Performance Evaluation of WRF (NMM) model for selected Tropical Cyclones over Bay of Bengal and Arabian Sea

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ABSTRACT

In this paper, performance of WRF (NMM) model was evaluated for tracks of some selected cyclones over the North Indian Ocean (NIO) region. The model was run at the resolution of 27 km for forecast up to 72 hours with the use of NCEP FNL data sets as the initial and boundary conditions. The study includes total 106 sets of initial and boundary conditions for the 19 cyclone episodes which occurred during the period from 2004 to 2010. Verification is carried out against the observed best track of cyclone as reported by India Meteorological Department (IMD). The forecast track errors for the NIO were less than 150 km for 12 hours to 24 hours forecasts; errors were between 150 km -250 km for 36 hours to 48 hours forecasts and errors were between 250 - 300 km for 60 hours to 72 hours forecasts. The model shows westward bias during first 36 hours forecast and then eastward bias during 48 hours to 72 hours forecast. It shows northward bias at all forecast hours. During the post-monsoon season, model showed faster west-ward track in the first 48 hours forecast and then eastward bias in the 60 hours to 72 hours forecast. During pre-monsoon season it shows north and west ward bias in the first 36 hours forecast and in the subsequent forecast hours it shows eastward bias. For the northeast recurvature cyclones, track errors were between 100 km to 150 km for 12 hours to 24 hours forecast and in the range 200 km to 300 km for 36 hours to 48 hours forecast. The track errors were greater than 300 km for 60 km to 72 hours. For the southwest recurvature cyclones, the track errors were between 250 km to 550 km for forecast up to 72 hours. Performance of the model was better than the CLIPER technique.

Key words: *WRF-NMM, Cyclone track prediction, North Indian Ocean, Forecast verification.*

1. Introduction

Tropical cyclones are one of the most important disastrous weather phenomena that affect large area and population. Accurate forecasts of their formation, movement and intensity were crucial for the early warning systems in the maritime regions along the coast. Application of dynamical models in the tropical cyclone prediction problems has been a subject of extensive study by the NWP community the world over. During past three decades there had been rapid developments in the field of the Numerical Weather Prediction (NWP), where several operational centers were utilizing high resolution global and regional models for tropical cyclone prediction. There had been rapid improvement in the quality of observations (especially the satellite and radar data) and improved understanding of physical processes and mechanisms that govern the motion of tropical cyclones. Though the skill of numerical models has greatly improved, accurate forecasting of tropical cyclone tracks and intensity by the models was still beset with problems.

The cyclonic disturbances in the North Indian Ocean (NIO), mainly move along westward/ northwestward direction, while some cyclonic disturbances recurve from an initial northwestward direction to a northward direction (often after reaching 15^{o}–20^{o}N latitude) and finally towards northeastward direction (IMD, 1996). These tracks of movement are dependent on many factors including the prevailing upper air environmental flow over the cyclone region (IMD, 2003).

The main objective of this paper is to investigate the performance statistics of WRF (NMM) for cyclone track prediction of selected cyclones for the period from 2004 to 2010. The evaluation was based upon comparisons between observed track and the track forecasts of cyclones simulated by WRF (NMM) for cyclones over the Bay of Bengal (BOB) and Arabian Sea (AS). Data and methodology used for the verifications are described in Section 2. Section 3 gives the model description and results of the study are discussed in Section 4. Finally, concluding remarks are given in Section 5.

1. Data and Methodology

19 tropical cyclones were selected that formed over the BOB and AS during the years from 2004 to 2010 for this study. The cyclones and dates of model integration were selected as per availability of data based on the initial conditions and boundary conditions (Table 1). The observed best track of these cyclones was obtained from Annual Cyclone Report of IMD. The freely available NCEP-reanalysis datasets that were available at 6 hourly intervals were used as initial and boundary conditions to run the model in this study.

Performance parameters computed for the validation exercise were:

- Direct position errors: This is the measure of distance between the forecast position and the observed position.
- Zonal (latitudinal) biases (DX): This is the positional error in North-South direction. It is positive when the forecast position was to the north of the observed position.
- Meridional (longitudinal) biases (DY): This is the positional error in East-West direction. It is positive when the forecast position is to the west of the observed position.

In order to compare and evaluate forecast quality, CLIPER (linking climatology and persistence) model was chosen as the reference model. The gain in skill in relation to CLIPER was quantified in percentage terms by;

Gain in skill = [(CLIPER DPE - DPE) / CLIPER DPE] x 100%

Positive skill indicates the model forecast was better than CLIPER. Negative skill indicates the CLIPER forecast was better than the model.

2. Model Description

Weather Research Forecast (WRF) – Non hydrostatic Mesoscale Model (NMM) (version 3.0) developed by the National Oceanic and Atmospheric Administration (NOAA)/ NCEP was designed to be flexible, that was portable and efficient on available parallel computing platforms. This model has the choice of convection, planetary boundary layer and radiation parameterization and microphysics schemes. The model physics options chosen for the present study were: GFDL longwave and shortwave radiation scheme (Lacis and Hansen, 1974), Monin-Obukhov surface layer scheme (Monin and Obukhov, 1954), Kain-Fritsch cumulus parameterization scheme (Kain-Fritsch, 1993), Mellor-Yamada-Janjic planetary boundary layer scheme (Mellor and Yamada, 1982) and microphysics after Ferrier et.al. (2002), as given in the Table 2. The schemes have been selected with intution depending on the different studies available and performances randomly checking with different schemes. Sensitivity experiments were conducted to study the role of the parameterisation schemes of convection, planetary boundary layer and explicit moisture schemes. The results indicate that convective processes play an important role in the cyclone track prediction and the scheme of Kain-Fritsch produces the best track and the planetary boundary layer processes control the intensification with the scheme of Mellor-Yamada producing the strongest cyclone. The mixed-phase scheme in combination with Kain-Fritsch and Mellor-Yamada produce the best simulation in terms of the track as well as intensification (Bhaskar Rao et. al. 1999). In numerical study heavy rainfall events were better represented by Kain-Fritsch (KF) scheme than Betts-Miller-Janjic (BMJ) and Grell-Deveneyi (GD) schemes (Bhanu Kumar et.al. 2012).

