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Evaluation of short range forecast for tropical cyclones over north Indian Ocean using TIGGE data

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सार – वर्ष 2010 से 2014 तक के TIGGE TC आँकड़ों के आधार पर तीन भूमंडलीय मॉडलों ECMWF, NCEP और UKMO के निर्धारणात्मक और समुच्चय पूर्वानुमानों से प्राप्त हुए उष्णकटिबंधीय चक्रवात (TC) पथों के पूर्वानुमानों का मूल्यांकन किया गया ताकि उत्तरी हिंद महासागर (NIO) में पथ पूर्वानुमान के दिशानिर्देशों के लिए इन मॉडलों की क्षमताओं का अध्ययन किया जा सके। भूमंडलीय मॉडल पूर्वानुमानों के निष्पादन को मापने के लिए आरंभिक स्थिति की त्रुटियों, माध्य व क्रास पथ तथा 72 घंटे तक के त्रुटिपूर्ण बायस पथ सहित पथ पूर्वानुमानों के सांख्यिकीय मूल्यांकन की श्रृंखलाओं को कार्यान्वित किया गया। NCEP और ECMWF के 72 घंटे के मॉडलसेट की निर्धारणात्मक पथ पूर्वानुमान त्रुटियां क्रमशः232 और 272 थी। हालांकि NCEP, ECMWF, UKMO के 72 घंटे के मॉडलसेट की समुच्चय माध्यट्रेक पूर्वानुमान की त्रुटियां क्रमशः 252, 322 और 374 कि. मी. थी। इससे यह पता चलता है कि ECMWF और UKMO की अपेक्षा NCEP के मॉडलों में कम त्रुटियां थी। भारत मौसम विज्ञान विभाग (IMD) के प्रचालनात्मक पथ पूर्वानमान त्रुटियों की अपेक्षा NCEP के निर्धारणात्मक और समुच्चय पूर्वानुमान में ±15 प्रतिशत के कौशल का पता चला है और ECMWF निर्धारणात्मक पूर्वानुमान द्वारा 24 से 72 घंटे तक के पूर्वानुमान रेंज से 4 से -19 प्रतिशत तक का कौशल देखा गया। भारत मौसम विभाग विभाग (IMD) के प्रचालनात्मक पूर्वानुमान पथ त्रुटियों की IMD के प्रचालनात्मक पूर्वानुमान पथ त्रुटियों की अपेक्षा ECMWF और UKMO समुच्चय पूर्वानुमानों से अत्यधिक मात्रा में नकारात्मक कौशल का पता चला है। तथापि IMD के प्रचालनात्मक पूर्वानुमान से सभी मॉडलों की अपेक्षा 12 घंटे तक के बेहतर कौशल का पता चला है। सभी मॉडलों में यह पाया गया है कि NIO में ECMWF और UKMO मॉडलों की अपेक्षा NCEP निर्धारणात्मक और समुच्चय पूर्वानुमानों में बेहतर कौशल हैं। बंगाल की खाड़ी और अरब महासागर के प्रत्येक बेसिन में किए गए स्वतंत्र अध्ययन से यह पता चला है कि ECMWF और UKMO मॉडलों की अपेक्षा दोनों बेसिनों में निर्धारणात्मक और समुच्चय पथ पूर्वानुमानों में कौशल बेहतर रहा। अरब सागर की अपेक्षा बंगाल की खाड़ी में ECMWF पूर्वानुमानों में मामूली सी बेहतर कौशल देखा गया। बंगाल की खाड़ी और अरब महासागर दोनों में UKMO समुच्चय पूर्वानुमानों की अत्यधिक मात्रा में नकारात्मक कौशल का पता चला है।

ABSTRACT. Forecasts of tropical cyclone (TC) tracks from three global models ECMWF, NCEP and UKMO deterministic and ensemble forecasts based on TIGGE TC data during the years 2010 to 2014 were evaluated to study the capability of these models for track forecast guidance over the North Indian Ocean (NIO). To measure the performance of the global model forecasts, a series of statistical evaluations of track forecasts including the initial position errors, mean and cross track and along track errors bias up to 72 hr were carried out. The deterministic track forecast errors of NCEP and ECMWF models at 72 hr were 232 and 272 km, respectively. However the ensemble means track forecasts errors of NCEP, ECMWF, UKMO models at 72 hr were 252, 322, and 374 km respectively. It shows NCEP models had less error than ECMWF and UKMO. Compared to India Meteorological Department (IMD) operational track forecast errors, NCEP deterministic and ensemble forecasts have shown skills within ±15% and ECMWF deterministic forecasts have shown 4 to -19% from 24 to 72 hr forecast range. The ECMWF and UKMO ensemble forecasts showed large negative skills compared to IMD operational forecast track errors. However, IMD operational forecasts showed better skill upto 12 hr compared to all the models. In all the models it shows that NCEP deterministic and ensemble forecasts have better skills compared to ECMWF and UKMO models over NIO. Independent study of each basin Bay of Bengal and Arabian Sea has shown that NCEP deterministic and ensemble track forecasts have shown better skills over both the basins compared to ECMWF and UKMO models. ECMWF forecasts have shown slight better skills over Bay of Bengal compared to Arabian Sea. The UKMO ensemble forecasts show large negative skill over both Bay of Bengal and Arabian Sea.

Key words – Tropical cyclone, North Indian ocean, Track, Direct position error, Forecast skills.

1. Introduction

During the last few decades there have been significant advances in tropical cyclone (TC) track forecasts along with the remarkable progress of numerical weather prediction (NWP) system. However, we all know that forecast uncertainty is one key unavoidable aspect of weather forecasting due to the chaotic nature of the atmosphere as well as the imperfection of NWP system. Tropical cyclone track forecasts are no exception. Consequently, sometimes an almost perfect forecast may only contain position error of less than 50 km in a 3-day forecast. However, sometimes the 3-day forecast error can be over 500 km. For this reason, the Ensemble Prediction System (EPS) has been attracting attention because it is expected to provide uncertainty information inherent to each forecast event based on ensemble mean and ensemble spread respectively (Puri *et al.*, 2001; Yamaguchi *et al*., 2009).

Komori *et al*. (2007) have verified the ensemble mean track of three global models from operational NWP centers, the European Centre for Medium-Range Weather Forecasts (ECMWF), Japan Meteorological Agency (JMA) and U. K. Meteorological Office (UKMO). In the verification of 48 hr and 96 hr predictions for the western North Pacific basin from 1991 to 2005, and for the Atlantic basin from 1999 to 2005, the ensemble mean has the best performance with respect to the best of the individual models with few exceptional years. Belanger *et al*. (2012) examined the performance of the ECMWF ensemble prediction system in extended range prediction over north Indian Ocean (NIO) Tropical Cyclones for the period 2007 to 2010. The EPS forecasts shown that tropical cyclone track forecasts made prior to TC genesis performed 15% - 30% better than track forecasts produced after TC genesis has occurred. For a lead time of 24 - 240 hr, the total mean track error grew at a rate of 76 km per day, such that by a lead time of 120 hr (240 hr), the average track error of all EPS forecast is 415 km (758 km).

