

Simulation of Tropical Cyclone ‘Phailin’ Using WRF Modeling System

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1 Introduction

Tropical cyclones (TCs) are one of the most devastating and deadliest meteorological phenomena worldwide. This devastation is mainly due to torrential rains, high winds and associated storm surges (Mohapatra et al. 2012, 2015). The TC genesis has been attributed to both thermodynamic and dynamical factors. Palmen (1948) showed that TCs form over regions where sea surface temperature (SST) is greater than 26 °C. In addition to SST, other important factors for genesis of TCs are: large Coriolis force (LCF), high low-level relative vorticity, weak vertical wind shear, moisture in the middle troposphere and convective instability. In the regions, moist convection dominates the process of transporting mass, energy, and momentum through the atmosphere. On longer timescales, the large-scale environment can influence and control the mesoscale organisation and activities. The long chain of multi-scale interactions of physical parameters is challenging task to handle in the numerical models of weather systems and hence, genesis of TCs is a particular example that has motivated the present study.

Synoptic and statistical methods have limitations in predicting track and intensity beyond 24-h over the North Indian Ocean (NIO; Mohanty and Gupta 1997; Gupta 2006). The Advance Research WRF (ARW) model is being widely used for

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the simulation of a variety of weather events, such as heavy rainfall, TC and real time numerical weather prediction (NWP) over the Indian monsoon region, and indeed globally, (Routray et al. 2010; Osuri et al. 2012). Weather agencies of various nations give forecasts of TC operationally. The high-resolution non-hydrostatic mesoscale atmospheric models are being used for research and operational forecasting of several mesoscale atmospheric phenomena. Various studies are reported on the simulation/prediction of TCs over the NIO (Mohanty et al. 2004, 2010; Osuri et al. 2011, 2012; Bhaskar Rao and Hari Prasad 2006, Srinivas et al. 2010, Osuri et al. 2014). The Bay of Bengal (BOB) is a potentially energetic region for the development of TCs and contributes about 7 % of the global annual storms. It is well known that TCs characteristics drastically change at different stages in the life cycle. Though there have been significant improvement in track and intensity forecast (Mohapatra et al. 2013a, b, c, 2015) still there is scope for improvement in prediction of intensity and motion of TCs especially from deepening period to mature stage and from mature stage to dissipation stage. There has been significant development in the field of TC track simulation for this region using mesoscale models. The models through grid resolution, physical parameterisations, and data assimilation, etc. among all, the physical parameterisations, which includes cumulus convection, surface fluxes of heat, moisture, momentum, and vertical mixing in the planetary boundary layer (PBL) play important role in simulating the development and intensification of TCs. The present study tells about the application of non-hydrostatic nested-grid mesoscale model to precisely simulate the various physical and dynamical processes of the storm environment and its evolution. For this purpose, an attempt is made to simulate the TC Phailin that formed in October 2013 over BOB using the Weather and Research Forecast (WRF) mesoscale model.

2 Description of the Very Severe Cyclonic Storm ‘Phailin’

Phailin is a very severe cyclonic storm (VSCS) formed in the BOB and had a duration of 7 days from 8 October 2013 to 14 October 2013. A low pressure system from north Andaman Sea intensified into depression at 0300 UTC of 8 October 2013 near latitude 12.0° N and longitude 96.0° E (RSMC, New Delhi, 2014). It moved northwestwards and intensified into a deep depression at 0000 UTC of 9 October 2013 near latitude 13.0° N and longitude 93.5° E with the speed of 170 km north-northeast of Port Blair, 1100 km east-southeast of Paradip and 1200 km east-southeast of Visakhapatnam and further intensified into a cyclonic storm, Phailin at 1200 UTC of 9 October 2013. The cyclonic storm continued to move in northwesterly direction and intensified into severe cyclonic storm at 0300 UTC of 10 October 2013 and centred at latitude 14.5° N and longitude 91.5° E intensified into very severe cyclonic storm at 0600 UTC near latitude 15.0° N and longitude 90.5° E of same day. Moving northwestward direction the system further rapidly intensified to 1200 UTC, 1500 UTC and 2100 UTC of 10 October 2013, respectively. The Phailin crossed the area of Odisha and adjoining north Andhra Pradesh coast near Gopalpur

(Odisha) around 22:30 h according to IST of 12 October 2013 with a sustained maximum surface wind speed (MSW) of 200–210 kmph around 1700 UTC near latitude 19.2° N and longitude 84.9° E. The system maintained its intensity of very severe cyclonic storm up to 7 h after landfall and cyclonic storm intensity till 1200 UTC of 13 October 2013, latitude 22.5° N and longitude 83.8° E.

