Evaluation of official tropical cyclone track forecast over north Indian Ocean issued by India Meteorological Department

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India Meteorological Department (IMD) introduced the objective tropical cyclone (TC) track forecast valid for next 24 hr over the north Indian Ocean (NIO) in 2003. It further extended the validity period up to 72 hr in 2009. Here an attempt is made to evaluate the TC track forecast issued by IMD during 2003–2011 (9 years) by calculating the direct position error (DPE) and skill in track forecast. The accuracy of TC track forecast has been analysed with respect to basin of formation (Bay of Bengal, Arabian Sea and NIO as whole), season of formation (pre-monsoon and post-monsoon seasons), intensity of TCs (cyclonic storm and severe cyclonic storm or higher intensities) and type of track of TCs (climatological/straight moving and recurving/looping type). The average DPE is about 140, 262 and 386 km and skill is about 27%, 39% and 50%, respectively for 24, 48 and 72 hr forecasts over the NIO as a whole during 2009–2011. Though the DPE is higher and skill is less as compared to those in northwest Pacific and north Atlantic Ocean, the rate of decrease (increase) in DPE (skill) is higher over the NIO in recent years. The DPE (skill) over the NIO has decreased (increased) at the rate of about 7.3 km (3%) per year during 2003–2011 for 24 hr forecasts.

1. Introduction

One of the more neglected components of post-storm analysis of tropical cyclone (TC) is the routine preparation of best tracks and detailed forecast performance statistics at the end of each season when more raw data and complete history of TC are available. Whilst this is a time-consuming task, which uses valuable resources, it provides the best possible storm archive, together with invaluable information on overall forecast performance and the relative performance of individual techniques. Such information is essential for:

- Developing new forecasting techniques and monitoring forecast improvements resulting from new algorithms, techniques and observing systems;

- Evaluation of value addition by forecasters to guidance received from the objective aids;
- Providing a basis for objectively estimating forecast uncertainty, which is used in deciding the timing and extent of warnings and watches, especially for critical regions;
- Providing feedback on the relative accuracy of available forecast techniques, perhaps including stratification into different synoptic, latitudinal, or seasonal types (e.g., Neumann and Pelissier 1981).

All the above is essential, as the most fundamental parameter in TC prediction is a storm's location or track. Improved short range (1–3 days) track forecasts lead to fewer unnecessary warnings and evacuations. It is due to the fact that the prediction

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of severe weather like storm surge depends on the predicted time and place of landfall, direction of movement towards land (crossing angle), speed of movement, etc. Similarly, the prediction of area and time of occurrence of heavy rainfall and gale wind along the coast depends on predicted track of the TC (IMD 2003). So, a better track forecast will yield improved forecasts of wind speed, storm surge, and precipitation along the coast during landfall of a TC.

IMD, as one of the six Regional Specialised Meteorological Centres (RSMCs), is responsible for TC monitoring and prediction over the north Indian Ocean (NIO). A cyclonic disturbance (CD) is considered as a TC over the NIO, when the associated maximum sustained surface wind (MSW) is 34 knots or more as per the classification adopted by IMD. It corresponds to the definition of tropical storms over other ocean basins like Pacific and Atlantic Oceans. Detailed classification of TCs into cyclonic storm (CS), severe cyclonic storm (SCS), very severe cyclonic storm (VSCS) and super cyclonic storm (SuCS) are given in cyclone manual published by IMD (2003). The depressions (with MSW) of 17–33 knots and TCs constitute the CDs over the NIO (IMD 2003).

IMD introduced the objective TC track forecast valid for next 24 hr over the NIO in 2003. It further extended the validity period up to 72 hr in 2009. It may be mentioned that the RSMC, Tokyo introduced 24 hr objective forecast in 1982, 48 hr forecast in 1988, 72 hr forecast in 1997 and 96 and 120 hr forecast in 2009 for north-west Pacific Ocean (RSMC, Tokyo 2011). Similarly, National Hurricane Centre (NHC) and RSMC, Miami, USA introduced 24 hr objective forecast in 1954, 48 hr forecast in 1961, 72 hr forecast in 1972, and 96 and 120 hr forecast in 2001 for Atlantic Ocean (NHC 2012). Prior to 2003, the TC forecasts issued by IMD for the NIO were subjective and textual in form without mentioning expected location of the TC in 12 and 24 hr forecast period.

