JTWC) best track data [14] to demonstrate the performance of the modelling exercise. The discussions of the model results are provided with necessary physical interpretations. In the present study JTWC best track data is considered as Observed.

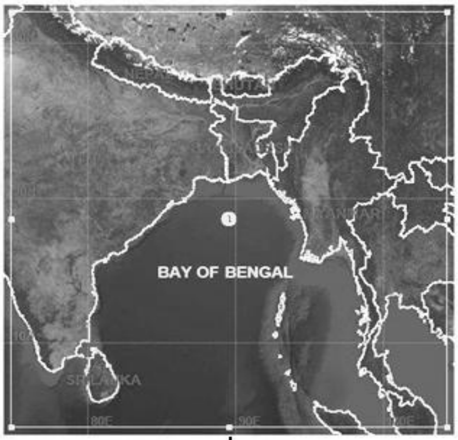

Fig.1: Model domain with 24km×24km horizontal resolution

Results and Discussion

Formation prediction

To study the formation of selected tropical cyclone the prediction experiments were performed up to 96 hrs using the initial field 48 hrs before the formation of the first low pressure system. The predictions have been updated every 6 hrs using the corresponding initial field of respective dates until the model could produce the low pressure system. Such experiments were performed to test, if the model was capable of capturing the formation process of the cyclonic system.

According to satellite observed information, an area of disturbed weather developed in the Bay of Bengal on 9 November 2007 with a weak low-level circulation near the Nicobar Islands. Considering this, the model was run before 48 hrs of formation of the disturbance with initial fields of 0000 UTC of 7 November 2007 to capture the formation of cyclone Sidr. In this case the model failed to produce perfect low pressure system. Then prediction has been updated every 6 hrs. Figure 2a shows the observed Sea Level Pressure (SLP) at 1200 UTC of 7 November 2007 which has been used as initial field for NWP experiment, where there was no well organized low pressure system, but there was an east-west extended low pressure zone. After 36 hrs of simulation at 0000 UTC of 9 November 2007 the model produced a low pressure system centered at 9.5^{o}N/94.5^{o}E (Fig. 2b). According to satellite observed data the system developed near southeast of the Andaman Islands centered at about 9.2^{o}N/94^{o}E. Therefore, the model simulated system centre is close to the observed position. At this position the Minimum Sea Level Pressure (MSLP) is about 1006 hPa. This low pressure system further intensified and moved north-west direction according to the model simulation, which matches well with observation.