3 Description of the ARW Model and Numerical Experiments

The WRF model (version 3.4, ARW dynamical core) is configured with two interactive nested domains in the present study. A resolution of 27 km and 173×189 grids are for the outer domain (D01) covering a larger region and the inner domain has 9-km resolution with 296×308 grids (D02) covering the BOB and its environments (Fig. 1) with 39 vertical levels. The initial and lateral boundary conditions for the ARW model are obtained from the analysis fields of the US-National Center for Environment Prediction (NCEP), Final Analysis (FNL). The lateral boundary conditions are updated in 6-h intervals with a fixed SST throughout the model integration, with no regional data assimilation used in this study. The land surface boundary conditions are taken from the US Geological Survey with a horizontal grid spacing of 10 min (D01) and 5 min (D02). The physics schemes used in the present study are Yonsei University (Hong et al. 2006), non-local diffusion scheme for PBL processes, Kain–Fritsch for cumulus convection (Kain and Fritsch 1993), Purde Lin scheme (Lin et al. 1983) for explicit moisture processes, five-layer soil thermal diffusion model for surface processes, Rapid Radiation Transfer Model (RRTM) for long-wave radiation (Mlawer et al. 1997) and Dudhia (1989) scheme for shortwave radiation. The TC Phailin is simulated with a total of five different initial conditions through 12-h cycles. The TC is initialised at 00 and 12 UTC between 00 UTC of 09–11 October 2013 (named as Case-1 to Case-5, respectively) and forecasted upto 12 UTC 13 October 2013.

4 Result and Discussion

4.1 Intensity Prediction of TC

The evolution of intensity at 12-h interval of the TC from Case-1 (IC: 00UTC 09 October 2013) is shown in Fig. 2a, b in terms of mean sea level pressure (MSLP) (hPa) and surface wind at 10 m (m/s) respectively from D01 and D02 simulations. The root mean square errors (RMSE) and standard deviation (Std. Dev.) of MSLP and 10 m surface wind from all the five ICs alongwith the mean of 5 simulations are represented in Fig. 2c, d.