India Meteorological Department (IMD) operationally running Quasi-Lagrangian Model (QLM) since year 2000 for its operational track forecast (Mathur, 1991; Prasad and Rama Rao, 2003). The QLM during 1998 - 2008 has the average track errors of 152 km for 24 hr, 235 km for 48 hr and 375 km for 72 hr (Rama Rao *et al*., 2010). Due to the limitation of QLM model in prediction of intensity, recently IMD installed HWRF model (based on Environmental Modeling Center (EMC)/National Centers for Environmental Prediction (NCEP), USA) for its operational track and intensity forecast guidance to Regional Specialized Meteorological Centre (RSMC), New Delhi over NIO region. The preliminary study of HWRF model average track errors for 9 major cyclonic storms formed during 2010 to 2013 over the Bay of Bengal and Arabian Sea had shown 83 km at 12 hr, 135 km at 24 hr, 176 km at 36 hr, 186 km at 48 hr, 233 at 60 hr and 319 km at 72 hr. The HWRF track forecast errors displayed an improvement of 7, 27, 25 and 15% over the IMD operational forecasts at 36, 48, 60 and 72 hr respectively (Das *et al*., 2015).

Many researchers in India have made experimental forecasts for TC track and intensity over the NIO region mainly using the WRF-ARW model. Bhaskar Rao *et al.* (2014) have shown that using variations in physical parameterizations, 5-day simulations for the Orissa super cyclone (1999) tracks from the ensemble mean had shown significantly better performance with errors less than 130 km up to 120 hr, while the individual members had track errors ranging from 96-240 km at 24 hr to 50-803 km at 120 hr. Osuri *et al*. (2013) evaluated track and intensity of TCs formed during the 2007-2011 period over the NIO using another variant of the WRF-ARW model shown that the model simulations run at 27 km resolution showed the mean track forecast errors over the NIO to be 113, 140, 276 and 375 km at 12, 24, 48 and 72 hr respectively. The same model with high resolution predictions (9 km) reduced the track errors by about 8% - 24% compared to 27 km resolution predictions. The higher resolution model has also shown improvement in intensity predictions.

IMD, which is a World Meteorological Organization (WMO) designated RSMC, provides the official tropical cyclone forecasts and warnings over NIO region. Basically, the forecast tracks result from a manually analyzed forecasting process, which relies on output from several NWP models including IMD QLM and Global Forecast System (GFS), ECMWF, UKMO, JMA, ARP-Meteo-France, NCEP-GFS and some ensemble means like multi-model ensemble (MME) (RSMC, 2010). Consensus forecasts that gather all or part of the numerical forecast tracks and synoptic-statistical guidance are utilised to issue official forecast. Though IMD uses all advanced NWP model products for day-to-day operational use, however, not much literature is available on performance of the latest generation of global numerical weather prediction models, particularly ensemble prediction products for tropical cyclones prediction over NIO region.

In this paper we discuss the verification results of three global models from operational NWP centers, the ECMWF and NCEP deterministic and ECMWF, NCEP and UKMO ensemble forecasts (EPS) to assess track uncertainty for a lead time of 3 days. A total of 11 TCs that formed during the years 2010-2014 has been considered including eight over the Bay of Bengal (BOB) and three over the Arabian Sea (AS). Section 2 describes

TABLE 1

Detailed formulation of TIGGE models used in the present study (updated November 2013)

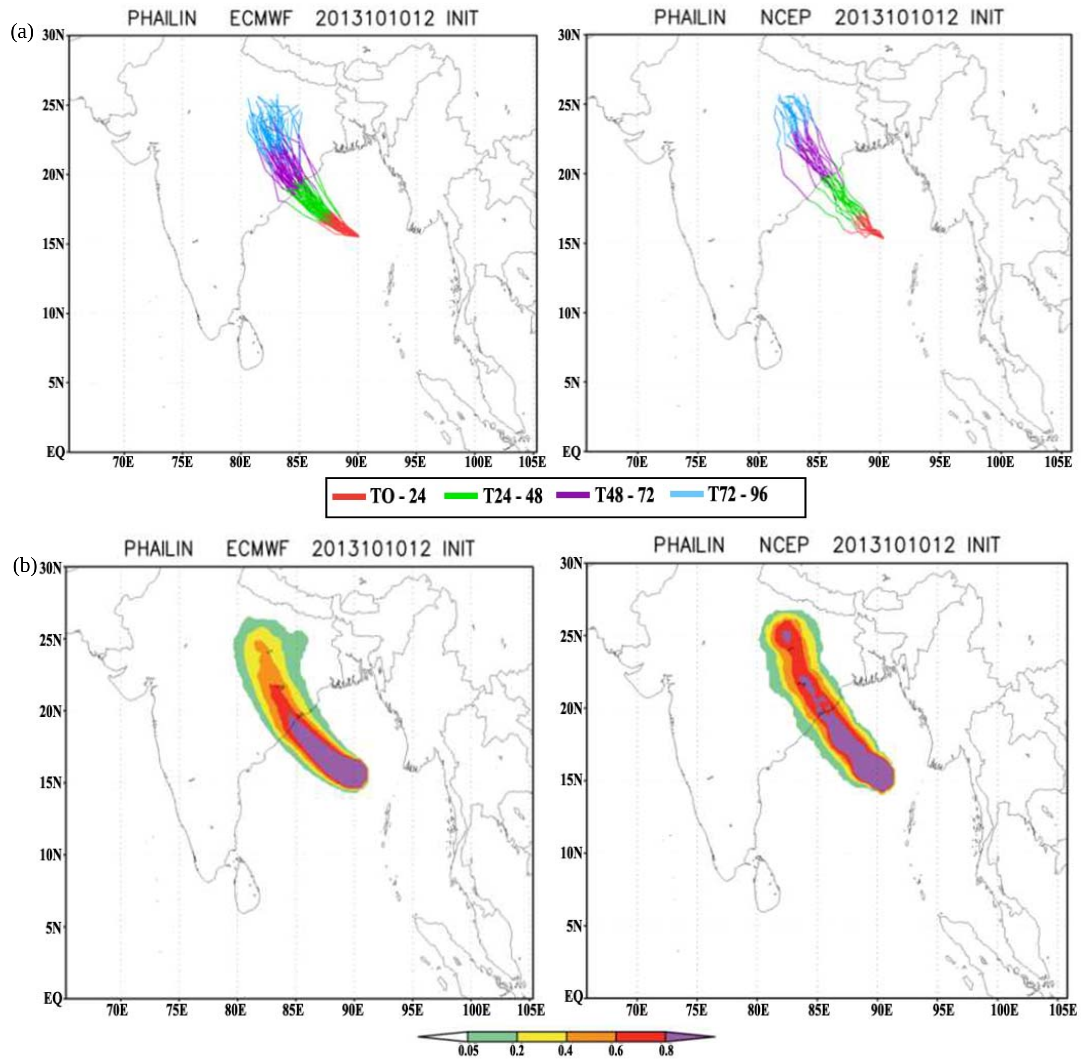
Centre	Initial pert method (area)	Horizon res.	# Vert Levels (hPa)	Fcst length (days)	# Pert mem	#runs per day (UTC)	# mem per day	Operational & in TIGGE since
ECMWF (EU)	4D VAR	T1279 (16 km)	137 (0.01)	0-10	-	2(0000/1200)	Deterministic	-
NCEP (USA)	Hybrid EnKF (T-254 – 80 mem)+3DVar GSI (T-574)	T574 (23 km)	64 (2.7)	16	-	4 (0000/0600/ 1200/1800)	Deterministic	-
ECMWF (EU)	SV(NH, SH, TC) + EDA	TL639 (0.28° × 0.28°) (30 km)	91 (0.01)	0-10	50+1	2(0000/1200)	51*2	11 Mar 08
		TL319 (0.56° × 0.56°) (60 km)	62 (5.0)	10-15	50+1	2(0000/1200)	51*2	-
NCEP (USA)	ETR(globe)	T254(35 km)	42 (2.7)	0-8	20+1	4 (0000/0600/ 1200/1800)	21*4	27 Mar 07
		T190 (0.75° × 0.75°) (70 km)	42 (2.7)	8-16	20+1	4 (0000/0600/ 1200/1800)	21*4	-
UKMO (UK)	ETKF(globe)	N216 (0.55° × 0.83°) (65 km)	85 (0.1)	15	23+1	2(0000/1200)	24*2	1 Oct 06