Most of the TC forecasting centres including NHC, USA and RSMC, Tokyo verify their TC track forecasts regularly on yearly basis. RSMC, New Delhi introduced the objective TC forecast verification in 2009 (RSMS, New Delhi 2010). The TC forecast errors can be analysed from several perspectives. The most common is the absolute track error or direct position error (DPE). The DPE is the great circle distance between a TC's forecast position and the observed position at the forecast verification time.

In order to compare forecasts made in extremely variable conditions like quasi-stationary/fast moving TCs, recurving/looping of TCs and rapidly intensifying/dissipating TCs and evaluate their

quality by including these forecasts' degree of difficulty (in particular with the aim of detecting forecasts' trends with time), there are several possible options. The first, being the measurement of gain (or loss) in skill in forecast in relation to a reference model. In other words, an essential component of the error analysis is to normalise all forecast errors by a standard technique. Climatology and persistence (CLIPER) model is a statistical forecast technique which is used as a standard in most of the TC forecasting centres as the standard technique to calculate the skill in track forecast. Here, an attempt is made to evaluate the TC track forecast issued by IMD during 2003–2011 (9 years) based on the calculation of DPE and skill in track forecast.

The forecaster's awareness of the above-mentioned track forecast error measures represents an important factor in the overall decision process relative to the formulation of TC warnings and advisories (Simpson 1971). It is due to the fact that though the TC track forecasts have been steadily improving for several decades, some uncertainty still remains due to variation in track forecast errors with respect to type of track, season of formation and intensity of the TC, etc. For example, in a very severe TC with climatological track such as TC, Thane (25–30 December 2011, figure 1), the average 24 and 48 hr track forecast errors were 77 and 160 km, respectively. On the other hand, in a very severe TC with recurving track such as TC, Phet (31 May–7 June, 2010, figure 1), the average 24 and 48 hr track forecast errors were 162 and 311 km, respectively. A part of this uncertainty is also due to an inherent predictability limit that future improvements in numerical models and in forecasting techniques will not be able to overcome (Fraedrich and Leslie 1989; Plu 2011). Therefore, end users of TC forecasts, such as risk managers and public agencies, need both reliable track forecasts and an estimation of the forecast uncertainty. A measure of standard error in track forecast is represented in the form of cone of uncertainty (COU) in the track forecast. The depiction of uncertainty in track forecast in the form of COU helps the disaster managers to decide upon the area of evacuation and mobilization of resources for TC disaster mitigation. Hence, apart from the utilities as mentioned in the first paragraph, this study can be utilized to interpret the track forecast properly and decide effective cyclone management response actions by the disaster managers. To determine the COU in track forecast, it is essential to know the track forecast errors and skill in the past years. For construction of the COU in track forecast, an uncertainty circle is built for each forecast lead time, whose radius is based on the distribution of DPE computed

Figure 1. Tracks of TCs during 2003–2011 under consideration in the study. Tracks ending with red colour arrows are recurring/looping tracks and others are climatological/straight moving tracks.

over several previous seasons (Dupont *et al.* 2011). IMD at present uses the average forecast error for past five years based on official forecast and quasi Lagrangian model (QLM) to construct COU in track forecast.

This study can also be utilised to further fine tune the COU definition used by IMD as track forecast errors gradually decrease over the years. The fine tuning of the COU may also demand adoption of some new techniques or algorithms. As the uncertainty in a track forecast is dependent on the atmospheric conditions of that forecast, dynamic predictions of uncertainty are expected to be superior. For example, in a high-predictability scenario such as a TC propagating westward/northwestward for days along the southern periphery of a subtropical ridge, the uncertainty (and therefore warning area) may be considerably smaller than a low-predictability scenario such as a TC that recurves northeastwards/southwestwards. Hence there is a need for development of COU forecast model using dynamical model forecasts of track and intensity of TCs. The ensemble prediction system (EPS) is such an approach, which aims to provide probabilities (and distributions) based purely on the flow and its inherent uncertainty governed by the spread in the numerical weather prediction (NWP) model. So, this study can be used to evaluate and adapt the EPS based COU in track forecast of TCs.