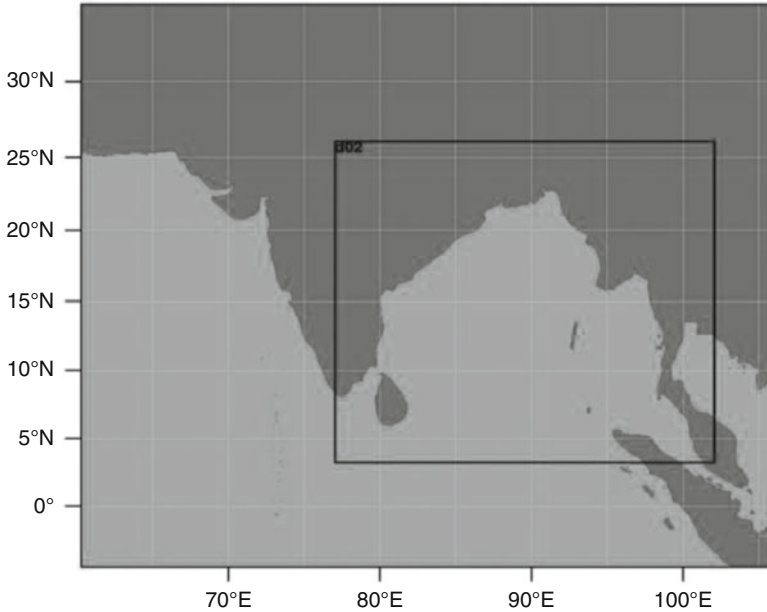


Fig. 1 Model domain considered in the study

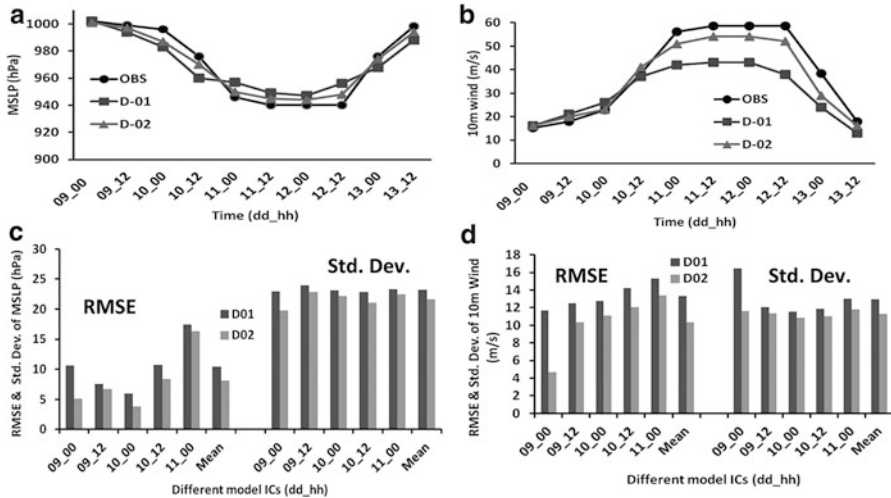


Fig. 2 Evolution of intensity with time (12-h interval) for (a) MSLP (hPa); (b) 10 m wind (m/s) from Case-1 (IC: 00UTC 09 October 2013). (c–d) same as (a–b) but for mean RMSE and standard deviation (Std. Dev.) from different model ICs

Table 1 Mean absolute errors (MAE) of MSLP (hPa) and 10 m surface wind (m/s)

Forecast length (h)	MAE of MSLP (hPa)		MAE of 10 m wind (m/s)		No. of f/c verified
	D01	D02	D01	D02	
00	14	12.2	6.74	5.54	5
12	9	6.4	10.27	9.06	5
24	7.4	6	10.51	7.67	5
36	4.4	1.8	11.66	9.56	5
48	5.2	2.8	13.03	9.83	5
60	6.6	4.6	12.31	8.31	5
72	8	5	13.35	9.09	5
Mean	7.8	5.5	11.12	8.44	4

Both the experiments simulate strong TCs in terms of MSLP in the case of VSCS Phailin (Fig. 2a). The trend of the evolution of the intensity of the storm in the D02 simulation is closer to the IMD observed trend as compared to the D01 simulation. The 10 m surface wind (Fig. 2b) is well simulated in the D02 during the intensity period of the TC which is not depicted in the D01 simulation. Similar results are also found in all cases when the model is initialised with different ICs. It is also clearly noticed from Fig. 2c, d, the RMSE and Std. Dev. of MSLP and 10 m wind are less in the D02 simulation for all the cases. The mean RMSE and Std. Dev. of MSLP (8.06 and 21.65 hPa) and 10 m wind (10.37 and 11.32 m/s) are significantly improved in the D02 simulations as compared to the D01 simulations (MSLP: 10.46 and 23.24 hPa; 10 m wind: 13.30 and 12.97 m/s, respectively).

The mean absolute errors of MSLP and 10 m wind at different forecast time as based on five cases are provided in Table 1. It is clearly seen from the Table 1 that the high resolution model simulations (D02) capture well the intensity of the TC throughout the forecast period as compared to the D01 simulations. The mean absolute errors of MSLP and 10 m wind are reduced by 29 % and 24 % in the D02 runs over the D01 runs.

4.2 Track Prediction

Figure 3a, b illustrates the model simulated (D01 and D02) storm tracks (location of minimum MSLP centre) along with IMD best track from five model ICs. The mean vector displacement errors (VDEs) 12-h interval and gain skill score (% of improvement) with respect to the D01 & D02 TC is depicted in Fig. 3c. It is clearly seen from the figure that the simulated tracks in D02 simulations (Fig. 3b) are reasonably better and closer to the IMD observed track as compared to the D01 simulation (Fig. 3a) in all IC cases. The mean VDEs (Fig. 3c) are significantly reduced in the high resolution model simulations (D02) as compared to the D01 simulations. The mean VDEs are gradually increased along with the increase of the forecast hours in all simulations, however the values of the VDEs are less in the