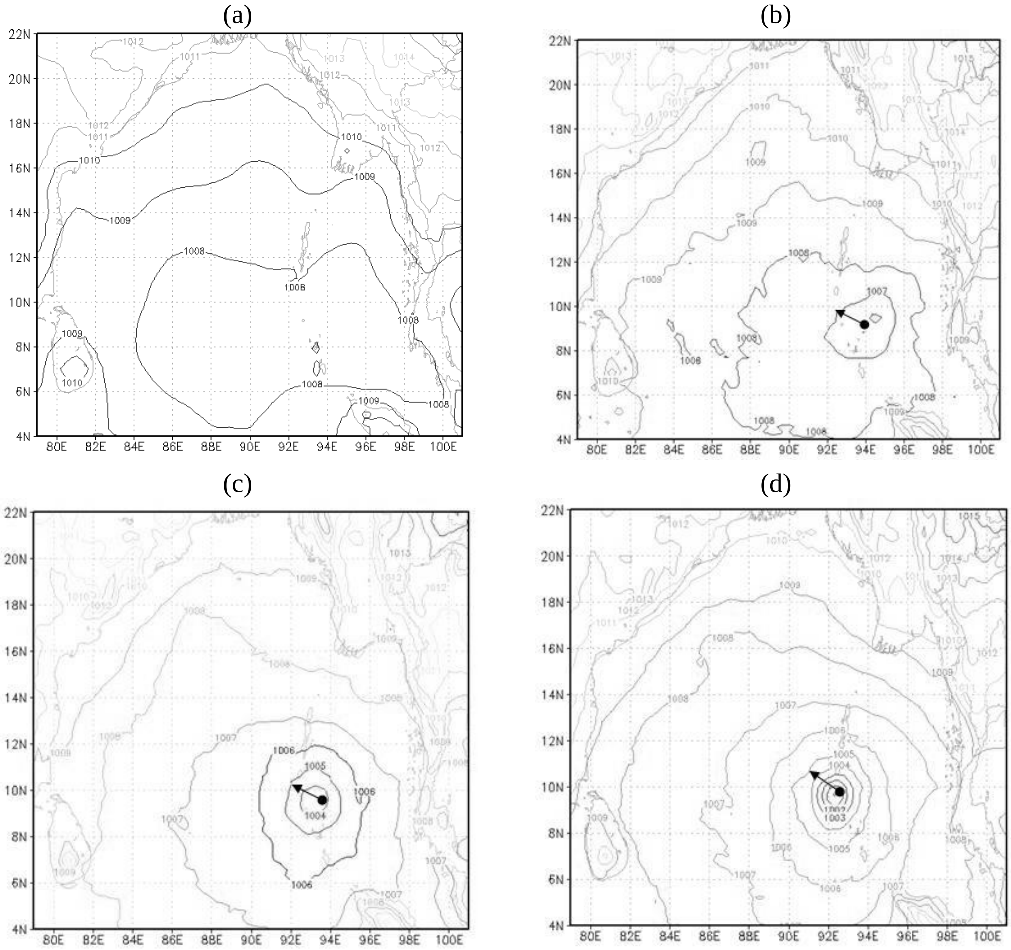

Fig.2: *(a) Observed SLP of Sidr at1200 UTC of 7 November 2007 used as model initial field, (b) 36 hrs simulated SLP at 0000 UTC of 9 November (c) 60 hrs simulated SLP at 1200 UTC of 10 November (d) 78 hrs simulated SLP at 1800 UTC of 10 November (arrow indicates the actual position of the centre and direction of movement of the system)*

The model results further show that at 0000 UTC of 10 November 2007 the system intensified into well-marked low with MSLP of about 1004 hPa and moved in the same direction (Fig. 2c). The centre of the predicted system was found at 9.7^{o}N/93.2^{o}E (observed position 9.5^{o}N/93.5^{o}E). It has been observed that there was pressure drop of 3 hPa. This system further intensified into depression after 78hrs of simulation at 1800 UTC of 10 November 2007 which centered at 9.9^{o}N/92.5^{o}E (Fig. 2d). At this time the observed system centre was at 9.8^{o}N/92.5^{o}E which is close to the predicted centre. Figure 2d shows that the predicted MSLP and pressure drop are of 1000 hPa and 6 hPa respectively. Later, this depression intensified into deep depression and moved to north-west direction. The predicted centres of the system were found to be very close to the observed centres. The model captured well north-west movement of the systems at the stage of formation.

Intensity prediction

The discussion in this section is mainly on the evolution of selected parameters of tropical cyclone viz. Minimum Sea Level Pressure (MSLP), Central Pressure Drop (CPD), Maximum Wind Speed (MWS), and Relative Vorticity. These parameters are directly related to the intensity of tropical cyclone. MSLP of a tropical cyclone is of great importance as it helps to measure the intensity of a cyclone. CPD of the tropical cyclone is determined as the difference between pressure of the outer most closed isobar and MSLP. MWS is another important parameter of tropical cyclone for measuring its intensity. It is of importance as it directly devastates the affected area at the time of landfall. In addition, it is the most active driving force of generating storm surge over the area of landfall. The surface wind is taken at the standard meteorological height of 10 m in an unobstructed exposure.

To study the evolution of tropical cyclone the model was run for 24, 48, 72 and 96 hrs before the approximate landfall time. Table 1 summarizes the modelled and observed MSLP, CPD and MWS of selected cyclone at the stage of its highest intensity. It is seen that the 96 hrs prediction simulates the lowest MSLP and the MSLP increases with the decrease of forecast hours. It is also seen that the model underestimates the intensity in terms of MSLP. The CPD and MWS show similar results as MSLP.

Table 1: *Different intensity parameters of selected tropical cyclone Sidr (2007) at the stage of its highest intensity*

Initial Date/ Time (UTC)	Forecast Hours	MSLP (hPa)		CPD (hPa)		MWS (ms^{-1})	
		Simulated	Observed	Simulated	Observed	Simulated	Observed
11Nov /1800	96	960 [15Nov/1200]	918 [15Nov/0600]	48 [15Nov/1200]	86 [15Nov/0600]	39.2 [15Nov/1200]	71.4 [15Nov/0600]
12Nov/1800	72	971 [-do-]	-do-	37 [-do-]	-do-	34.5 [-do-]	-do-
13Nov/1800	48	982 [15Nov/1800]	-do-	28 [15Nov/1800]	-do-	20.5 [15Nov/1800]	-do-
14Nov/1800	24	998 [-do-]	-do-	11 [-do-]	-do-	18.5 [-do-]	-do-

Figures 3(a-c) show the time variations of observed and 72 hrs model simulated MSLP, CPD, and MWS of tropical cyclone Sidr. It is seen that there is a general offset of MSLP. This is because of the higher values of the pressure field in the low resolution initial data. It appears from Figure 3a that model simulated and observed MSLPs gradually drop with time and attains peak intensity just before the landfall time and thereafter it (MSLP) increases. But the temporal plot shows that the simulated MSLPs are more or less systematically higher than the observed values. Time variations of simulated CPD and

MWS show similar patterns as MSLP. In both cases, it increases with time up to the highest maturity stage of the selected cyclone and then it decreases, which are more or less in good agreement with the observed variations (Fig.3b,c). But the values of simulated CPD and MWS recorded at 6 hourly interval are much lower than the observed values. The plot of the model simulated low level relative vorticity maxima at 850 hPa is shown as function of time (Fig.3d)). The analysis reveals that there is a sharp rise in the vorticity value in the first 66 hrs of integration of the model with little fluctuations. Thereafter the value shows a fall. This temporal pattern demonstrates usually expected feature. The model simulated maximum vorticity at 850 hPa of selected tropical cyclone is found at 1200 UTC of 15 November 2007 with the value of $200\times10^{-5}s^{-1}$.