The model was configured for a single static domain covering the region 15^0S latitude to 40^0N latitude and 50^0E longitude to 110^0E longitude with a grid spacing of 27 km and time step of 60 seconds. A hybrid coordinate system with sigma levels upto 420 hPa (24 levels) and pressure levels from 420 hPa to 10hPa (14 levels); total 38 levels were used for vertical discretization. The top of the model was at about 10 hPa. Model equations in the terrain following sigma co-ordinate were written in flux form and solved in Arakawa E grid. Implicit time integration scheme with time splitting technique was used in model integration.

Table 1 presents a brief description of the 19 selected Tropical Cyclones for which the initial and boundary conditions were available. Initial conditions used for model run, starting from depression stage to the point of landfall dissipation. The model was run using 106 sets of initial and boundary conditions for the 19 cyclones.

WRF-NMM model was run with 27km resolution domain as cyclone being a synoptic scale system, 27km was chosen that would be sufficient to capture the cyclones features. The computational time would be reasonable for 27km resolution as compared to 3km resolution domain. 3km resolution requires large computational time for entire the domain that would be more cost effective.

4. Results and Discussion

Table 1 presents a brief description of the cyclones in the present study, their movement, intensity, initial conditions used for model run, starting from depression stage to the point of landfall/ dissipation. The 12 hourly predicted cyclone tracks were determined objectively from the respective mean sea level pressure fields using a cyclone tracking software. The mean track position errors and the latitudinal/longitudinal biases were computed from the best track positions as reported by IMD. The best tracks of the cyclones selected for the present study were given in the Figure 1. The performance results of the study were discussed below:

Out of the 19 cyclones (as shown in Figure 1) in the NIO, eight cyclones (FANOOS, SIDR, NISHA, KHAIMUK, RASHMI, AILA, LAILA and JAL) that formed over Bay of Bengal moved either northward or northwestward and five cyclones (MALA, NARGIS AKASH, GIRI, BIJLI) showed north-east recurvature and WARD cyclone had southwest recurvature over the Bay of Bengal. Four cyclones namely GONU, AGNI, PHYAN, PHET formed over the Arabian Sea.

4.1. Mean Track Errors

4.1.1 Basin-wise errors

The mean track position errors, latitudinal and longitudinal biases, gain/loss of skill for 12 hourly forecasts of 19 cyclones were given in Table 3. The mean forecast track position errors were 115 km, 142 km, 176 km, 211 km, 256 km and 279 km for the forecasts at 12 hours, 24 hours, 36 hours, 48 hours, 60 hours and 72 hours respectively. The forecast track errors were less than 150 km for 12 hours to 24 hours forecasts; forecast errors were between 150 km - 250 km for 36 hours to 48 hours forecasts and the errors were between 250 km - 300 km for 60 hours to 72 hours forecasts.

The mean track position errors for the Bay of Bengal cyclones were computed for 15 cyclones, which were given in Table 3. In this case, model was run for 15 cyclones with 78 initial conditions. The forecast track position errors were 128 km, 152 km, 202 km, 243 km, 317 km and 315 km for 12 hour, 24 hour, 36 hour, 48 hour, 60 hour and 72 hour respectively. The forecast track errors was less than 150 km for 12 hours forecast; between 150 km - 250 km for 24 hours and 48 hours forecasts and errors were between 300 km - 350 km for 60 hours and 72 hours forecasts.

The mean track position errors for the Arabian Sea cyclones were computed for 4 cases with 29 different initial conditions as given in Table 3**.** The mean track positions errors were 94 km, 151 km, 187 km, 240 km, 275 km and 357 km for forecasts at 12 hours, 24 hours, 36 hours, 48 hours, 60 hours and 72 hours. The forecast track errors was less than 100 km for 12 hours to 24 hours forecast; errors were between 150 km - 250 km for 24 hours to 48 hours forecast and errors lie between 250 km - 350 km for 60 hours to 72 hours forecasts.

The mean latitudinal biases were found to be 24 km, 25 km, 46 km, 72 km, 81 km and 12 km for the forecasts at 12 hours, 24 hours, 36 hours, 48 hours, 60 hours and 72 hours respectively (Fig. 2). The values of the mean latitudinal biases indicate that the forecast has the northward bias. The mean longitudinal biases were 11 km, 19 km, 12 km indicate westward bias during 12 hours, 24 hours and 36 hours forecast and -10 km, -50 km, -36 km for 48 hours, 60 hours and 72 hours respectively (Fig. 5). The model shows westward bias during first 36 hours forecast and then eastward bias during 48 hours to 72 hours forecasts.

The mean latitudinal biases for 15 cyclone cases in BOB with 78 initial conditions was found to be 19 km, 24 km, 45 km, 73 km, 84 km, 47 km for the forecasts at 12 hour , 24 hour, 36 hour, 48 hour, 60 hour and 72 hour respectively, as given in Fig. 2. The values of the mean latitudinal biases for the Bay of Bengal also indicate that all the forecast positions have northward biases. The mean longitudinal biases were found to be 8 km, 4 km, 10 km, -4 km, -12 km, -85 km for the forecasts at 12 hours, 24 hours, 36 hours, 48 hours, 60 hours and 72 hours respectively (Table 4). The values of the mean longitudinal biases over the Bay of Bengal indicate that the model has the westward bias for the forecast up to 36 hours and then it shows eastward bias.