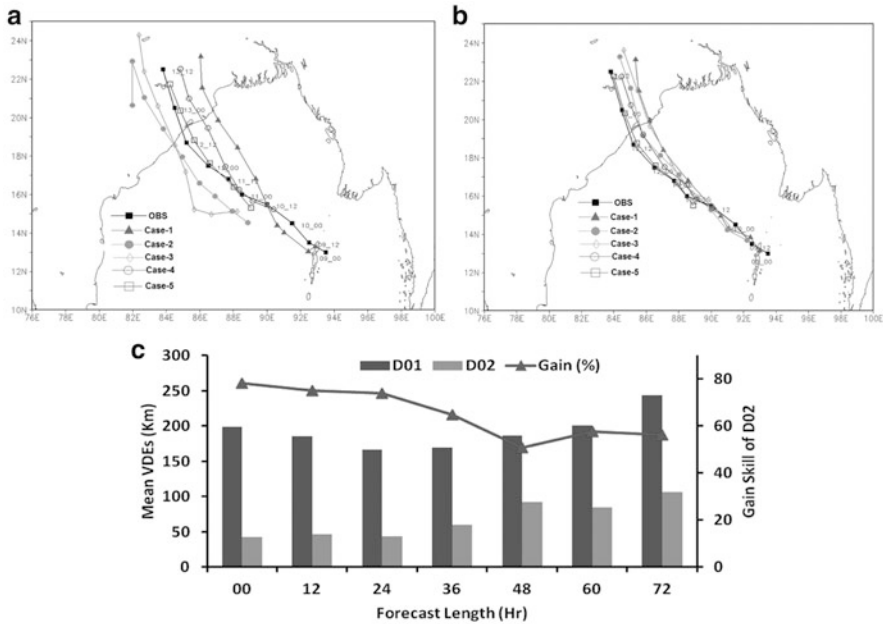


Fig. 3 Model simulated tracks from (a) D01 and (b) D02. (c) Mean vector displacement errors (VDEs, km) in 12 hr interval from different model initial conditions (histograms) and the gain in skill (%) of D02 over D01

D02 as compared to the D01 simulation. The mean VDEs at different forecast hours are varies in the range of 43–107 km in D02 as compared to 266–243 km in D01 runs. The ensemble mean (averaged all forecast hours) VDEs are also less in the D02 simulation in comparison to the other simulation.

The skill of the D02 is significantly higher compared to that of the D01 simulation. The gain in skill of the D02 simulation (with respect to D01) ranged from 51 to 78 % throughout forecast period. Thus, the mean gain in skill of the D02 simulation is about 65 % over the D01. The gain in skill of D02 is gradually decreased as forecast length increased. The model characterised more realistic meso-convective features embedded within the large-scale environmental field IN D02 case due to increase of horizontal resolution, which leads to improved model forecasts.

The landfall (LF) position and time errors are provided in Table 2 from D01 and D02 simulation covering the different initial conditions. The LF position errors are significantly reduced in the D02 simulations as compared to the D01 simulations. The LF position errors are reduced by 24 % in the D02 simulation with respect to D01 runs. The error at the time of landfall is not exactly simulated by any of the runs, however, the landfall time error of the storm is less in the D02 simulation (Table 2) as compared to the D01 run.

Table 2 Landfall point errors (km) and time errors (hours) from D01 and D02

Different ICs (October 2013)	Observed LF time	LF position errors (km)		LF time errors (hours) +/- sign represents ahead/delay in time	
		D01	D02	D01	D02
00 UTC 09th (Case-1)	17 UTC 12 October 2013	375.88	158.23	+02 (15 UTC 12 October 2013)	+05 (12 UTC 12 October 2013)
12 UTC 09th (Case-2)		156.38	98.88	-01 (18 UTC 12 October 2013)	+02 (15 UTC 12 October 2013)
00 UTC 10th (Case-3)		102.34	180.56	+17 (00 UTC 12 October 2013)	+05 (12 UTC 12 October 2013)
12 UTC 10th (Case-4)		302.99	240.82	+02 (15 UTC 12 October 2013)	+02 (15 UTC 12 October 2013)
00 UTC 11th (Case-5)		224.02	203.66	-01 (18 UTC 12 October 2013)	+02 (15 UTC 12 October 2013)
Mean position errors (% of Improvements)		232.32	176.43 (24%)		

4.3 Reflectivity

The simulated cloud band structure of the TC from different simulations is analysed at 06 UTC 12th and landfall time corresponding to 12 UTC 12 October 2013 using simulated radar reflectivity from D01 to D02 respectively and compared with India Meteorological Department (IMD) Visakhapatnam Doppler Radar reflectivity (Fig. 4a–f). Both the simulations show a comma cloud organisation around the TC. The reflectivity pattern as well as intensity obtained from D02 is close to the IMD Visakhapatnam Doppler Radar reflectivity. However, the distribution and intensity are not well simulated in D01. During the landfall time, the D02 (Fig. 4f) well simulated the reflectivity, but the D01 simulation shows away from coast. The structure is well matched with the observed reflectivity (Fig. 4d).