the data and methodology. Section 3 describes the performance and track evaluation results. The summary and conclusions are presented in section 4.

2. Data and methodology

The Observing System Research and Predictability Experiment (THORPEX) Interactive Grand Global Ensemble (TIGGE) is a World Weather Research Programme (WWRP) project of WMO. The TIGGE archive contains global ensemble predictions from ten operational NWP centres. As part of WMO Program to provide numerical guidance to TC forecast in near real-time for the ESCAP/WMO Member Countries based on the TIGGE Cyclone XML (CXML) data, JMA developed software for generation of deterministic and ensemble track forecasts and strike probability maps. The strike probability is defined as the proportion of EPS members that predict the tropical cyclone will pass within a 120 km radius of a given location at any time during the next four days with each member having equal weight (Van der Grijn *et al.*, 2004). In other words, the time dimension is eliminated. This allows for a quick assessment of high-risk areas, regardless of the exact timing. In the present study, the TC track positions and intensity were collected from MRI/JMA (http://tparc.mri-jma.go.jp/cyclone/) site accessible under the WMO Tropical Cyclone Programme**.** The software provided by MRI/JMA processes Cyclone XML (CXML) data and makes images of deterministic and ensemble track forecasts, strike probability map based on ensemble TC track forecasts and time series at cities likely to be effected during the next 96 hr. Using this software, ECMWF deterministic and ensemble (51 members), NCEP deterministic and ensemble (21 members), UKMO ensemble (24 members) track positions (latitude/longitude) and intensity (maximum wind, mean sea level pressure) data based on 0000 UTC and 1200 UTC runs are used from depression stage onwards. The detailed formulation of the models used in the present study is given in Table 1. Note that the NCEP performed ensemble predictions initiated at 0600 and 1800 UTC as well, but only the ensemble predictions initiated at 0000 and 1200 UTC were used in this study. Also for UKMO, only the ensemble predictions were considered because the deterministic predictions were not available in the TIGGE archive. More information about ensemble system and data is available at http://cawcr.gov.au/projects/ THORPEX/TC/ index.html.

The ECMWF and NCEP ensemble forecast tracks, strike probability maps based on 1200 UTC/10 October, 2013 of Very Severe Cyclonic Storm TC 'Phailin' which formed over Bay of Bengal during 8-14 October, 2013 and crossed Odisha coast of India near Gopalpur on 1800 UTC/12 October, 2013 are given in Figs. 1(a&b) and Fig. 2 as an example. These plots are generated from ECMWF and NCEP model CXML data from each individual ensemble member track forecasts [Fig. 1(a)] and strike probability map [Fig. 1(b)] based on ensemble TC track forecasts and time series at cities likely to be affected during the next 96 hr (Fig. 2). In Fig. 2, time series of the strike probability plot at stations - Konark and Puri based on 1200 UTC of 10 October, 2013



Figs. 1(a&b). The 4-days ECMWF, NCEP models ensemble track forecast of the TC 'Phailin' based on 1200 UTC of 10 October, 2013. Above (a) tracks from each individual ensemble member forecasts; below (b) strike probability - the probability that the cyclone will pass within 120 km

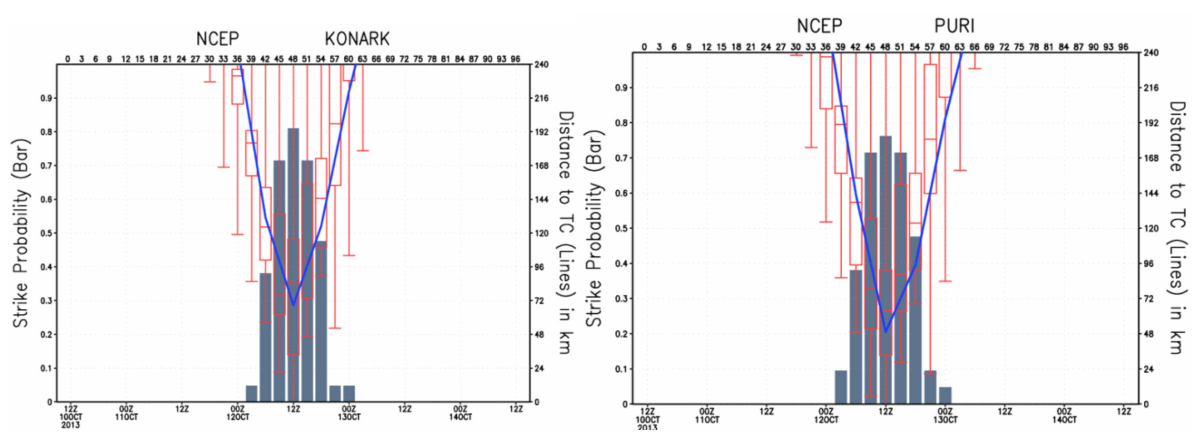


Fig. 2. A time series of the strike probability plot at stations forecast for 4 days – Konark and Puri based on NCEP model forecast of 1200 UTC 10 October, 2013 for TC 'Phailin'. Bar: Strike probability (percentage of members within 120 km from station at each forecast time). Red lines: Distance between TC centres in each ensemble members and station at each forecast time. Blue line: Distance between TC centres in the deterministic model