The mean latitudinal biases in AS were found to be 41 km, 30 km, 50 km, 67 km, 70 km, -11 km for forecasts at 12 hours, 24 hours, 36 hours, 48 hours, 60 hours and 72 hours respectively, as shown in Fig 2. The values of the mean latitudinal biases for the Arabian Sea area indicate that the forecast position lies to the northward of the observed position for the forecasts up to 60 hours and then it shows southward bias at 72 hour forecast. The mean longitudinal biases were 35 km, 79 km, 103 km, 121 km, 126 km, 76 km for the forecasts from12 hours to 72 hours respectively, as shown in Fig 3. The result indicates model has the westward bias at all forecast hours.

The gain/loss skills for the three regions namely, NIO, BOB and AS were shown in the Fig 4. For the entire NIO, the gain in skill was 7%, 36%, 37%, 39%, 44% and 37 % at 12 hours, 24 hours, 36 hours, 48 hours, 60 hours and at 72 hours forecasts respectively. The skill gain was 5%, 32%, 31%, 38%, 45% and 37% from12 hours to 72 hours forecast over the BOB. The skill gain was 17%, 50%, 56%, 42%, 41%, 37% at 12 hours, 24 hours, 36 hours, 48 hours, 60 hours and at 72 hours forecast over the AS respectively. The positive values of skill, which were computed against the CLIPER direct positional errors (DPE), indicate that the model has better skill over the CLIPER forecast over NIO (BOB and AS). The model performance was much better at 60 hours, followed by 48 hours, 36 hours and 24 hours. The performance of the model was less at 12 hour forecast compared to other forecast hours. Skill may be low due to spinup problem in the first 12 hours. Some studies showed model spin-up during the first 18-24 hours model integration lead to faster intensification than that of the real atmosphere, thus weaker initial vortex evolved more realistically (Srinivas and Bhaskar Rao 2014).

4.1.2 Seasonal variations

The cyclones over the NIO generally form during two seasons namely pre-monsoon (April-May) and post-monsoon (October, November and December). Cyclones formed during post-monsoon and pre-monsoon were considered for study. The frequency of the cyclones during post-monsoon season was more compared to pre-monsoon. Mean track positional errors, latitudinal and longitudinal biases and gain/loss in the skill thus computed for each of the season were discussed here. During post-monsoon season, the mean track position errors for the cyclones during the post monsoon season were computed for 10 cyclones with 58 sets of initial conditions (Table 4). The mean track errors were found to be 115km, 149 km, 196 km, 205 km, 241 km and 252 km for the forecasts from 12 to 72 hours respectively. The forecast track errors were less than 150 km for 12 hours to 24 hour forecasts; errors were between 150 km - 250 km for 36 hours to 48 hours forecasts and between 250 km - 350 km for 60 hours to 72 hours forecasts. The mean latitudinal biases were found to be 23 km, 33 km, 52 km, 106 km, 116 km, 67 km for the forecasts of 12 hours, 24 hours, 36 hours, 48 hours, 60 hours and 72 hours respectively, as given in Fig. 3. The mean longitudinal biases thus computed for the post monsoon season were 18 km, 32 km, 24 km at 12 hours, 24 hours, 36 hours and 4 km, -54 km and -57 km at 48 hours, 60 hours and 72 hours respectively. The results show that the model has the northward biases at all forecast hours. It showed westward bias for the forecast up to 48 hours and then eastward bias for the forecasts at 60 hours to 72 hours.

During pre-monsoon season, the mean track position errors for the cyclones that formed during the pre monsoon season either in the BOB and AS were thus computed for 8 cyclones with 48 initial conditions (Table 4). The forecast mean track errors were found to be 104 km, 122 km, 152 km, 182 km, 236 km, 275 km for the forecasts at 12 hours to 72 hours respectively. The forecast track errors were less than 150 km for 12 hours to 24 hours forecast; errors were 150 km to 250 km for 24 hours to 60 hours forecasts and between 250 km – 300 km for 72 hours forecast respectively. The mean latitudinal biases were 15 km, -2 km, 9 km, 32 km, 51 km, -31 km for forecasts at 12 hours to 72 hours respectively, as given in Fig. 3. The results show northward biases for all the forecast hours except at 24 hours forecast. The mean longitudinal biases were 16 km, 21 km, 32 km, -25 km, -47 km, 18 km for forecasts at 12 hours, 24 hours, 36 hours, 48 hours, 60 hours and 72 hours respectively as shown in Fig. 6. The model showed the eastward bias for the 48 hours and 60 hours forecast, otherwise it showed westward bias. During the post monsoon season the skill gain was 23%, 39%, 27%, 26%, 23% and 1 % at 12 hours, 24 hours, 36 hours, 48 hours, 60 hours and 72 hours forecasts respectively and the skill gain was 2%, 48%, 52%, 52%, 48% and 46% at 12 hour, 24 hour, 36 hour, 48 hour, 60 hour and 72 hour forecast respectively for pre-monsoon season (Fig 5). The above skill gain indicates that the model forecast was of better accuracy than the CLIPER forecast both during the post-monsoon as well as pre-monsoon season.