It is noted that, though Sidr was a super cyclonic storm, the simulated intensity fields do not show realistic intensity. This could be due to lower resolution of the FNL field and inadequacy of the modelling of the physical processes of ARW itself which need to be further investigated. But the model is capable of capturing the intensification process of the cyclonic system.

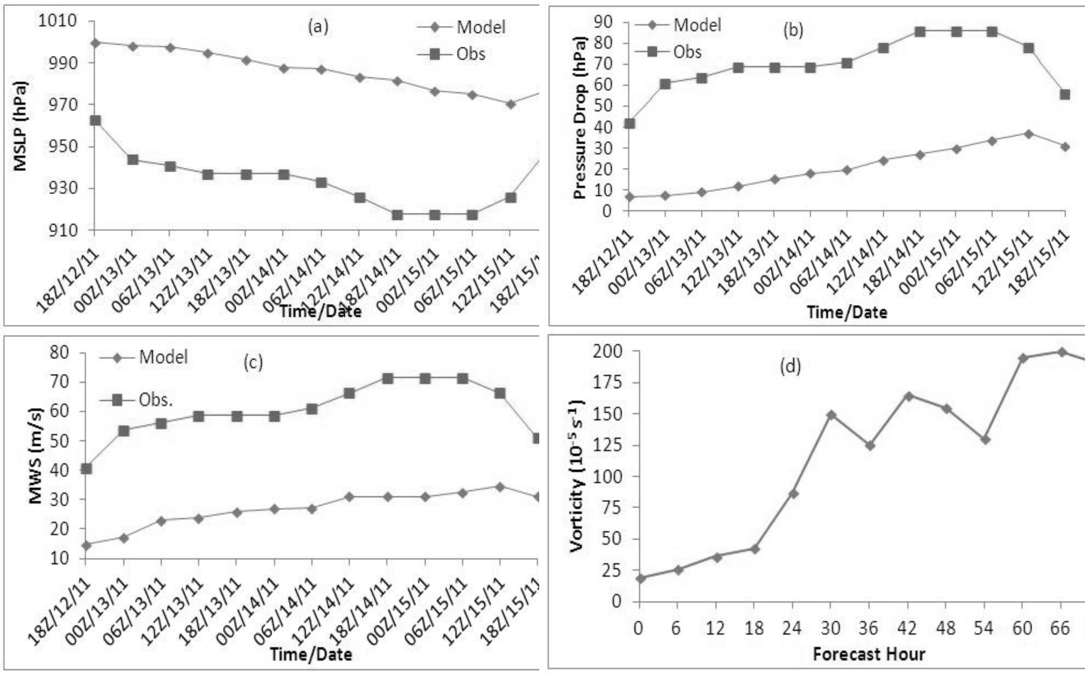

Fig.3: *Time variation of model simulated and observed (a) MSLP (hPa) (b) CPD (hPa)(c) MWS (m/s)and (d) simulated Relative vorticity (s^{-1}) at 850 hPa of selected cyclone Sidr (2007)*

Structure of tropical cyclone

To study the structure of the selected tropical cyclone, the surface pressure, wind and relative vorticity at different layers, temperature anomaly and relative humidity have been analyzed. To investigate the structure of the system the model outputs are taken at the stage of its highest intensity according to model simulation. To analyze the structure of cyclone Sidr the model was run for 72 hrs with the initial field at 1800 UTC of 12 November 2007. But after 66 hrs of simulation at 1200 UTC of 15 November 2007 the system attained the stage of highest intensity. The structure of the tropical cyclone Sidr at that stage is discussed below based on model results.

Pressure, wind and vorticity field

The horizontal distribution of pressure field at sea level has been shown in Figure 4a.The figure shows that the isobar has near circular arrangements around the cyclone centre. The contour interval is 3 hPa. Considering the outermost closed isobar, the system's horizontal size is estimated as 5.5 Lon. (600 km) in the east-west direction and 6.2 Lat. (680 km) in the north-south demonstrating a strong spatial asymmetry in its circular structure having an oval shape with elongation in the north-south direction i.e. in the direction of the movement of the cyclone. In the front of the cyclone the isobaric lines are more dense compared to the rear side of the cyclone. The distribution of the sea level pressure along east-west section passing through its centre (20.25^{o}N 88.6^{o}E) has been shown in Figure 4b. The figure demonstrates the strong pressure gradient around the centre with maximum gradient at around 40-50 km from the centre. Thus the radius of the cyclone eye is found to be just lower 40 km according to the simulation.