TABLE 2

Details of the tropical cyclones (TCs) under consideration

S. No.	Year	Life period	Maximum Intensity/ Name of TC	Basin of formation	Season of formation	Type of track of TC	Land falling/ dissipating TC	Landfall time/point
1.	2010	19-23 May	CS/ Bandu	AS	PM	S/C	D	0000 UTC/23 May weakened over Gulf of Aden
2.	2010	31 May -7 Jun	VSCS/ Phet	AS	PM	R	L	0000-0200 UTC/4 June at Oman Coast
3.	2010	17-21 May	SCS/Laila	BOB	PM	R	L	1100-1200 UTC/20 May at Bapatla, A.P.
4.	2010	04-08 Nov	SCS Jal	BOB	PS	S/C	L	1600 UTC/7 November at North of Chennai
5.	2011	25-31 Dec	VSCS/Thane	BOB	PS	S/C	L	0130 UTC of 30 December at South of Cuddalore, T.N.
6.	2013	10-16 May	CS/ Viyaru	BOB	PM	R	L	0800 UTC/16 May at South of Feni, Bangladesh
7.	2013	8-14 Oct	VSCS/Phailin	BOB	PS	S/C	L	1800 UTC/12 October Gopalpur, Odisha, India
8.	2013	19-23 Nov	SCS/Helen	BoB	PS	S/C	L	0800 UTC/22 November South of Machilipatnam, (A.P)
9.	2013	23-28 Nov	VSCS/Lehar	BoB	PS	S/C	L	0830 UTC/28 November north of Machilipatnam, (A.P)
10.	2014	7-14 Oct	VSCS/Hudhud	BoB	PS	S/C	L	1200 UTC/12 October at Visakhapatnam (A.P)
11.	2014	25-31 Oct	VSCS/Nilofar	AS	PS	R	D	0300 UTC/31 October Weakened over NE Arabian Sea off north Gujarat Coast

CS : Cyclonic storm, SCS : Severe cyclonic storm, VSCS : Very severe cyclonic storm, BOB : Bay of Bengal, AS : Arabian Sea; R : Recurving/looping, S/C : straight moving/climatological,; L : Landfalling, D : Dissipating over sea, PM : Pre-monsoon, PS : Post-monsoon

TABLE 3

Number of forecast runs verified from IMD operational (based on corresponding case runs: 2010-14) ECMWF and NCEP deterministic and ensemble and UKMO ensemble for TCs over the NIO (Bay of Bengal/Arabian Sea)

Forecast (hr)	IMD Operational	ECMWF-DET	NCEP-DET	ECMWF-EPS	NCEP-EPS	UKMO-EPS
0	178 (137/41)	55 (40/15)	87 (59/28)	2805 (2040/765)	1827 (1239/588)	1392 (792/600)
12	178 (137/41)	55 (40/15)	87 (59/28)	2805 (2040/765)	1827 (1239/588)	1392 (792/600)
24	158 (121/37)	54 (39/15)	87 (59/28)	2754 (1989/765)	1827 (1239/588)	1368 (768/600)
36	135 (105/30)	44 (31/13)	76 (51/25)	2244 (1581/663)	1596 (1071/525)	1200 (672/528)
48	115 (89/260	36 (26/10)	65 (43/22)	1836 (1326/510)	1365 (903/462)	1056 (600/456)
60	94 (71/23)	27 (19/8)	56 (37/19)	1377 (969/408)	1176 (777/399)	888 (504/384)
72	76 (55/21)	19 (13/6)	46 (30/16)	969 (663/306)	966 (630/336)	696 (384/312)

of NCEP model forecast of TC 'Phailin' is given. It shows the strike probability of percentage of members within 120 km from station and distance at each forecast time. Distance between TC centres in each ensemble members and station at each forecast time is represented by a box-and whiskers plot showing the median (red line) and the minimum and maximum distance from station (vertical lines).

3. Results and discussion

Using the ECMWF, NCEP and UKMO deterministic and ensemble models forecast data, tropical cyclones deterministic and ensemble mean track direct position error (DPE) and cross/along track (CT/AT) position bias errors over NIO region are calculated. The observed TC position is taken for verification from the best track

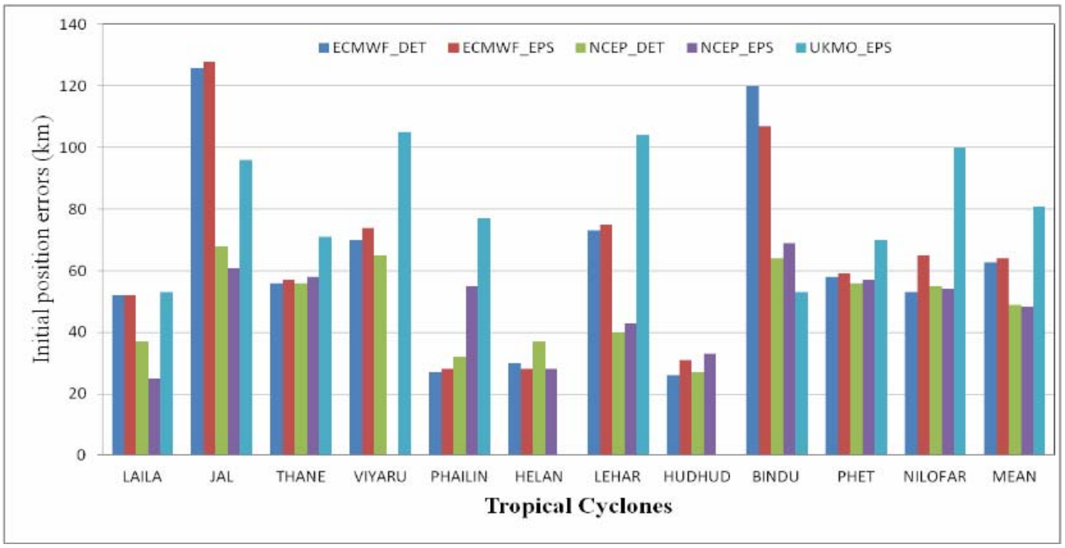


Fig. 3. Mean initial vortex position error (km) for each TC based on overall mean