4.1.3 Variations with respect to their recurvature

Variations in the forecast track errors with respect to the northeast (NE) and southwest (SW) recurvature were given in the Table 5. The mean track errors of the northeast recurvature cyclones range between 110 km and 360 km for 12 hours to 72 hours forecast period. The forecast track error of the cyclone WARD had southwest recurvature. The errors thus analyzed for the WARD cyclone show that the track errors lie in range of 250 km to 350 km for 12 hour to 36 hours forecasts and range between 450 km to 550 km for 48 hours to 72 hours forecasts. The results of the recurving cyclones indicate that the northeast recurved cyclones have less track errors than the southwest recurved cyclones. The track errors of the northeast recurvature lies between 100 km - 150 km for 12 hours and 24 hours and lie in the range 200 km - 300 km for 36 hours and 48 hours forecasts. The track errors were greater than 300 km for 60 hours to 72 hours forecasts. The southwest recurving cyclone has track errors ranged from 250 km - 550 km. Skill scores for the recurvature of the cyclones was shown in Fig.6. The northeast moving cyclones showed better skill as compared to the southwest recurved cyclones. But many more cyclones to be considered and separate study may be done for understanding the movement of recurved cyclones.

4.1.4 Variations with respect to the intensity of the cyclone at the initial conditions

Variations in the forecast track errors with respect to the initial conditions based on the intensity (depression, cyclone, severe cyclone and very severe cyclone stages) were given in the Table 6. In case of depression the mean track errors were 165 km, 189 km, 211 km, 324 km, 320 km and 381 km, 141 km, 188 km, 250 km, 268 km, 279 km and 390 km for cyclone stage; 110 km, 144 km, 180 km, 244 km, 424 km and 612 km for severe cyclonic storm stage; 109 km, 157 km, 243 km, 354 km, 517 km and 359 km at 12 hour, 24 hour, 36 hour, 48 hour, 60 hour and 72 hour respectively for very severe cyclonic storm. Thus the mean track errors were found to be better at more intense stages (SCS and VSCS) as compared to low intensity stages (D and CS). Skill scores (Fig. 7) showed the skill is very less at initial 12 hours forecast as compared to the other forecast periods (24hours to 72 hours). However, the skill was good for all the four intensity stages until 48 hours. But the skill shows the forecast with initial conditions of the higher intensity cyclones(SCS and VSCS) showed better performance when compared to the forecast with initial conditions of lower intensity cyclones(D and CS).

4.1.5 Interannual variations

Year-wise performance of the model was shown in Fig 8. The track errors thus showed that these mean track errors from 12 hour to 72 hour have increased (on average 120km to 320km). It was also noticed that the track errors were found to less during 2010 when compared to the track errors of the other years. This may due to the differences in the initial conditions and their movement of cyclones. The better performance during recent year 2010 may be due to improvement of initial conditions. Years with recurved cyclones showed large errors. However, the recurving of the cyclones need to be forecasted better and may study with higher resolution of 3km.

5. Conclusions

In this paper, performance of WRF (NMM) model was evaluated for tropical cyclone track prediction over the NIO. The model was run at the horizontal resolution of 27 km and 38 vertical levels for the forecast up to 72 hours with the use of NCEP FNL data sets as the initial and boundary conditions. The model was run with the available initial and boundary conditions for the selected 19 cyclone with different categories, which occurred during the period from 2004 to 2010 over the NIO. The dataset of observed best track of cyclone as tabulated was used for computation of various performance parameters namely, direct position errors, latitudinal /longitudinal biases and gain/loss of skill (against CLIPER). Following inferences are made:

i) The forecast track errors for the NIO were less than 150 km for 12 hours to 24 hours forecasts; errors were between 150 km - 250 km for 36 hours to 48 hours forecasts and errors were between 250 - 300 km for 60 hours to72 hours forecasts. The model shows westward bias during first 36 hours forecast and then westward bias during 48 hours to 72 hours forecast. It has north ward bias at all forecast hours.

ii) During the post-monsoon season, model shows west-ward bias in the first 48 hours forecast and eastward bias in the 60 hours to 72 hours forecast. During pre-monsoon season it shows north and west ward bias in the first 36 hours forecast and in the subsequent forecast hours it shows eastward bias. The biases were more over Arabian Sea compared to the Bay of Bengal and NIO.

iii) For the northeast recurvature cyclones, track errors were between 100 km to 150 km for 12 hours to 24 hours forecast and in the range 200 km to 300 km for 36 hours to 48 hours forecast. The track errors were greater than 300 km for 60 km to 72 hour. For the southwest recurvature cyclones, the track errors were between 250 km to 550 km for the forecast up to 72 hours. Northeast recurved cyclones have less track errors than the southwest recurved cyclones.

iv) The mean track errors were found to be less with intial conditions of more intense stages (SCS and VSCS) as compared to the intial conditions of less intense stages (D and CS).

v) Interannual variations of the mean track errors showed improvement in performance during 2010 cyclones, which may be due to improve initial conditions. However, this shows the recurving of cyclones may have influenced the efficiency of track forecast during past years and need to be further studied with higher resolution.

vi) Skill scores thus obtained from the comparison with CLIPER technique showed performance of the model had better performance.