2. Data and methodology

The data sample for evaluation of track forecast is composed of the tracks of all TCs with different intensities (cyclonic storm and above) over the NIO (north of equator and between longitude 45° and 100°E), over the period of nine years (2003–2011). The track forecast has been issued by RSMC, New Delhi from deep depression stage onwards since 2009 for 12, 24, 36, 48, 60 and 72 hr forecast periods. It has been issued during CS stage onwards during 2003–2008 and for 12 and 24 hr forecast periods only. The TC forecast issued 4 times a day at the interval of six hours, i.e., based on 00, 06, 12 and 18 UTC observations valid up to 24 hr during 2003–2008 and up to 72 hr during 2009–2011 have been considered for evaluation of forecast performance. The forecasts are issued about three hours after the above-mentioned observation time.

IMD follows a standard operation procedure (SOP) for monitoring and forecasting of TCs over the NIO. The detailed procedure is discussed in cyclone manual published by IMD (2003). Basically, the forecast tracks result from a manually analyzed forecasting process, which relies on output from several NWP models (RSMC 2010) including IMD Global Forecast system (GFS), European centre for Medium range Weather forecast (ECMWF), the UK Meteorological Office, Japan Meteorological Agency (JMA), ARP-Meteo-France, National

Centre for Environmental Prediction (NCEP) GFS and some ensemble means like multi-model ensemble (MME). Consensus forecasts that gather all or part of the numerical forecast tracks and uses synoptic and statistical guidance are utilised to issue official forecast.

A total of 28 TCs during 2003–2011 (figure 1) has been considered in the study including 20 over the Bay of Bengal (BoB) and 8 over the Arabian Sea (AS). Detailed characteristics of the TCs considered in the study are given in table 1. The total number of forecast verified for all forecast lengths (12, 24, 36, 48, 60 and 72 hr) is 671 including 261, 222, 70, 51, 39 and 28 numbers of forecast for 12, 24, 36, 48, 60 and 72 hr lead periods, respectively (table 2). The number of such forecasts decreases with increase in forecast length, as some of the CDs have less life period and some weaken below the intensity of deep depression within 72 hr of their genesis (figure 1).

All the TC track forecasts issued by IMD have been verified against the observed track of IMD. In this study, the DPE and skill of track forecast have been calculated for all the TCs during 2003–2008 for 12 and 24 hr forecast and during 2009–2011 for 12, 24, 36, 48, 60 and 72 hr forecast. The observed TC positions are taken from the official RSMC best-track dataset (IMD 2012). An example of calculation of the DPE based on forecast track and the observed best track is shown in figure 2. The DPE is measured by the distance between the RSMC forecast and the RSMC best-track position at the corresponding forecast verification time.

In order to measure the skill in track forecast, the CLIPER model has been used as a reference model. The CLIPER model is based on combination of persistence forecast using the past 12 hr trend in motion of the current TC and climatological forecast of movement of TC using the data of past years. The climatological forecast assumes

Table 1. *Details of the tropical cyclones (TCs) under consideration.*

Sl. no.	Year	Life period	Maximum intensity	Basin of formation	Season of formation	Type of track of TC	Landfalling/dissipating TC
1	2003	10–19 May	VSCS	BoB	PM	R	L
2	2003	12–15 November	SCS	AS	PS	S/C	D
3	2003	11–16 December	VSCS	BoB	PS	R	L
4	2004	30 September–3 October	SCS	AS	PS	R	L
5	2005	13–17 January	CS	BoB	Winter	S/C	D
6	2005	17–21 September	CS	BoB	Monsoon	R	L
7	2005	28 November–2 December	CS	BoB	PS	S/C	D
8	2005	6–10 December	CS	BoB	PS	S/C	L
9	2006	25–29 April	VSCS	BoB	PM	R	L
10	2006	21–24 September	SCS	AS	Monsoon	R	D
11	2006	29–30 October	CS	BoB	PS	S/C	L
12	2007	13–15 May	CS	BoB	PM	S/C	L
13	2007	1–7 June	SuCS	AS	Monsoon	S/C	L
14	2007	11–16 November	VSCS	BoB	PS	R	L
15	2008	27 April–3 May	VSCS	BoB	PM	R	L
16	2008	25–27 October	CS	BoB	PS	S/C	L
17	2008	13–16 November	CS	BoB	PS	S/C	L
18	2009	14–17 April	CS	BoB	PM	R	L
19	2009	23–26 May	SCS	BoB	PM	S/C	L
20	2009	9–12 November	CS	AS	PS	R	L
21	2009	10–15 December	CS	BoB	PS	R	L
22	2010	17–21 May	SCS	BoB	PM	R	L
23	2010	19–23 May	CS	AS	PM	S/C	D
24	2010	31 May–7 June	VSCS	AS	PM	R	L
25	2010	20–23 October	VSCS	BoB	PS	S/C	L
26	2010	4–8 November 2010	SCS	BoB	PS	S/C	L
27	2011	29 October–4 November	CS	AS	PS	R	L
28	2011	25–31 December	VSCS	BoB	PS	S/C	L