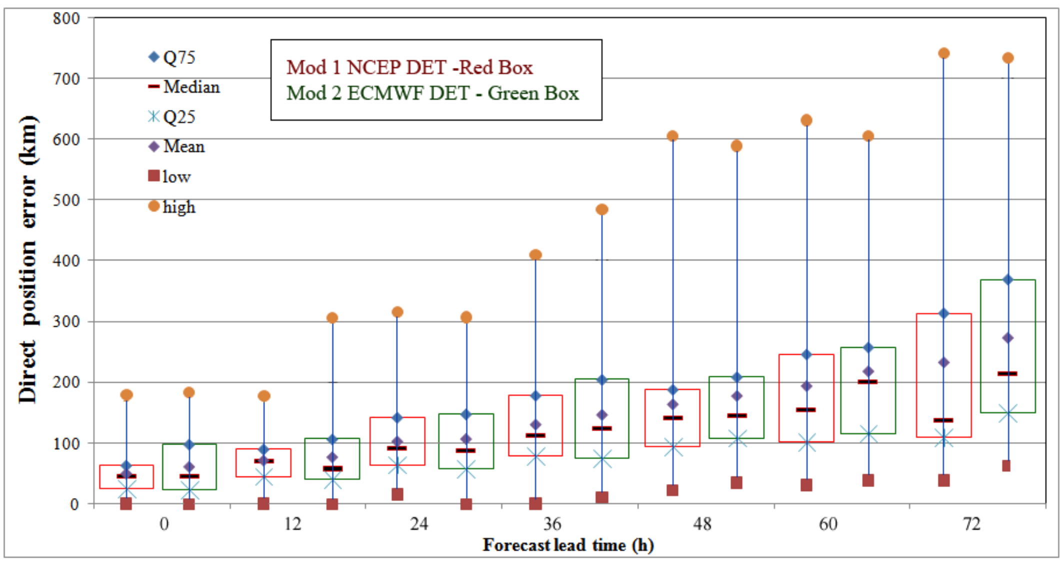


Fig. 4. Box plots to represent the distributions of mean track position errors (DPE) for TC forecasts. Red and Green box plots represent the track errors from NCEP and ECMWF deterministic models. Central box area represents the 0.25th to 0.75th quantile values of a distribution, horizontal line inside box is the median value, and whisker ends represent the smallest and largest values

available from RSMC, New Delhi reports. In the present study, a total of 11 TCs formed during the years 2010-2014 has been considered including eight over the Bay of Bengal (BoB) and three over the Arabian Sea (AS). Detailed characteristics of the TCs considered are given in Table 2. The total number forecast verified for all forecast lengths (12, 24, 36, 48, 60 and 72 hr) are given in Table 3. The number of forecasts verified in deterministic forecasts over Arabian Sea are less due to limited availability of data; however, the ensemble runs are sufficient in number to represent the forecast trend. It is noteworthy that most of the systems over NIO region have very short life from tropical depression stage to landfall. In view of this, we have considered forecast lead time upto 3 days only.

3.1. *Initial vortex position errors*

The ECMWF, NCEP and UKMO deterministic and ensemble TC initial vortex position errors of all the TCs

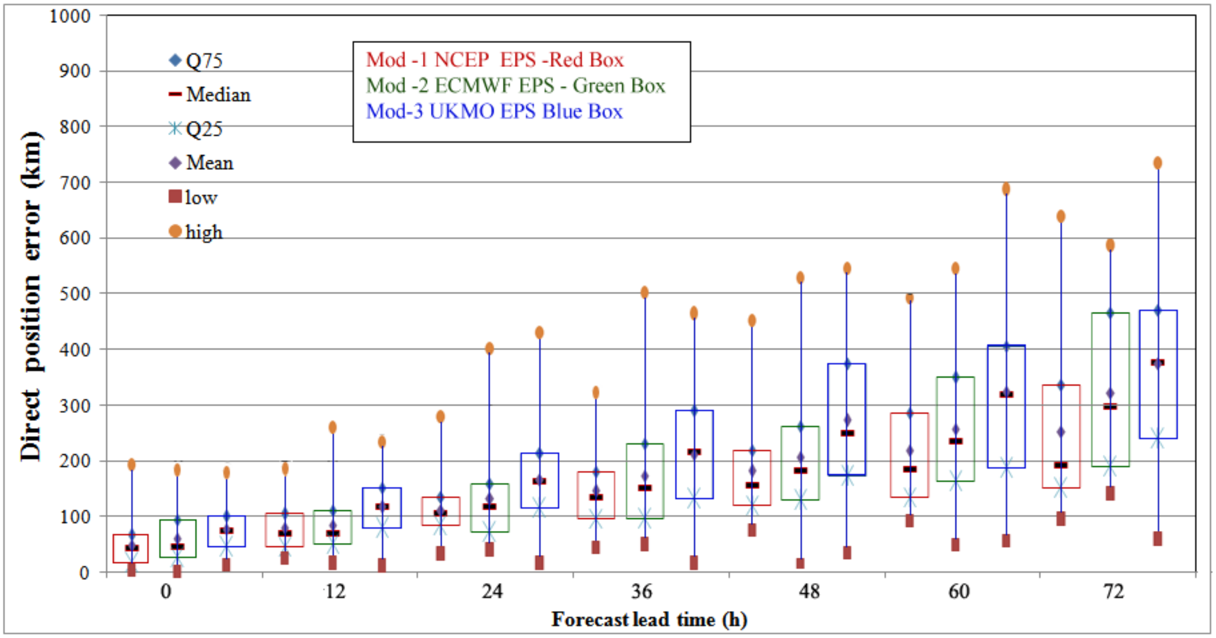


Fig. 5. Ensemble mean track position error for NCEP, ECMWF and UKMO ensemble models same as Fig. 4

considered are given in Fig. 3. The mean initial vortex position errors vary from 48 km to 81 km for 11 TCs. However, for individual cases the error varies from 25 km to 128 km. The large initial position errors of order 128 km are observed in two cases of Jal and Bandu which had very short life span and weakened over the sea before landfall. The TC 'Bandu' over Arabian Sea weakened into a well marked low pressure area and dissipated over the Gulf of Aden and TC 'Jal' over Bay of Bengal crossed north Tamilnadu - south Andhra Pradesh coast close to north of Chennai as depression. The average initial position errors of 11 cases in deterministic ECMWF and NCEP analysis are about 63 km and 48 km and in case of ensemble mean of ECMWF, NCEP, UKMO are 64 km, 48 km and 81 km, respectively. The large initial position error may be due to poor data near and around the vortex over the NIO region and also to the coarser resolution of global models. In the present study, IMD best track positions were used for calculation of model positional errors, since IMD is the official agency for determination of best track for TCs over the NIO. However, the NCEP and UKMO considers Joint Typhoon Warning Center (JTWC) based observed TC positions for vortex relocation/initialisation in their global models and ECMWF does not use any vortex initialisation. There is approximately 30 km to 70 km difference between the IMD and JTWC best track positions over the NIO (Falguni *et al.*, 2004). Thus the difference between the estimates of TC positions by JTWC and IMD might have contributed to this initial position error to some extent.