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Table.1: Brief description of cyclones selected during 2004 to 2010

Cyclone	Date	Movement	Landfall	Time of Initial conditions used for model run
Very Severe cyclonic storm over the Bay of Bengal	May 16-19, 2004	Northwestwards /further moved northeastwards	crossed Myanmar coast north of Aakyab between 0400 UTC and 0500 UTC of 19 May	1200 UTC of 16 May, 0000 UTC and 1200 UTC of May 17-19, 2004
Severe cyclonic storm 'AGNI' over Arabian Sea	November 29 to December 2 2004	Northwesterly	The system maintained its intensity and further weakened into a low pressure werea on 3rd December.	0000 UTC and 1200 UTC of November 30 and December 1, 2004
Cyclonic storm 'FANOOS' over Bay of Bengal	December 6-9, 2005	Northwesterly direction /westerly	Crossed the Tamilnadu coast near Vedarayanam around 10 December 0530 UTC.	0000 UTC and 1200 UTC of December 6- 9, 2005
Very sever cyclonic storm 'MALA' over Bay of Bengal	April 25-29, 2006	Northwesterly/ recurved and moved northeastward.	crossed Arakan coast as a severe cyclonic storm at about 100km south of Sandoway	0000 UTC and 1200 UTC of April 25-29, 2006
Cyclonic storm 'AKASH' over the Bay of Bengal	May 13-15, 2007	northerly/ north-northeasterly direction	----	0000 UTC and 1200 UTC of May 12-14, 2007
Very Severe cyclonic storm' SIDR' over the Bay of Bengal	November 11-16, 2007	Northwesterly	crossed Bangladesh coast as VSCS near long 89.8 deg. East around 1600 UTC of 15 November.	0000 UTC and 1200 UTC of November 11-16, 2007
Super cyclonic storm 'GONU' over the Arabian Sea	June 1-7, 2007	Northwesterly/ west-northwesterly	crossed Oman coast as very severe cyclonic storm between 0300 and 0400 UTC of 6 June The system further	0000 UTC and 1200 UTC of June 1-6, 2007

			moved into Gulf of Oman, moved in north-northwesterly direction and made second landfall over Iran coast near long. 58.5^0E between 0300 UTC and 0400 UTC of 7 June 2007 as cyclonic storm	
Severe cyclonic storm 'NISHA' over the Bay of Bengal	November 25-27, 2008	Northwards	crossed the Tamilnadu coast north of Karaikal at 0100 UTC of 17 November 2008.	0000 UTC and 1200 UTC of November 24-27, 2008
Cyclonic Storm 'KHAIMUK' over the Bay of Bengal	November 13-16, 2008	West-northwesterly	crossed south Andhra Pradesh coast close to the north of Kavali between 2200UTC and 2300 UTC of 15 November	0000 UTC and 1200 UTC of November 14-15, 2008.
Cyclonic Storm' RASHMI' over the Bay of Bengal	October 25-27, 2008	North-northeasterly	crossed Bangladesh coast at about 50kms west of Khepupura between 2200 UTC - 2300 UTC of 26 October, 2008	0000 UTC and 1200 UTC of October 25-27, 2008
Very Severe cyclonic Storm 'NARGIS' over Bay of Bengal	April 27- May 3, 2008	Northwestwards /re-curving northeastwards and subsequently moved eastwards	crossed southwest coast of Myanmar between 1200 UTC and 1400UTC, along Lat 16.0^0 N	0000 UTC and 1200 UTC of April 27-30 and May 1-2, 2008.
Cyclonic storm 'BIJLI' over the Bay of Bengal	April 14-17, 2009	North-northwesterly/ recurved north-northeast	south of Chittagaon around 1600 UTC of 17 April 2009.	0000UTC and 1200 UTC of April 14-16, 2009
Severe Cyclonic Storm 'AILA' of Bay of Bengal	May 23-26, 2009	Northward	crossed West Bengal coast near Sagar Island between 0800 UTC	0000 UTC and 1200 UTC of May 23-25, 2009

			and 0900 UTC of 25 May 2009	
Cyclonic storm 'WARD' over the Bay of Bengal	December 10-15, 2009	West-southwestwards	crossed northeast Srilanka coast close to the south of Trincomalee between 0800 UTC and 0900UTC of 14 December	0000 UTC and 1200 UTC of December 10-13, 2009
Cyclonic storm 'PHYAN' over the Arabian Sea	November 10-12, 2009	North-northeastward	crossed north Maharastra coast between Alibag and Mumbai during 1000 UTC and 1100 UTC of 11 November	0000 UTC and 1200 UTC of November 8-11, 2009
Severe cyclonic storm 'LAILA' over Bay of Bengal	May 17-21, 2010	West-northwesterly	crossed Andhra Pradesh coast near Bapatla between 1100 UTC -1200 UTC	0000 UTC and 1200 UTC of May 17-21, 2010 .
Cyclone 'JAL' over Bay of Bengal	November 4-8, 2010	West-northwesterly	crossed north Tamilnadu – south Andhra Pradesh coast, around 1630 UTC IST of 7 November 2010	0000 UTC and 1200 UTC of November 4-7, 2010
Very Severe Cyclonic Storm (VSCS) 'PHET' over the Arabian Sea	May 31 – June 7, 2010	West-northwestwards/ easterly	Crossed Oman coast between 0000 & 0200 UTC; Crossed Pakistan coast, close to south of Karachi between 1230 UTC and 1330 UTC.	0000 UTC and 1200 UTC of June 1-6, 2010
Very severe cyclonic storm, 'GIRI'	October 20-23, 2010	North-eastwards	crossed Myanmar coast between Sittwe and Kyakpyu around 1930 1400 of 2 October 2010	0000 UTC and 1200 UTC of October 21-22, 2010

Table 2: Description of WRF-NMM model

Dynamics	Non-hydrostatic
Model domain	15^0 S to 45^0 N latitude and 40^0E to 110^0E longitude
Horizontal grid distance	27 km
Integration time step	60 sec
Vertical levels	38 hybrid levels
Radiation parameterization	GFDL longwave and short wave schemes(Lacis and Hansen, 1974)
Surface layer parameterization	Monin-Obukhov (Janjic) scheme(Monin and Obukhov, 1954)
Cumulus parameterization	Kain and Fritsch(1993)
PBL parameterization	Mellor-Yamada-Janjic scheme(Mellor and Yamada, 1982)
Microphysics	Ferrier et.al.(2002)