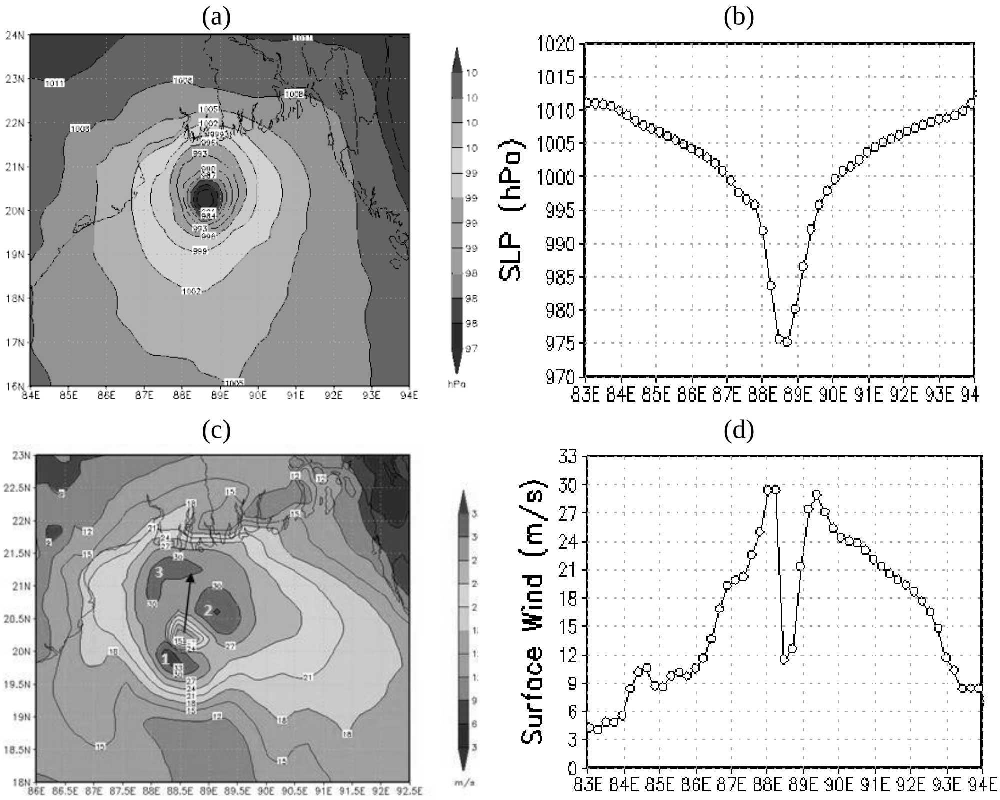

Fig. 4: *(a) Distribution of model simulated SLP (hPa) (b) E-W sectional view of simulated SLP through the centre (20.25^{o}N 88.6^{o}E) (c) Distribution of model simulated surface wind (speed in m/s) (d) E-W sectional view of simulated surface wind through the centre (20.25^{o}N 88.6^{o}E) at mature stage of cyclone Sidr valid for 1200 UTC of 15 November 2007*

The distribution of simulated surface wind (10-m wind) has been shown in Figure 4c. The figure shows that the wind field of the cyclone is highly asymmetric in the horizontal direction. There are 3 areas showing strong wind bands. The strongest wind field (>33 m/s) is found at a distance of around 40 km in the south-southwest of the centre. This field is annotated as '1' in the figure. The next maximum is 76 km in the northeast of the centre. This area is annotated as '2'. The third highest wind field (annotated as '3') is located to the north-northwest of the centre at a distance of around 100 km. It may be noted that the model has generated much lower wind speed (125 km/hr) than the observed which was around 260 km/hr. This low intensity of the model generated wind is probably due to the poorly represented initial field. Figure 4d shows the distribution of the surface wind along east-west section passing through its centre (20.25°N 88.6°E) at the same time. Here the sharp gradient in the vicinity of the centre is evident. The figure demonstrates that a calm region is found at the eye of the system and maximum wind is found in the eyewall. The radius of maximum wind of the cyclone Sidr is found to be around 40 km according to the simulation.