CS: Cyclonic storm, SCS: Severe cyclonic storm, VSCS: Very severe cyclonic storm, SuCS: Super cyclonic storm.

BoB: Bay of Bengal, AS: Arabian Sea, R: Recurring/looping, S/C: straight moving/climatological, L: Landfalling, D: Dissipating over sea, PM: Pre-monsoon, PS: Post-monsoon.

Table 2. Statistics of official six hourly track forecasts verified during 2003–2011.

Forecast period (hrs)	Basin of formation			Season of formation		Type of track		Intensity of CD	
	BoB (20)	AS (8)	NIO (BoB+AS) (28)	Pre-monsoon (10)	Post-monsoon (18)	Climatological/straight moving (14)	Recurving/looping (14)	CS (13)	SCS and higher intensity (15)
12	195	66	261	122	139	104	157	75	186
24	164	58	222	106	116	80	142	54	168
36	49	21	70	33	37	26	44	20	50
48	33	18	51	25	26	17	34	11	40
60	24	15	39	20	19	12	27	7	32
72	14	14	28	18	10	8	20	2	26
Total	479	192	671	324	347	247	424	169	502

Figures given within parentheses in the first row indicate the number of TCs.

Figure 2. An example of forecast track based on 0000 UTC of 27 December 2011, observed track of very severe cyclonic storm, Thane (25–30 December 2011) and the direct position error at different forecast verification time.

that TC will move with average speed and direction of all past TCs near that location. Since CLIPER is based entirely on current position and motion and derives its forecast from past storms, techniques that do not improve on this have no real skill. This normalisation also allows a ready comparison between ‘easy’ and ‘difficult’ forecast years and different ocean basins (Pike and Neumann 1987). Thus, CLIPER is an excellent measure of forecast difficulty and normalising all forecasts by the CLIPER errors provides a homogeneous indication

of forecast skill. In this study, the CLIPER model suggested by Neumann and Mandal (1978) has been used to calculate the DPE of CLIPER model with respect to TCs over the NIO. This CLIPER model gives equal weightage to persistence and climatological forecasts.

The gain in skill in relation to CLIPER, is quantified in percentage terms by:

$$\text{Gain in skill} = \frac{(\text{CLIPER DPE} - \text{DPE})}{\text{CLIPER DPE}} \times 100\%$$

The accuracy of TC track forecast has been analysed with respect to basin of formation (BoB, AS and NIO as whole), season of formation (pre-monsoon and post-monsoon seasons), intensity of TCs (CS and SCS or higher intensities) and type of track of TCs (climatological/straight moving and recurving/looping type) by calculating DPE and skill separately. The dataset include 13 CS and 15 SCS or higher intensity (table 2). The TCs show bi-modal behaviour in their genesis with primary maxima in post-monsoon season (October–December) and secondary maxima in pre-monsoon season (March–May). There have been nine TCs in pre-monsoon and 15 TCs in post-monsoon season respectively out of 28 TCs considered in the study. There have been three TCs during monsoon months (one in June and two in September) and another in winter season (table 1). Since the TC in the month of June 2007 (SN 13 of table 1) occurred during onset phase of monsoon, it had pre-monsoon characteristics. So it has been considered as the TC in pre-monsoon season for analysis purpose. Similarly, the TCs in September (SN 6 and 10 of table 1) have been considered in the category of the post-monsoon season, as it occurred during withdrawal phase of monsoon. The only cyclone in winter season (January–February) has also been considered in the post-monsoon season category, as it occurred in the northeast monsoon phase in January 2005 (SN 5 of table 1). As such, there are 10 and 18 TCs during pre-monsoon and post-monsoon seasons respectively. The performance of TC track forecast has been analysed during these two seasons separately, as their track, genesis and intensification characteristics are different in these two different seasons.