Table 3: Mean Track Position Errors over North Indian Ocean (NIO), Bay of Bengal (BOB), Arabian Sea (AS) over the period 2004 -2010 (* Figures in bracket indicates number of initial conditions for model run)

Forecast Hours	**Mean (km) (NIO)** (106)*****	**Mean(km) (BOB)** (78)*	**Mean(km) (AS)** (28)*
12	115	121	94
24	142	139	151
36	176	173	187
48	211	202	240
60	256	251	275
72	279	260	357

Table 4: Mean Track Position Errors during post-monsoon and pre-monsoon Season
(* Figure in bracket indicates number of initial conditions for model run)

Forecast Hours	Mean(km) (post-monsoon) (58)*	Mean(km) (pre-monsoon) (44)*
12	115	104
24	149	122
36	196	152
48	205	182
60	241	236
72	252	275

Table 5: Track Errors (km) -Recurving cyclones

Forecast Hour	North East moving	Southwest moving	Mean
	(BOB+AS)	(BOB)	
12	115	274	194
24	154	303	228
36	235	343	289
48	267	465	366
60	338	491	414
72	370	531	450

Table 6: Mean Track Errors (km) with the initial condition at different stages of intensity

Forecast hours	Depression	Cyclone	Severe cyclonic storm	Very severe cyclonic storm
12	165	141	110	109
24	189	188	144	157
36	211	250	180	243
48	324	268	244	354
60	320	279	424	517
72	381	390	612	359

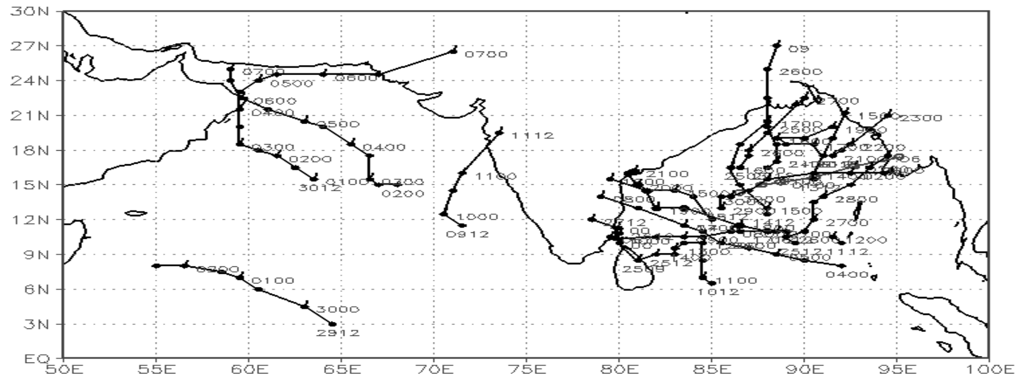

Fig. 1 Best tracks of the tropical cyclones in Bay of Bengal and Arabian Sea for selected cyclones during 2004-2010.

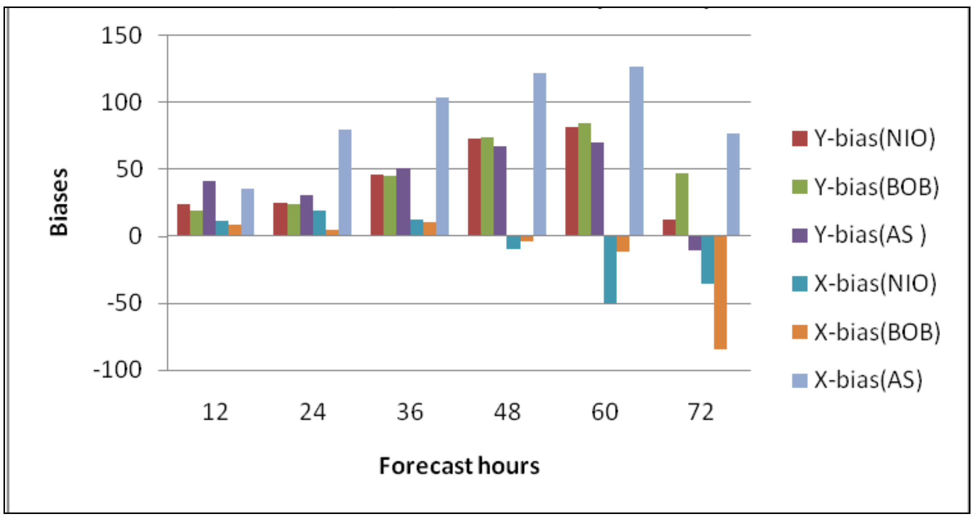

Fig. 2 Biases of model tracks over North Indian Ocean, Bay of Bengal and Arabian Sea