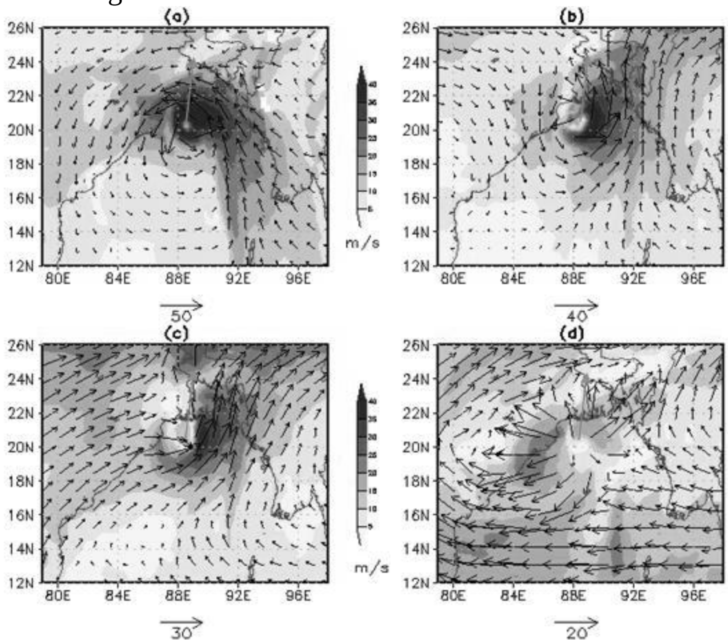

Fig. 5: *Model simulated wind vector and magnitude at (a) 850 hPa (b) 500 hPa (c) 300 hPa (d) 100 hPa level of cyclone Sidr at 1200 UTC of 15 November 2007 (Blue arrow indicates the simulated centre and direction of the system)*

The horizontal distribution of vector and magnitude of the wind field for 850, 500, 300 and 100 hPa has been shown in Figures 5(a-d). The figures show that the cyclonic motion is clear in the 850 and 500 hPa levels having speed 50 m/s and 40 m/s respectively. At 850 hPa the strong wind is observed at the front right side of the moving storm close to the centre. At 500 hPa the strongest wind is found at right side of the cyclone. At 300 hPa the circular distribution of cyclonic wind does no longer exist, but a trough like structure is evident. The strong wind is found to the right side of the cyclonic centre at the ridge axis of the anticyclonic system located east of the cyclone. At 100 hPa level strong outflow is evident from the central part of the cyclone. The strong outflow wind is found in the left side of the cyclonic centre. The figures thus demonstrate inflow in the lower level and outflow in the upper level.

The horizontal distribution of the relative vorticity at 850, 500, 300 and 100 hPa levels has been shown in the Figures 6(a-d). According to the Figure 6a, it is seen that the vorticity is distributed with maximum value in the centre (20.25°N 88.6°E). The distribution maintains near circular pattern with some asymmetric features in the outer periphery. A large band of negative vorticity field is found to the western (i.e. left) side of the cyclone which extends from north-northwest to south. Then another positive vorticity band is found to the western side of this negative band. In 500 hPa, the distribution of relative vorticity shows a highly asymmetric character in the horizontal distribution. The strong vorticity is distributed in a semicircular curved band with curvature along northeast-south-southwest and west. A few bands of negative vorticity is found in the outer periphery of the cyclone. The horizontal distribution of 300 hPa level relative vorticity shows highly asymmetric character of the horizontal field. The strong vorticity is distributed in a large band located within 50-150 km east of the centre of the cyclone. To the western side the field of the positive vorticity is located at a distance of 50-100 km which is followed by a positive and negative vorticity fields. The overall structure of the vorticity field follows a wave distribution with strong positive field in the east-northeast with intermittent negative, positive and negative fields towards west-southwest. In the 100 hPa level the centre of the cyclone indicates negative vorticity while a band of positive vorticity is located to the west and northwest of the centre of cyclone.