3.2. *Direct position error (DPE) and skill in TC track forecast*

Direct position error (DPE) is defined as the great-circle distance between the forecast position and the RSMC, New Delhi best-track position of a TC center. In Figs. 4, the distribution of DPEs over all TCs are shown for ECMWF and NCEP deterministic model and in Figs. 5, for ECMWF, NCEP and UKMO ensemble models from the initial time (00 hr) and then every twelve hours until 72 hr. The distributional approach in the box plots can highlight the distributions of the errors in the forecasts and enable one to look more closely at performance of the track forecast. As can be seen, the accuracy of track forecasts decreased linearly with increasing lead time in both deterministic and EPS. The inter-quartile range of the model became larger as a result of a widening error distribution, which may have been due to decreasing predictability for longer forecast ranges. The ECMWF forecast errors over NIO shows the deterministic forecasts had less error than ensemble forecasts. The ECMWF 24, 48 and 72 hr deterministic (ensemble) DPE shows 105 (130), 177 (206) and 272 (322) km, respectively. In case of NCEP, the deterministic and ensemble forecast errors did not show much difference. The 24, 48 and 72 hr deterministic (ensemble) forecasts shows 102 (111), 163 (181), 232 (252) km. The UKMO 24, 48 and 72 hr ensemble forecast shows DPE of 165, 272 and 374 km respectively. It shows that the NCEP model has less error than ECMWF and UKMO. In Fig. 4,

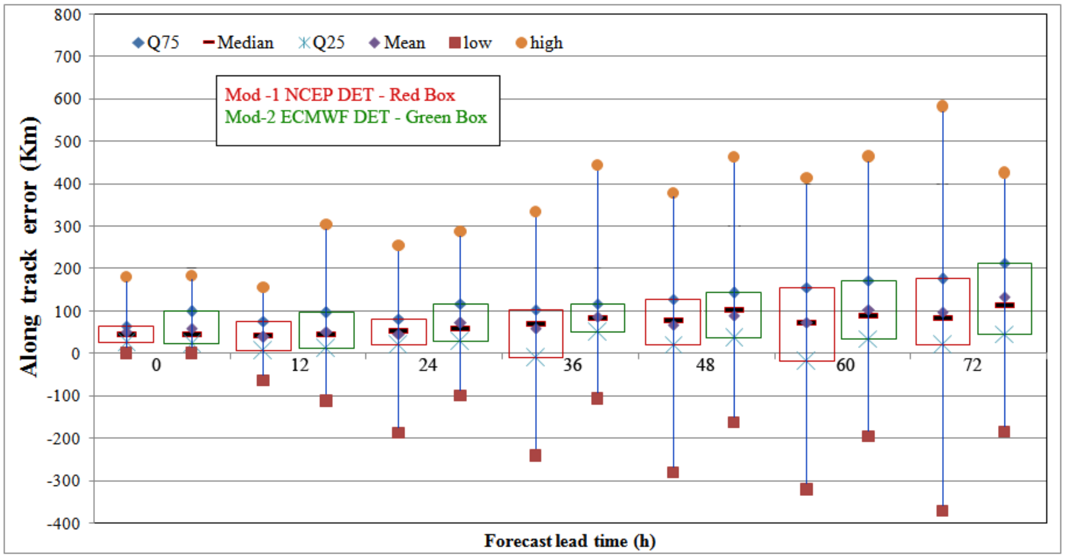


Fig. 6. Same as Fig.4 for mean along track (AT) position error bias (km) based on NCEP and ECMWF deterministic models

TABLE 4

Gain in skill (%) of the models over IMD operational track forecast errors (based on corresponding case runs: 2010-14) over NIO, Bay of Bengal and Arabian Sea

Forecast (hr)	ECMWF-DET			NCEP-DET			ECMWF-EPS			NCEP-EPS			UKMO-EPS		
	NIO	BoB	AS	NIO	BoB	AS	NIO	BoB	AS	NIO	BoB	AS	NIO	BoB	AS
12	-20	-10	-38	-12	-6	-21	-21	-26	-49	-24	-10	-31	-84	-88	-66
24	4	11	-9	7	13	-1	-8	-8	-31	-1	7	0	-50	-42	-45
36	-8	8	-39	3	14	-12	-10	-10	-52	-8	6	-16	-57	-36	-68
48	-7	7	-25	2	9	0	-8	-2	-35	-9	4	-4	-63	-48	-54
60	-14	-4	-20	-2	3	4	-27	-19	-26	-15	-4	3	-70	-70	-39
72	-19	-28	-4	-2	-13	17	-65	-84	-8	-10	-5	18	-63	-105	-5

we can also see some minor differences in the performance between ECMWF and NCEP deterministic models. The slope for the box-plot of the ECMWF track forecast errors is almost the same as that for the NCEP track forecast errors. However, the increase in the median error of NCEP is much smaller than that of ECMWF, indicating the proportions of large errors in ECMWF was much more than those in NCEP, especially at long lead times (60, 72 hr). In Fig. 5, we can see similar trends in EPS. The increase in the median error of NCEP is much smaller than that of ECMWF and UKMO, indicating the proportion of large error in ECMWF and UKMO was much more than those in NCEP, especially at long lead times (48 to 72 hr).