The results are analysed and presented in section 3. The limitations and future scope are presented in section 4. The broad conclusions are presented in section 5.

3. Results and discussion

The DPE and skill have been analysed with respect to basin of formation (NIO as a whole, BoB and AS) of TCs, type of track, intensity of TCs (CS and SCS or higher intensities) and season of formation (pre-monsoon and post-monsoon) and the results are presented and discussed in subsections 3.1–3.4. The interannual variations in the DPE and skill are analysed and discussed in subsection 3.5.

3.1 Average DPE and skill in TC track forecast

The statistics of DPE and track forecast skill are shown in figure 3(a and b) respectively. It is found that the average DPE during 2003–2011 is about 148 km for 24 hr forecast. Considering the

Figure 3. (a) Average direct position error (km) and (b) skill of track forecast issued by IMD for the TCs over the BoB, AS and NIO as a whole.

Table 3. Average track forecast error (km) and skill (%) of IMD for TCs over the NIO during 2009–2011.

Forecast period (hrs)	Track error (km)	Skill (%)	Number of forecasts verified
12	72	22.3	109
24	140	26.9	93
36	193	30.3	70
48	262	39.0	51
60	320	46.5	39
72	386	50.0	28

period of 2009–2011 when there has been significant improvement in monitoring and prediction of TCs over the NIO due to modernisation programme of IMD, the DPE is about 140, 262 and 386 km for 24, 48 and 72 hr forecasts, respectively (table 3). It increases with increase in forecast length like other ocean basins. Comparing the DPE over the NIO with that over the other TC basins, it is found that the DPE over the NIO is higher than that over the northwest Pacific and north Atlantic Oceans. The average DPE of NHC, USA for the TCs over the northern Atlantic Ocean during 2003–2011 is about 95, 150 and 250 km for 24, 48 and 72 hr forecasts, respectively (NHC 2012). Similarly, the DPE of RSMC, Tokyo for the TCs over the northwest Pacific Ocean is about

113, 208 and 310 km for 24, 48 and 72 hr forecasts respectively during 2003–2011 (RSMC, Tokyo 2011). The lower accuracy over the NIO may be due to the fact that the NIO is a data sparse region compared to northwest Pacific and north Atlantic Oceans, as there is no aircraft probing facility in the NIO unlike the northwest Pacific and north Atlantic Oceans. Further, the *in-situ* data from the meteorological buoys are significantly less over the NIO, with only five buoys working during 2003–2010 and 12 in 2011 (Mohapatra *et al.* 2012). Scarcity of observational data leads to poor initial condition in NWP models. The poor initial condition leads to increase in forecast error of NWP models (Mohanty *et al.* 2010; Osuri *et al.* 2012), which are the backbone for official track forecast of TCs, especially in 36–72 hr forecast range. However, better initial condition is not the sufficient condition for improvement of track forecast. The higher resolution, better physical parameterization and consideration of physical processes like ocean–atmosphere coupling and assimilation of various remotely sensed and directly observed data are also necessary for improvement in track forecast by NWP models.

Considering the skill of track forecast, it is about 23% for 24 hr forecast period during 2003–2011. Considering the period of 2009–2011, the skill of track forecast is about 27%, 39% and 50% for 24, 48 and 72 hr forecasts (figure 3b). Comparing with that over the north Atlantic and northwest Pacific, the skill is also less over the NIO. The average skill of NHC, USA for the TCs over the north Atlantic Ocean during 2003–2011 is about 45%, 55% and 54% for 24, 48 and 72 hr forecasts, respectively (NHC 2012). The skill over the NIO thus lags from that over north Atlantic Ocean by about 22%, 16% and 4% for 24, 48 and 72 hr forecast periods. Similarly, the skill of RSMC, Tokyo for the TCs over the northwest Pacific Ocean is about 51%, 58% and 62% for 24, 48 and 72 hr forecasts, respectively during 2003–2010 (RSMC, Tokyo 2011). It may be mentioned that the skill of TC track forecast by RSMC, Tokyo is calculated based on persistence method as standard reference method. Hence it shows higher skill even compared to that over the north Atlantic Ocean by NHC, USA. The skill forecast by NHC, USA is based on CLIPER model as the reference model like that for the NIO by RSMC, New Delhi.