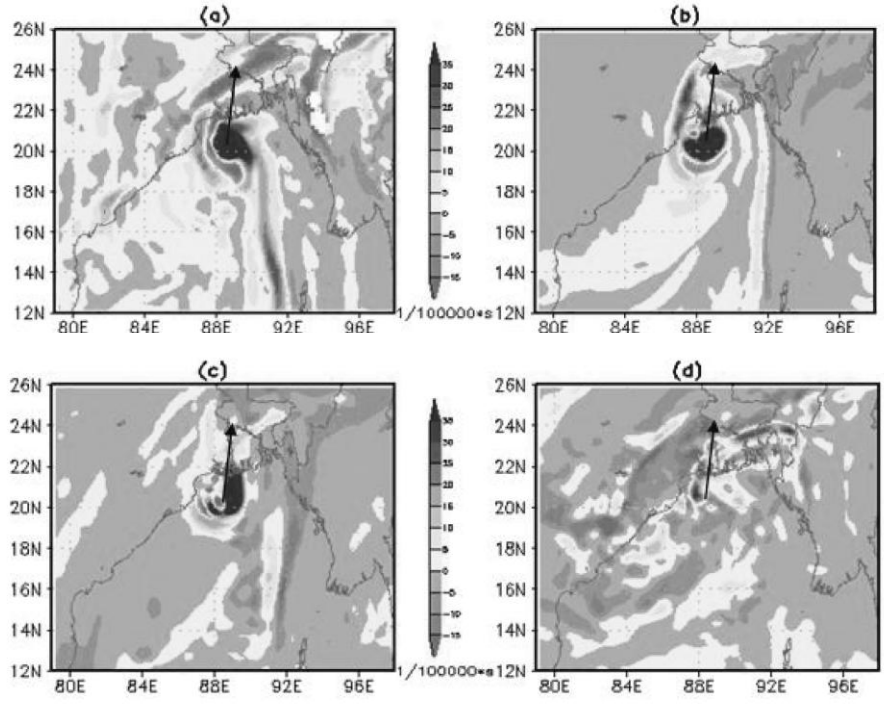

Fig. 6: *Model simulated vorticity field at (a) 850 hPa (b) 500 hPa (c) 300 hPa (d) 100 hPa level of cyclone Sidr at 1200 UTC of 15 November 2007 (Arrow indicates the simulated centre and direction of the system)*

Temperature anomaly and relative humidity

The vertical section of simulated temperature anomaly of Sidr at 1200 UTC of 15 November 2007 is shown in Figure 7a. It is seen that a sharp warm core with 4-5.5^{o}C is observed in 900-250 hPa layer with maximum spread in 400-200 hPa level. The vertical section of relative humidity at the same time is presented in Figure 7b. It is noted that high relative humidity (more than 90%) associated with moisture spreads in outer range of eyewall up to 400 hPa level. Low relative humidity is found at the centre of the system above 900 hPa level. Another high relative humidity band is found in the rain band of the system situated at right side of the eyewall.

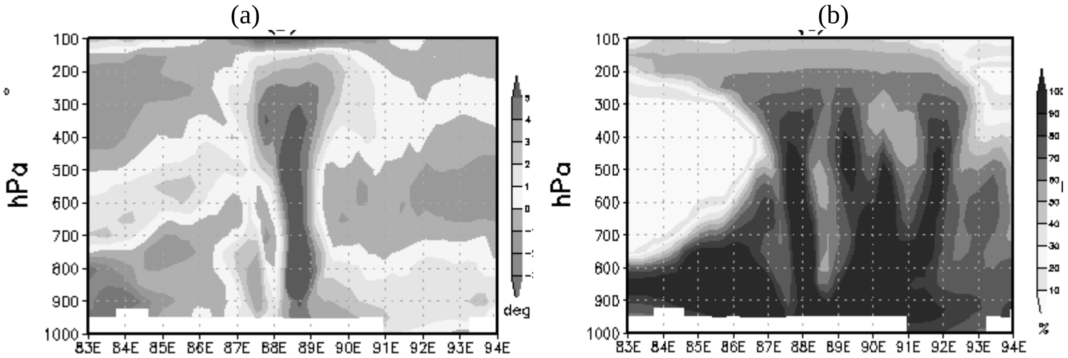

Fig.7: *E-W vertical cross section of (a) temperature anomaly and (b) relative humidity of cyclone Sidr through the centre (20.25^{o}N 88.6^{o}E) at 1200 UTC of 15 November 2007*

Track and landfall prediction

Track forecasting has been a challenging task for meteorologists over the last few decades in spite of the rapid development of numerical weather prediction techniques. Accurate track forecasting is of great importance for disaster management for taking proactive measures to mitigate the damages to life and property.

Table 2 summarizes the predicted average translational speeds of selected tropical cyclone Sidr along with the corresponding observed speeds. The observed average translational speed is calculated for respective model forecast hour (24, 48, 72 and 96 hrs) and also for full observed track. Observed full track average implies that the average translational speed of cyclone Sidr was about 15 km/hr. The table demonstrates that the translational speed of the system increases as it intensifies and moves towards landfall position. It is also found from the table that, the simulated translational speed of Sidr is quite low compared with the actual speed of the system.

Table 2: *Average translational speed of selected tropical cyclone Sidr (2007)*

Initial Date/Time (UTC)	Forecast Hours	Simulated Average Translational Speed (km/hr)	Obs. Translational Speed (km/hr) [Respective Forecast Hours Average]	Obs. Translational Speed (km/hr) [Full Track Average]
12Nov/0600	96	15.0	17.3	15.0
13Nov/0600	72	14.8	20.4	
14Nov/0600	48	15.6	25.4	
14Nov/1800	24	20.1	28.4	

The track forecasts of Sidr (2007) for 96, 72, 48 and 24 hrs based on the initial fields of 0600 UTC of 12 November, 0600 UTC of 13 November, 0600 UTC of 14 November and 1800 UTC of 14 November respectively are shown in Figures 8(a-d). Figures show that model was able to generate northwest, north and northeast movement of the system very well. It reveals that 24 and 48 hrs tracks are closes to the JTWC best track compared to 72 and 96 hrs tracks. The simulated 24 and 48 hrs predictions of landfall points of cyclone Sidr are very close to the observed track. However, there are some errors in the positions with respect to time which shows some lag in landfall. The 72 and 96 hrs predictions in this case showed the storm tracks drifted to the west of the observed track by a distance of 80-90 km but the tracks are found to run parallel showing the direction of motion quite well. The indicated landfall points were consequently in large error (about 120 km to the west).