To assess the forecast skills of all the three models over IMD operational track errors, the model forecast track errors are compared with IMD operational mean track forecast errors (Mohapatra *et al*., 2013). The forecast improvement in relation to IMD operational forecast is quantified in percentage terms by :

Model forecast skill = 100* (Operational DPE - model DPE) / Operational DPE

Table 4 shows gain in skill (%) of the model forecast over average IMD operational average track forecast errors (based on corresponding TCs during 2010-14) over

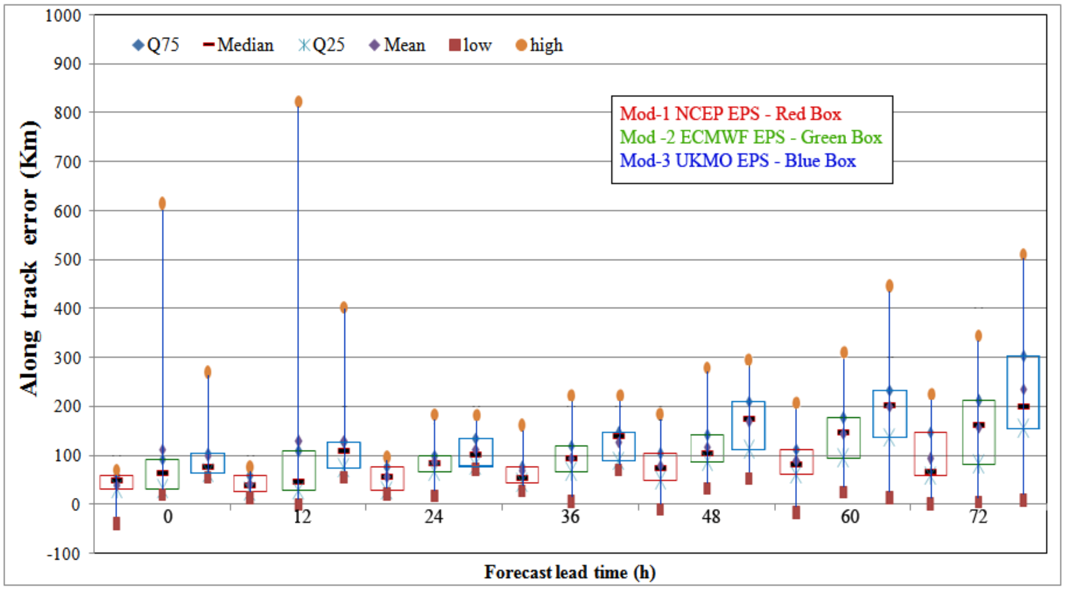


Fig. 7. Same as Fig. 4 for ensemble mean along track (AT) position error bias (km) based on NCEP, ECMWF and UKMO ensemble models

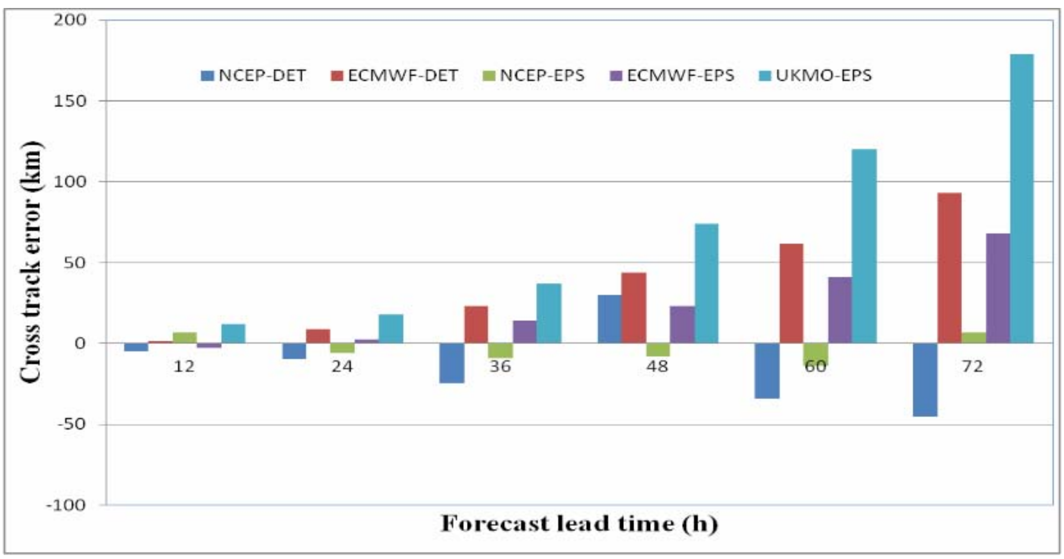


Fig. 8. Mean cross track (CT) position error bias based on NCEP, ECMWF deterministic and NCEP, ECMWF and UKMO ensemble forecast over North Indian Ocean (NIO)

NIO. The positive/negative skill indicates the model forecasts are better/worse than operational forecasts. The IMD operational forecasts have shown better skill upto 12 hr compared to all model forecasts. The NCEP deterministic forecasts have shown positive skill of 7% at 24 hr then reduced to -2% at 72 hr; in ensemble forecasts, it has -1% at 24 hr then reduces to -10% at 72 hr. The ECMWF deterministic forecasts have shown 4% at 24 hr then reducing to -19% at 72 hr and ensemble forecasts showed around -8% from 24 at 48 hr then reduced to -65% at 72 hr. However, the UKMO ensemble forecasts showed large negative skills from -50% at 24 hr to -63% at 72 hr. It shows the NCEP deterministic and ensemble forecasts have better skills over NIO compared to ECMWF and UKMO models. Independent study of each basin Bay of Bengal and Arabian Sea has shown (Table 4)

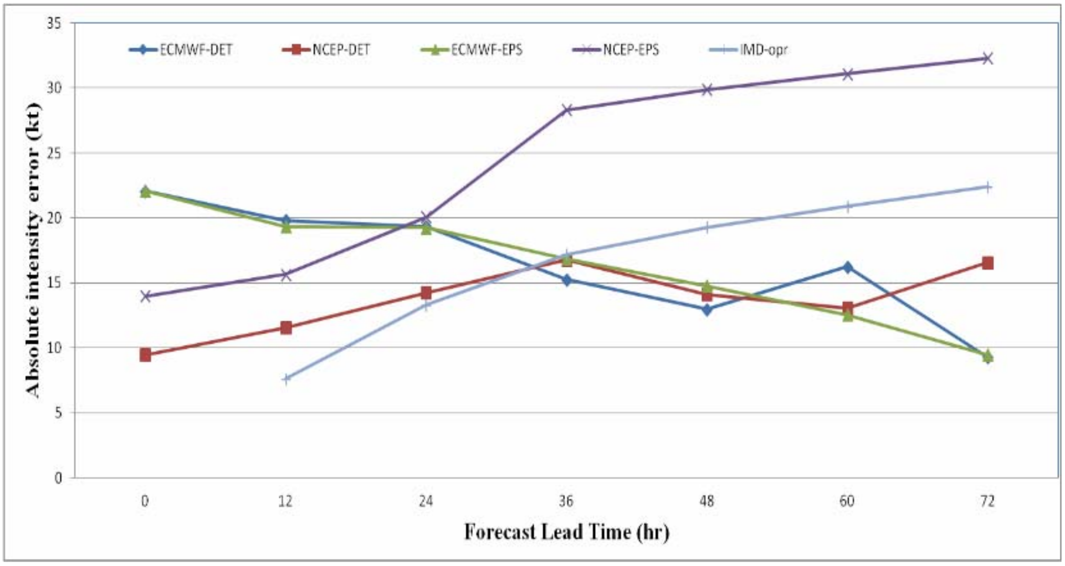


Fig. 9. Average Absolute Intensity error (kt) based on ECMWF, NCEP deterministic and ensemble mean forecast and IMD operational errors based on corresponding case runs for three tropical cyclone formed during 2013 over Bay of Bengal

that NCEP deterministic and ensemble forecasts have shown better skills over both the basins compared to ECMWF and UKMO. The ECMWF forecasts showed better skill within +/-15% in 24 hr to 60 hr and at 72 hr it showed large negative skill over Bay of Bengal; over Arabian Sea it had large negative skill in both deterministic and EPS. The UKMO ensemble forecasts showed negative skill over both Bay of Bengal and Arabian Sea in all forecast range upto 72 hr. During the year 2013-14 the NCEP track improved, where this improvement is believed to be mainly due to the implementation of the hybrid data assimilation system and vortex initialisation.