3.2 Average DPE and skill in track forecast with respect to basin of formation of TCs

The statistics of DPE and skill in track forecasts are shown in figure 3 for the TCs over BoB and AS. There are 20 and eight TCs in BoB and AS respectively during 2003–2011. There are 479 and 192

cases of track forecasts for different forecast lengths (table 2) for TCs over the BoB and AS respectively. It is found that there is no significant difference in DPEs over the BoB and AS for the 12, 24 and 36 hr forecasts. However, the DPE is less over the BoB than over the AS for 48 to 72 hr forecasts by about 80, 140 and 325 km, respectively. Considering the skill in track forecast (figure 3b), the skill is also generally higher over the BoB for all forecast lengths under consideration except 24 hr forecast. The difference in skill increases with increase in forecast length. The higher accuracy over the BoB may be attributed to the fact that the open sea area, which is a data sparse region is relatively less in case of BoB than in AS. While there is a dense observatory network along the coast surrounding the BoB due to dense coastal observatories and cyclone detection radars, the coastal area surrounding AS does not have such a network. It leads to more accurate determination of location and intensity over BoB than in AS (Mohapatra *et al.* 2012). The higher initial error in location and intensity estimation of CDs over the AS leads to higher track forecast error (Mohanty *et al.* 2010; Osuri *et al.* 2012). Another reason for higher DPE over the AS may be due to the fact that the percentage of recurving/looping TCs is higher over the AS than over the BoB. While five out of eight (63%) TCs over the AS are recurving/looping type, it is nine out of 20 (45%) over the BoB, which are recurving/looping type.

Figure 4. (a) Average direct position error (km) and (b) skill of track forecast issued by IMD for the straight moving/climatological TCs and recurving/looping TCs over NIO.

3.3 Average DPE and skill in track forecast with respect to nature of the track and season of formation of TCs

As it is evident from figure 1, the TCs follow different track characteristics. It is a well established fact that the predictability is less in case of recurving and looping TCs and more in case

of straight moving TCs. Neumann and Pelissier (1981) have demonstrated it over the Atlantic Ocean based on official forecast of NHC. To find out the impact of nature of track on TC track forecast, the TCs over the NIO have been further categorized as climatological/straight moving and recurving/looping TCs and the corresponding track forecast errors have been analysed and

Figure 5. Tracks of TCs during (a) pre-monsoon and (b) post-monsoon seasons over the period of 2003–2011 under consideration.

discussed. There are 14 such TCs of different intensities in each of these two categories. There are 247 and 424 cases of track forecast for different forecast lengths (table 2) for climatological/straight moving and recurving/looping TCs respectively.

The statistics of DPE and skill in track forecast are shown in figure 4 for the climatological/straight moving and recurving/looping TCs. It is found that the DPE is significantly higher in case of recurving TCs, being about 50, 200 and 300 km more for 24, 48 and 72 hr forecasts respectively than that for the straight moving/climatologically moving TCs. Considering the skill in track forecast (figure 4b) for the above two categories of TCs, the skill is significantly higher in case of climatological/straight moving TCs and significantly less in case of recurving/looping TCs. It is less by about 19%, 42% and 39% for 24, 48 and 72 hr forecasts respectively than that for the straight moving/climatologically moving TCs. However, the average skill is still positive for all forecast periods indicating the fact that the method adopted is still skillful for track forecasting of recurving/looping TCs.