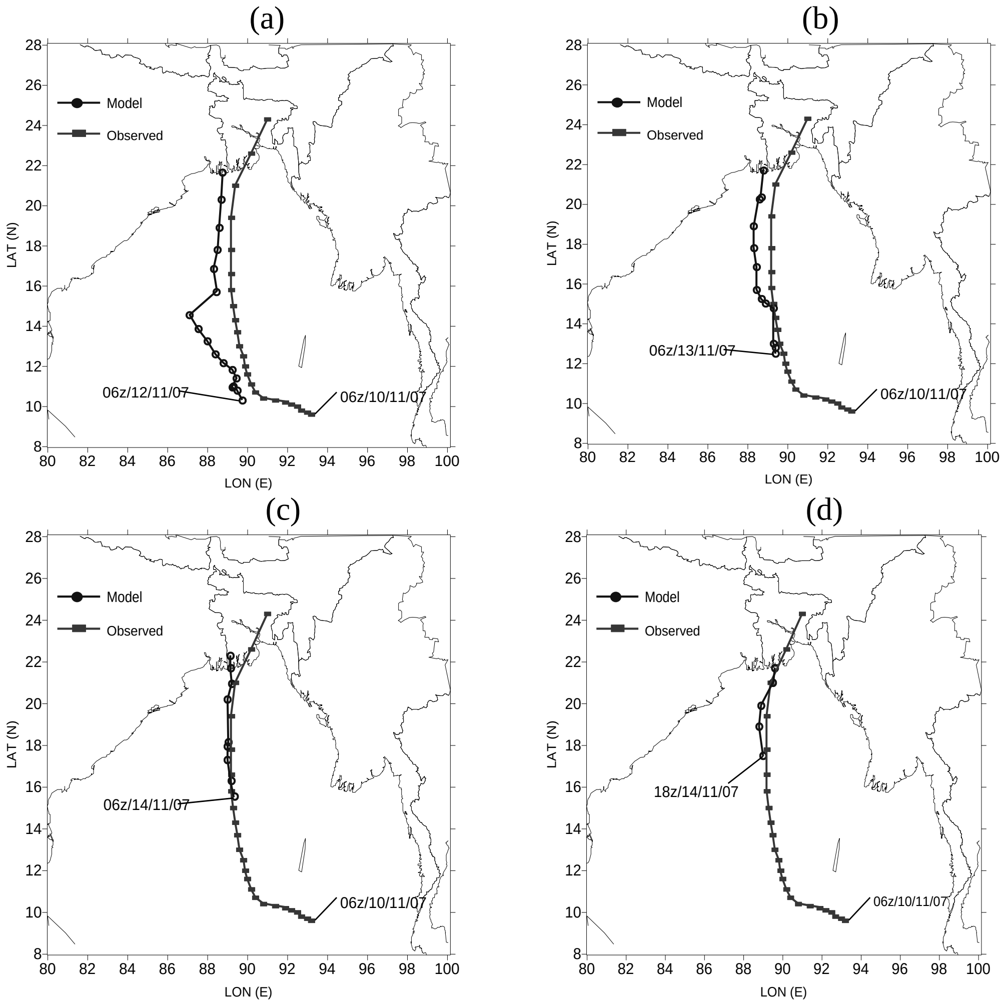

Fig. 8: *Model simulated and observed track of super cyclone Sidr (2007) (a) 96hrs forecast beginning 0600 UTC/12 Nov (b) 72hrs forecast beginning 0600 UTC/13 Nov (c) 48hrs forecast beginning 0600 UTC/14 Nov and (d) 24hrs forecast beginning 1800 UTC/14 Nov*

Table 3: *Landfall point and time error during severe cyclonic storm Sidr (Nov 2007)*

Base Date/Time (UTC)	Forecast Hours	Landfall Forecast		Actual Landfall		Error	
		Position (Lat ^{0}N/ Lon ^{0}E)	Date/Time (UTC)	Position (Lat ^{0}N/ Lon ^{0}E)	Date/Time (UTC)	Distance (km)	Time (hrs)
12/0600	96	21.55/88.7	16/0500	21.83/89.8	15/1600	125w	13 D
13/0600	72	21.55/88.75	16/0300	-do-	-do-	120w	11 D
14/0600	48	21.6/89.1	15/2300	-do-	-do-	81w	7 D
14/1800	24	21.7/89.6	15/1800	-do-	-do-	26w	2 D

Note: D indicates forecast landfall time delayed as compared to actual landfall time. w indicates west of actual landfall position.