5 Conclusion

This study is aimed at assessing the performance of the non-hydrostatic model WRF-ARW with nested domain for simulation of VSCS Phailin over BOB. For this purpose, the model is integrated with 27 km (D01) and 09 km (D02) horizontal resolutions with five different model ICs using FNL analyses as initial and boundary conditions. The broad conclusions drawn are given as follows.

The intensity of the TC in terms of MSLP and 10 m surface wind is well simulated in the D02 as compared to the D01 simulation. The magnitude of 10 m

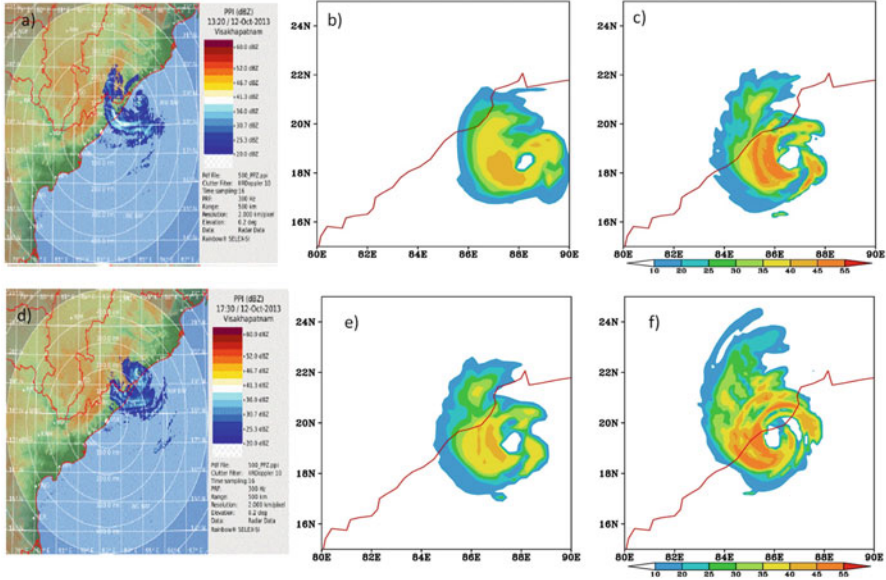


Fig. 4 Reflectivity (dBz) from observation (IMD Visakhapatnam Doppler radar) and model simulations (a) Observed, (b) D01 and (c) D02 valid at 06 UTC of 12th October 2013 (78 h forecast) (d–f) are same as (a–c) but at landfall time

surface wind is not well simulated in the D01 during intensification of TC as compared to observed. The mean RMSE and standard deviations of MSLP and 10 m surface wind is reasonably less in D02 simulation as compared to the D01 simulations with different ICs. Similarly, the absolute errors are less in D02 run in different forecast hours.

The track of the TC is well confined with IMD best track in the D02 simulations as compared to the D01 simulations. The mean VDEs are significantly reduced in the D02 simulation throughout the forecast hours compared to the error from D01 run. The ensemble mean (averaged all forecast hours) VDEs are also less in the D02 simulation in comparison to the other simulation. The landfall position and time errors are significantly reduced in D02 simulation in comparison with D01 simulation.

The skill of the D02 is significantly higher compared to that of the D01 simulation. The gain in skill of the D02 simulation (with respect to D01) ranged from 51 to 78 % throughout forecast period. Thus, the mean gain in skill of the D02 simulation is about 65 % over the D01. The gain in skill of D02 is gradually decreased as forecast length increased the landfall of TC is delayed around 3 h in D01 simulation.

The intensity and spatial distribution of the reflectivity (dBz) is well simulated in the D02 simulation mainly in the landfall time which is comparable with observed reflectivity obtained from IMD Visakhapatnam DWR. The features are not simulated in the D01.

This study concludes that the model WRF framework with the increased resolution has a positive impact in the prediction of cyclonic storms. However, to further support this conclusion, more TC case studies and also assimilation of observations from different platforms are required.

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