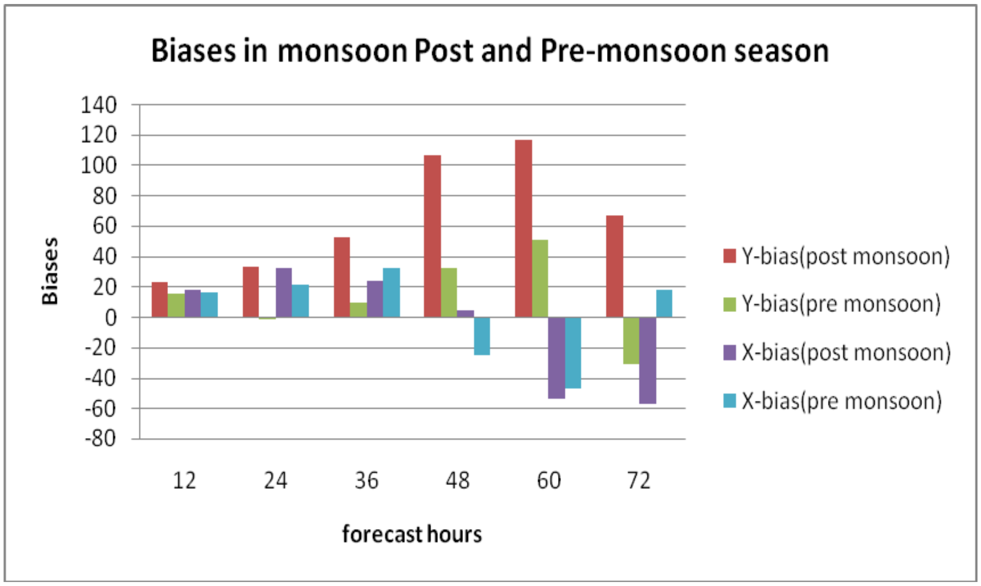

Fig. 3 Biases of model tracks during post and pre-monsoon seasons in North Indian Ocean

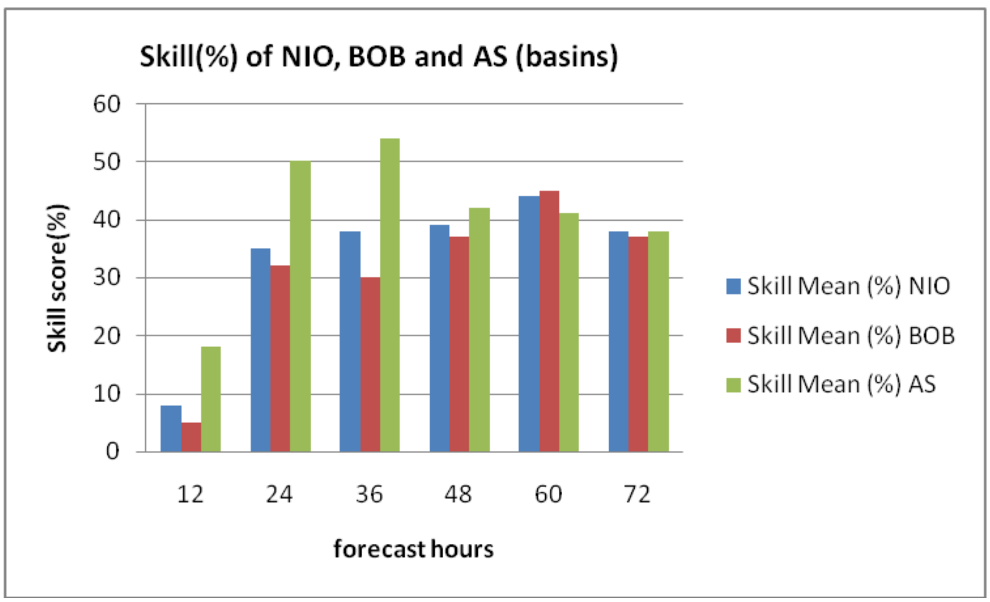

Fig. 4 Skill of the model tracks over North Indian Ocean, Bay of Bengal and Arabian Sea

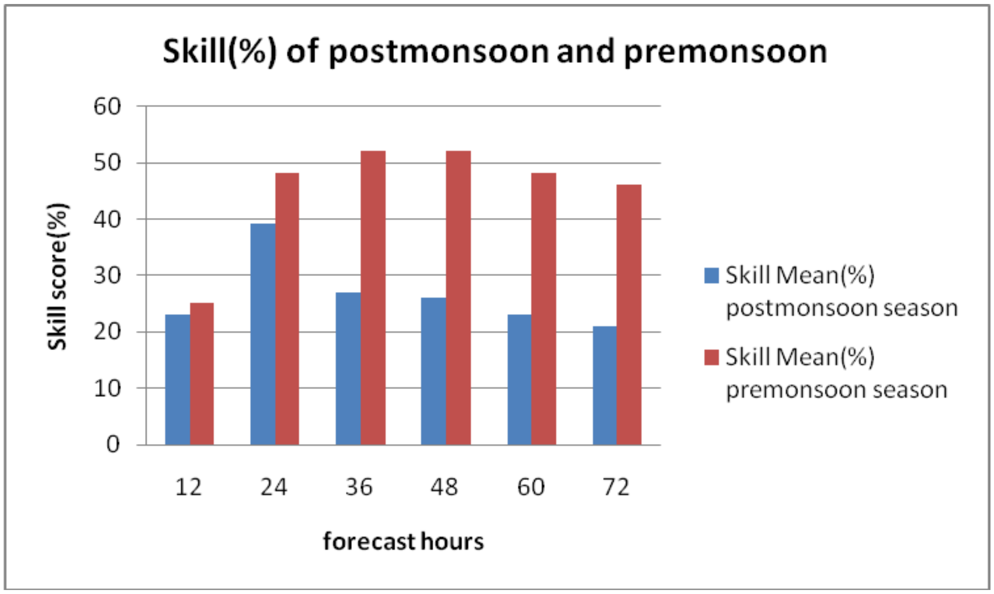

Fig. 5 Skill of the model tracks over post-monsoon and pre-monsoon in North Indian Ocean