As landfall of tropical cyclones is very important to the cyclone forecasters, the landfall position and time errors are investigated for evaluating the model performances. The results are presented in Table 3. The table shows that the 24 and 48 hrs predictions exhibit low landfall position and time errors whereas 72 and 96 hrs predictions have comparatively high landfall position and time errors. It reveals that reducing the prediction hours with updated initial fields reduces the landfall errors. It is noted that the 24 hrs prediction of cyclone Sidr beginning from 1800 UTC of 14 November 2007 has the lowest landfall position error which is only 26 km in the west of actual position with 2 hour delayed landfall. This demonstrates thatthe ARW model has potential to forecast position and time of landfall of the Bay of Bengal cyclone with the certain amount of uncertainty.

Conclusions

From the discussion as given above, the following conclusions are drawn:

i. The ARW model is capable of forecasting the formation of the first low pressure system 36 hrs ahead from its actual genesis without incorporation of any artificial vortex. The model is also capable to forecast the formation of the first depression 78 hrs in advance.

ii. The model successfully simulates the realistic evolution or intensification process of tropical cyclone Sidr. But the model underestimates the intensity of the cyclonic system.

iii. The model generates a realistic structure of the tropical cyclone with high spatial details without use of any idealized vortex in the initial. This has been possible due to the higher spatial resolution of the regional model.

iv. The model has successfully predicted the tracks and probable areas and time of landfall of the selected tropical cyclone with the certain amount of errors.

Acknowledgement

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References

1. Krishnamurti, T.N., and B. J. 1998. Cyclone track prediction. *Sädhanä*, **23**, 653-684.
2. Davis, C.A., and L.F. Bosart. 2001. Numerical simulations of the genesis of Hurricane Diana (1984), Part I: Control simulation. *Mon. Wea. Rev.*,**129**, 1859-1881.
3. Barun, S.A. 2002. A cloud-Resolving simulation of Hurricane Bob (1991): Storm structure and eyewall buoyancy. *Mon. Wea. Rev*., **130**, 1573-1592.
4. Trivedi, D.K., J. Sanjay and S.S. Singh. 2002, Numerical simulation of a super cyclonic storm, Orissa (1999): Impact of initial conditions. *Meteorol. Appl.*, **9**, 367-376.
5. Mohanty, U.C., M. Mandal and S. Raman. 2004. Simulation of Orissa super cyclone (1999) using PSU/NCAR meoscale model. *Natural Hazards*, **31**, 373-390.
6. Prasad, K. (Quadir, D.A. ed.). 2004.Cyclone track prediction experiments with a Quasi-Lagrangian model. *SAARC Meteorological Research Centre (SMRC) Report* No.9, Dhaka, Bangladesh, 72p.
7. Goswami, P., A. Mandal, H.C. Upadhyaya and F. Hourdin. 2006, Advance forecasting of cyclone track over north Indian Ocean using global circulation model. *Mausam,***57(1)**, 111-118.
8. Pattanayak, S. and Mohanty, U. C. 2008. A comparative study on performance of MM5 and WRF models in simulation of tropical cyclones over Indian seas. *Current Science*, **95(7)**, 923-936.
9. Lin, I.-I., C.H. Chen, I.F. Pun, W.T. Liu and C.C. Wu. 2009.Warm ocean anomaly, air sea fluxes, and the rapid intensification of tropical cyclone Nargis (2008). *Geophysical Research Letter*, 36, L03817, doi:10.1029/2008GL035815, p.1-5.
10. Basnayake, B. R. S. B., Akand, M. A. R. and Nesa, F. F. 2010. Structure and movement of tropical cyclones over the North Indian Ocean simulated by WRF-ARW model, *SAARC Meteorological Research Centre (SMRC), Scientific Report* No 33, 42p.
11. Mohanty, U. C., Osuri, K. K. and Pattanayak, S. 2013. A study on high resolution mesoscale modeling systems for simulation of tropical cyclones over the Bay of Bengal. *Mausam*, **64(1)**, 117-134.
12. Skamarock, W.C., J.B. Klemp, J. Dudhia, D.O. Gill, D.M. Barker, M.G. Duda, X.-Y. Huang, W. Wang and J.G. Powers. 2008, *A description of the Advanced Research WRF Version 3. NCAR Technical Notes*, NCAR/TN-475+STR, Boulder, Colorado, USA, 113p.
13. Choudhury, A. M. 2009. Protecting Bangladesh from Natural Disasters, *Academic Press and Publishers Library*, Dhaka, 206p.
14. Joint Typhoon Warning Center (JTWC) best track data. 2010. (Online) available on: *http://www.unso.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/ioindex.html*