There are 10 and 18 TCs in pre-monsoon and post-monsoon seasons respectively considered in the study (figure 5). There are 324 and 347 cases of TC track forecasts for different forecast lengths (table 2) for TCs in pre-monsoon and post-monsoon seasons respectively during this period. The statistics of DPE and skill in track forecast are shown in figure 6 for the TCs in pre-monsoon and post-monsoon seasons. It is found that the DPE is less in case of TCs during post-monsoon season. The DPE varies from 86 km for 12 hr forecast to 229 km for 72 hr forecast during post-monsoon season. Considering the skill in track forecast (figure 6b), the track forecast skill is also higher in post-monsoon season than in pre-monsoon season. The difference in skill also increases with increase in forecast length. The higher accuracy during post-monsoon season may be attributed to the fact that the percentage of climatological/straight moving TCs out of total TCs is more in post-monsoon than in pre-monsoon season (figure 5). Out of 10 TCs, six (60%) are recurving/looping type in pre-monsoon season, whereas eight out of 18 (44*) TCs are recurving/looping type in post-monsoon season. As discussed in the previous paragraph, the accuracy in track forecast is more in case of climatological/straight moving than in case of recurving/looping TCs.

3.4 Average DPE and skill in track forecast with respect to intensity of TCs

As the TCs intensify gradually, their location and intensity estimation become more accurate with

Figure 6. (a) Average direct position error (km) and (b) skill of track forecast issued by IMD for the TCs during post-monsoon and pre-monsoon seasons over NIO.

well developed characteristic features of TCs such as eye, central dense overcast (CDO) and curved band features (IMD 2003). It results in more accurate location and intensity estimation over the open seas using satellite and radar techniques. Available buoy, ship, coastal and island observations suffice the observations of satellite and radar. With more accurate determination of location and intensity, the accuracy of track forecasts increases in NWP models (Mohanty *et al.* 2010; Osuri *et al.* 2012). Hence, it is hypothesized that the official track forecast accuracy would increase with increase in intensity of TCs. To verify this hypothesis, the TCs have been classified into two categories, viz., (i) CS (maximum surface wind speed of 34–47 knots) and (ii) SCS and higher intensity (48 knots or more). The definition of the TCs analysed here is same as that adopted by IMD (2003). There are 13 and 15 TCs with intensity of CS and SCS or higher intensity respectively during 2003–2011 (figure 7). There are 169 and 502 cases of TC track forecasts for different forecast lengths (table 2) for TCs with intensity of CS and SCS or higher intensity respectively. The statistics of DPEs and skills are shown in figure 8. It is found that the DPE is less in case of SCS or higher intensity TCs. Similarly, the track forecast skill is also significantly higher in case of SCS. This result proves the hypothesis mentioned above that the track forecasting is easier in the severe TCs.

3.5 Interannual variation in DPE and skill of TC track forecast

Verification of TC track forecast is important to evaluate the year on year improvement (or otherwise). So the interannual variation in TC track forecast has been analysed based on DPE and skill of forecast. The results are shown in figure 9. The DPE has decreased gradually and

the skill has increased during the period of study as evident in the trend lines. The improvement in track forecast error (reduction in DPE) is about 5.9 and 7.3 km/year for 12 and 24 hr forecasts, respectively during 2003–2011 (table 4). In terms of percentage improvement, it is about 7.3% and 4.2% per year respectively. The trend in improvement is statistically significant at 97.5% and 95% level respectively for 12 and 24 hr forecasts

Figure 7. Tracks of (a) severe cyclonic storms and higher intensity and (b) only cyclonic storms over NIO.

Figure 8. (a) Average direct position error (km) and (b) skill of track forecast issued by IMD for the severe cyclonic storm and higher intensity and only cyclonic storms over NIO.

according to one tailed Student's 't' test. Considering the improvement in skill in track forecast, it has improved by about 9% and 3% per year respectively for 12 and 24 hr forecasts and are significant at 99% and 90% level.

Comparing with the trends in northwest Pacific Ocean, it is found that the 24 hr DPE has decreased insignificantly only at the rate of 0.9 km/year during 2003–2010. Accordingly, there has been improvement in skill by about 0.3% per year (RSMC, Tokyo 2011). Similarly, the rate of decrease over the north Atlantic Ocean is about 1.7 km/year and the skill has improved at the rate of 1.9% per year during 2003–2011 (NHC 2012). It indicates the fact that the rate of reduction in TC track forecast error has decreased significantly and hence the DPE is almost reaching the saturation stage in 24 hr forecast range over the northwest Pacific and northern Atlantic Ocean. However, there is still scope for further reduction in 24 hr forecast error over the NIO to about 100 km from the existing 140 km based on the latest technology including aircraft reconnaissance, deployment of buoys, assimilation of more observational data from satellite and Doppler weather radars, etc., in the NWP models.