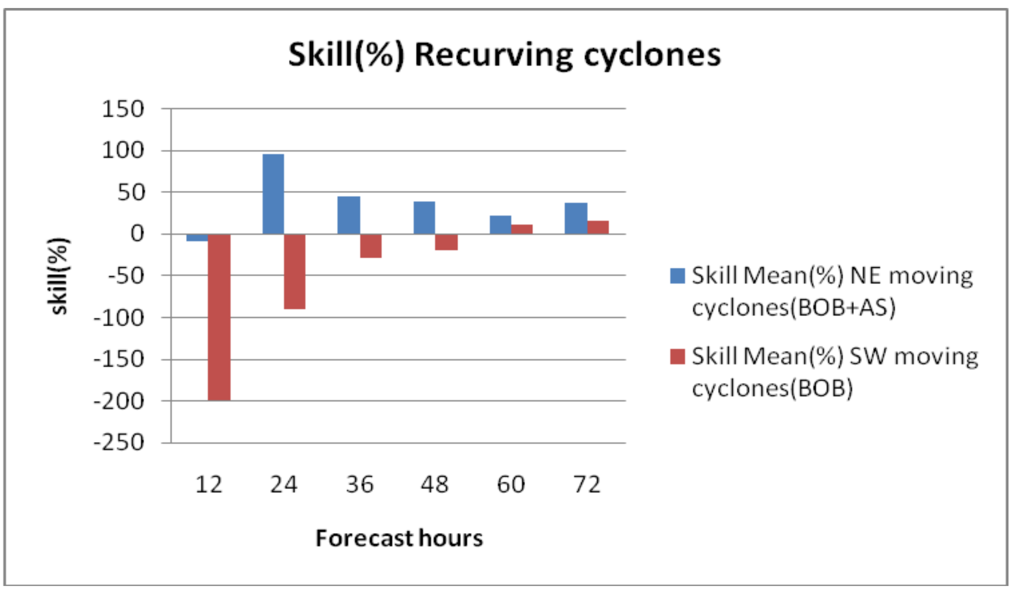

Fig. 6 Skill scores of model tracks of recurving cyclones in North Indian Ocean

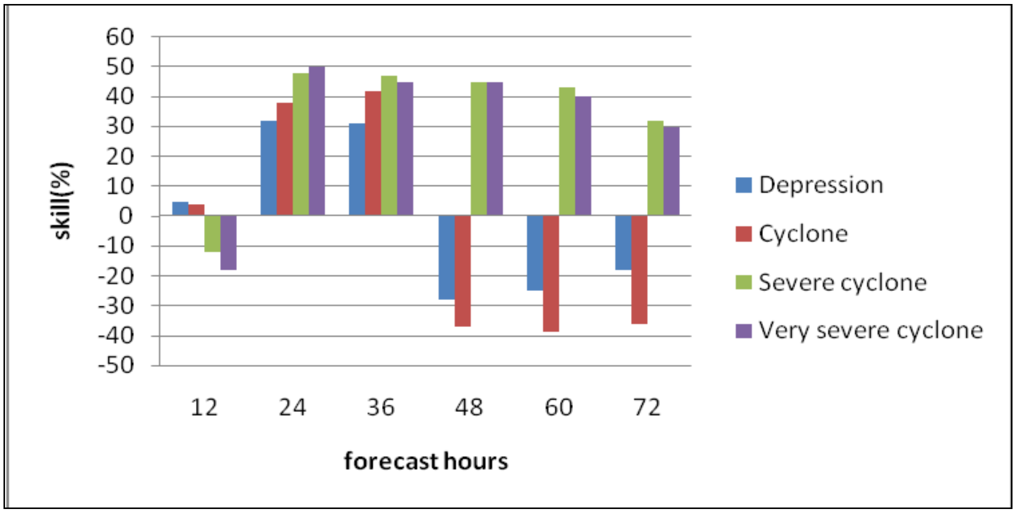

Fig. 7 Skill scores of model tracks at different stages of intensity in North Indian Ocean

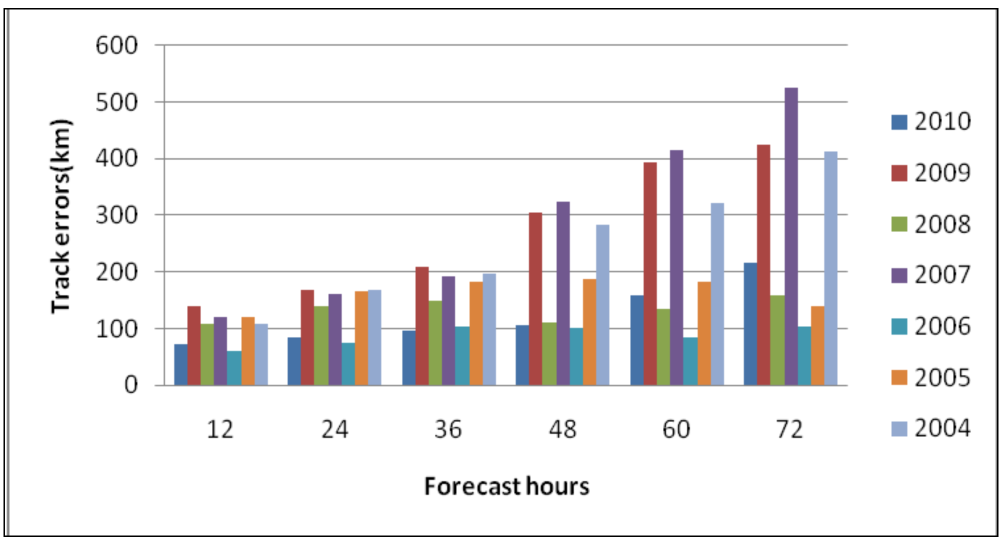

Fig. 8 Year-wise model track errors (2004 to 2010) in North Indian Ocean