3.3. *Cross track and along track errors*

Figs. 6 & 7 show the distribution of mean along track (AT) position error bias for ECMWF, NCEP deterministic and ECMWF, NCEP, UKMO ensemble models and Fig. 8 shows the mean cross track (CT) errors bias from the initial time (00 hr) and then every twelve hours until 72 hr. Positive CT errors indicate forecasts deviate to the right of the observed path, while negative numbers indicate forecasts deviate to the left of the observed path. Positive AT errors indicate forecasts are too fast and negative numbers indicate they are too slow. In NCEP deterministic forecast and ensemble, the AT errors were within 100 km in 72 hr forecast range. The ECMWF models showed AT errors of 132 km and 156 km in deterministic and EPS forecast, and UKMO has shown 235 km in 72 hr forecast range. In Fig. 6, we can also see some minor differences in the performance between ECMWF and NCEP deterministic models. The slope for the box-plot of both NCEP and ECMWF models showed a slight increase at 72 hr forecast in ECMWF model. In Fig. 7, the ensemble forecasts showed the increase in the median error of NCEP is much smaller than that of ECMWF and UKMO, indicating the proportions of large error in ECMWF and UKMO were much more than those in NCEP, especially at long lead times (24 to 72 hr). It shows all the models have fast tendency for all the leading time with NCEP models showing less than ECMWF and UKMO models. In Fig. 8, the cross track position error bias shows, the NCEP deterministic model has pronounced bias to the left-of-track, while, NCEP EPS shown error bias within ± 10 km. However ECMWF and UKMO models shown large right-of-track bias. However, in all the models, the CT is less than the AT error bias which shows the models have better skill in prediction of landfall point with slightly fast bias in 72 hr forecast range. It also shows NCEP ensemble forecasts are more accurate in predicting TC landfall time and location in 72 hr forecast range.

3.4. *Intensity errors*

Fig. 9 gives the ECMWF, NCEP deterministic and ECMWF, NCEP, UKMO ensemble forecasts average absolute intensity errors (kt) of three cyclone cases that formed during 2013 (Viyaru, Phailin, Lehar) along with the IMD operational errors based on corresponding TCs. The initial mean intensity bias is large in ECMWF (deterministic and ensemble) reducing from 22 kt to 9 kts in 72 hr forecast length. The NCEP GFS errors increased linearly with time from near 9 kt to 17 kt in 72 hr forecast range and NCEP ensemble mean intensity increased from 13 kt to 32 kt in 72 hr forecast length. The IMD operational forecast errors also increased linearly from 7 kt at 12 hr to 22 kt at 72 hr forecast. It shows that the IMD operational forecasts showed better skill upto 36 hr, beyond which high resolution models showed better skill of 5 to 8 per cent over IMD operational forecast. Since the spatial resolution in ensemble models are rather coarse compared with typical TC structures, global ensemble models are generally less good at predicting cyclone intensities than high-resolution deterministic models.

4. Conclusions

In the present study, tropical cyclone track forecasts based on ECMWF, NCEP deterministic and ECMWF, NCEP, UKMO ensemble were evaluated. It was observed that the initial position errors are large in all the models. The mean initial vortex position errors vary from 25 km to 128 km for 11 TC cases which affected the TC errors in subsequent forecasts for next 72 hr. The deterministic track forecast errors of ECMWF forecast errors over NIO shows the deterministic forecasts have less error than ensemble forecasts. The ECMWF 24, 48 and 72 hr deterministic (ensemble) DPE shows 105 (130), 177 (206), 272 (322) km, respectively. In case of NCEP, the deterministic and ensemble track forecast errors have not shown much difference. The 24, 48 and 72 hr deterministic (ensemble) forecast track errors were 102 (111), 163 (181), and 232 (252) km, respectively. The UKMO 24, 48 and 72 hr ensemble forecast had track errors of 165, 272 and 374 km, respectively. It shows that the NCEP model has less error than ECMWF and UKMO.

Compared to India Meteorological Department (IMD) operational track forecasts, NCEP deterministic and ensemble forecasts have shown skills within +/-15% and ECMWF deterministic forecasts have shown skill of 4 to -19% from 24 to 72 hr forecast range. The ECMWF and UKMO ensemble forecasts showed large negative skills compared to IMD operational forecast track errors. However, IMD operational forecasts shown better skill upto 12 hr compared to all the models. NCEP deterministic and ensemble forecasts have better skills compared to ECMWF and UKMO models over NIO. Independent study of each basin Bay of Bengal and Arabian Sea has shown that NCEP deterministic and ensemble forecasts have shown better skills over both the basins compared to ECMWF and UKMO models; however, ECMWF forecasts have shown slight better skills over Bay of Bengal compared to Arabian Sea. The UKMO ensemble forecasts show large negative skill over both Bay of Bengal and Arabian Sea.

The along track error bias shows all the models have fast tendency for all the lead time with NCEP models showing less error than ECMWF and UKMO models. The cross track position error bias showed the NCEP deterministic model has pronounced bias to the left-of-track, while NCEP EPS showed error bias within ± 10 km. However ECMWF and UKMO models showed large right-of-track bias. In all the models, the CT is less than the AT error bias which shows the models have better skill in prediction of landfall point with slightly fast bias in 72 hr forecast range. It also shows NCEP ensemble forecasts are more accurate in predicting TC landfall time and location in 72 hr forecast range.

The IMD operational forecasts showed better skill than the models in intensity forecasts upto 36 hr, beyond which high resolution model shown better skill of 5 to 8 per cent over IMD operational forecast. Since the model resolution in ensemble models are rather coarse compared with typical TC structures, global ensemble models are generally poorer at predicting cyclone intensities than high-resolution deterministic models. The present study is considered upto 72 hr forecast because of limitation of data availability. Efforts will be made to evaluate the same in medium range of 5 to 7 days forecast.

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