Recent improvement in track forecast may be attributed to the improvement in the observations including:

- surface based observations through automatic weather stations (AWSs) in addition to conventional synoptic observations from manned observatories,

Figure 9. (a) Average track forecast error (km) and (b) track forecast skill (%) of IMD for TCs over NIO during 2003–2011.

Table 4. Average annual improvement per year (IMP), variance explained (Var), statistical significance (Sig) of trend lines shown in figure 9.

Forecast period (hrs)	IMP in track forecast error		Variance (%)	Sig. level of trend line	IMP in track forecast skill (%)	Variance (%)	Sig. level of trend line	Number of forecasts verified
	In km	In %						
12	5.9	7.3	48.5	97.5%	8.8	62	99%	261
24	7.3	4.2	35.8	95%	3.3	28	90%	222

- upper air observations based on GPS sonde,
- Doppler weather radar observations along the coast,
- satellite based observations like surface wind through Oceansat-II and microwave imageries and products in addition to conventional visible, infrared and water vapour based imageries and products.

The enhanced observation has resulted not only in better synoptic guidance to forecaster, but also has helped in improving the initial conditions for the global and regional NWP models and hence their predictions. Further, there has been improvement in NWP capabilities through the access to array of global and regional models in recent years including IMD-GFS, ECMWF, UKMO, JMA, NCEP and Meteo-France global models, regional models like WRF and QLM and MME based on various global and regional models. Also, the tools and techniques for analysis and forecasting have improved with the introduction of Tropical Cyclone Module (TCM) in the digitised forecasting system available with the forecaster. It helps in comparing various NWP, synoptic and statistical guidance to develop a consensus track forecast of TC. Details about the improvement in observational, NWP and analysis and forecasting tools and techniques in recent years have been discussed by Mohapatra *et al.* (2013).

4. Limitations and future scope

The analysis is based on data of limited period, especially in the forecast range of 48–72 hr period. However, the results are very interesting and in agreement with the global trend during the same period. The study has not included other measures of track forecast error, such as across track error which measures whether forecast tracks have a leftward or rightward bias and along track error which determines whether forecast tracks are slow or fast (Heming and Goerss 2010). Similarly, the study does not include the evaluation of location of landfall forecast error which is an alternative to the DPE (Powell and Abernson 2001). These two aspects are being dealt with in separate studies.

5. Conclusions

The following broad conclusions are drawn from the above results and discussion.

The average DPE is about 140, 262 and 386 km and skill is about 27%, 39% and 50% respectively for 24, 48 and 72 hr forecasts over the NIO as a whole during 2009–2011. Though the DPE is higher and skill is less as compared to those in northwest Pacific and north Atlantic Ocean, the rate of decrease (increase) in DPE (skill) is higher over the NIO in recent years. The DPE (skill) over the NIO has decreased (increased) at the rate of about 7.3 km (3%) per year during 2003–2011 for 24 hr forecasts. This improvement has been possible due to improvement in observation, analysis tools and techniques and NWP modelling.

There is still scope for further reduction in track forecast error over the NIO based on the latest technology including

- further improvement in initial condition of the atmosphere and Ocean through aircraft reconnaissance and deployment of more buoys,
- assimilation of more observational data from satellite and Doppler weather radars, etc., in the NWP models,
- implementation of high resolution mesoscale ocean–atmosphere coupled model like hurricane weather research and forecast (HWRF),
- implementation of ensemble prediction system (EPS) for global and mesoscale models, and
- implementation of grand global ensemble through international collaboration, etc. IMD is already taking up all these aspects through its continuous upgradation programme.

The DPE is less and the skill is higher over the BoB than over the AS for all forecast lengths up to 72 hr. Similarly, the DPE is less and the skill is higher during the post-monsoon season than during pre-monsoon season. The DPE is also less and the skill is higher for the severe TCs than the marginal TCs. Similarly, the DPE is less and the skill is higher for climatologically moving/straight moving TCs than for the recurving/looping TCs. Comparing these results, the type of track and the intensity of the system are also the crucial factors in determining the DPE and skill of track forecasts.

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