

# Reduction in uncertainty in tropical cyclone track forecasts over the North Indian Ocean

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*Over the North Indian Ocean (NIO) basin, the uncertainty in tropical cyclone (TC) track forecast is depicted by constructing a cone of uncertainty (COU) around the forecast track for the benefit of disaster managers in their decision-making, especially with respect to area of evacuation. The COU is constructed by drawing a tangent to the circles with the radii equal to average track forecast errors during the past five years for forecast times of 12, 24, 36, ..., up to 120 h. The COU which is revised periodically to reflect the track forecast accuracy, has been recently revised by India Meteorological Department (IMD) from the post-monsoon season of 2014. Hence, a study has been undertaken to evaluate this newly introduced COU forecast by IMD. The revised radii used to construct the COU have shrunk by 20–30% due to improved TC track forecast in the recent years (2009–2013). For the new COU, the radii of circles for 24, 48, 72, 96 and 120 h forecasts are 65, 105, 140, 170 and 200 nm respectively, against 80, 135, 185, 235 and 285 nm for the previous COU (2009–2013). The accuracy of the newly constructed forecast COU is 70–80% and is comparable with those of other leading TC forecasting centres in the world.*

**Keywords:** Cone of uncertainty, forecast, ocean basin, track, tropical cyclone.

TROPICAL cyclones (TCs) are the most devastating phenomena among all natural disasters, having taken more than half a million lives all over the world in the last five decades. The extensive coastal belts of India are exposed to TCs, which originate in the North Indian Ocean (NIO), including the Bay of Bengal and the Arabian Sea every year<sup>1,2</sup>. On an average about five TCs develop over NIO in a year<sup>3</sup>, which is about 7% of the global TCs. However, the Indian seas have historically witnessed higher number of human deaths due to the TCs. There is therefore a need to provide accurate forecast to disaster managers with sufficient lead time to combat disaster due to TCs.

India Meteorological Department (IMD) is the nodal agency to monitor and predict cyclonic disturbances over NIO. It provides early warning services for management of TCs. The track of a TC is one of the most fundamental parameters needed by disaster managers for its management. The TC warning bulletin includes current location and intensity of the cyclone, and the forecast positions (track) six hourly for the first 24 h and 12 hourly up to the next 120 h. This forecast is consensus based on the guidance from various numerical weather prediction (NWP) models and subjective analysis of various satellite-derived products, radar and synoptic observations.

Each individual deterministic NWP model exhibits errors in predicting the track (location of centre) of a TC at different forecast lengths like 12, 24, ..., 120 h depending upon the model characteristics. Also, the track forecasts from different models differ from each other as different NWP models have different resolutions, initial and boundary conditions, data assimilation techniques and physics. To minimize this spread or uncertainty in track forecast, a consensus track forecast is generated by the forecasters using objective methods like multi-model ensemble technique<sup>4</sup> blended with subjective analysis of synoptic and climatological guidance based on latest available observations<sup>5</sup>. It is imperative on the part of the forecaster to indicate the above uncertainty in the track forecast in order to effectively convey the accuracy in the track and landfall location forecasts. The most popular and effective method of expressing the uncertainty in the track forecast is by the depiction of a cone of uncertainty (COU) based on the historical margin of error in the forecast track<sup>6</sup>. This helps the disaster managers in decision-making with respect to area of evacuation, etc. As the points on a forecast map are timed out every 12 h, the margin of error increases in 12-h increments. The margin of error is expressed with circles radiating out from the forecast location of the centre of the storm. Each circle, for a given forecasting period, has a radius equal to the average error in all forecast tracks over the previous 5–10 years. The COU is constructed by connecting the outer boundaries of the series of these circles by a tangential

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line. The vertex of the cone represents the present location of the centre of the storm.

Most World Meteorological Organization (WMO) designated Regional Specialized Meteorological Centres (RSMCs) for TCs, including New Delhi, Miami, Tokyo, etc. and Tropical Cyclone Warning Centers (TCWCs) display COU along with their official track forecasts. For each forecast lead time, the uncertainty circle is built with its radius taken as a fixed quantile (e.g. 67% by RSMC Miami, 70% by RSMC Tokyo) of the distribution of direct position error (DPE; the great circle distance between the positions of the forecast centre and the observed centre for a given time of observation) computed over several previous seasons<sup>7</sup>. The National Hurricane Center (NHC), USA, first introduced depiction of COU in the forecast track in 2002 (ref. 6). The radii of the circles constructed by them to create the COU are the same as the average errors during past five years for different forecast times. Thus, for the Atlantic and the northeast Pacific (NEP) basins, the size of each circle has been set by NHC such that two-thirds (67%) of historical official forecast errors over a five-year sample ([www.nhc.noaa.gov/aboutcone.shtml](http://www.nhc.noaa.gov/aboutcone.shtml)) lie inside the circle. The Joint Typhoon Warning Center (JTWC) in Hawaii constructs COUs for TCs over the Pacific Ocean and Indian Ocean, whose radii are the sum of the climatological average DPE and the predicted 34-knot wind radius around the centre of the TC. As most of these centres construct COU based on DPE during the recent past five years, it is subject to change depending on the change in DPE between the earlier and the latest five-year periods. Recently, RSMC, La Reunion has introduced a dynamical COU in its track forecast using European Centre for Medium Range Weather Forecast (ECMWF) ensemble prediction system (EPS) with 51 members<sup>8</sup>. In case of dynamical COU, the radii of circles used to construct the forecast COU are based on the standard spread in forecast tracks from the mean track for different forecast times up to 120 h in the interval of every 12 h. As the dynamical track forecast by the EPS-based models as well as their spread change for each initial condition of the model, the COU thus constructed changes each time the forecast is made during the life cycle of a TC. It also changes from

one TC to another. On the other hand, the COU based on past average errors is static in nature, as it remains the same during the life cycle of all TCs in a year for a given ocean basin.

The uncertainty in the track forecast of TCs over the NIO, which includes the Bay of Bengal and the Arabian Sea is also depicted by RSMC, New Delhi in the form of COU with effect from 2009 (ref 6). The objective of this study is to discuss the evolution and present status of construction of COU for the NIO basin.

### Cone of uncertainty for the NIO basin

IMD introduced objective TC track forecast for the NIO with forecast lead time of 24 h. The forecast validity period was extended up to 72 h in 2009 (ref. 5) and 120 h in 2013 (ref. 9). During the period 2003–2008, TC track forecasts were issued for 12 and 24 h lead periods from the time the low pressure system attained the intensity of a TC (maximum sustained wind (MSW)  $\geq 34$  knots). Since 2009, IMD has been issuing TC track forecasts from the time it attains an intensity of MSW  $\geq 28$  knots, which corresponds to the intensity stage of deep depression (DD) according to the classification of low-pressure systems by IMD<sup>10</sup>.

From 2009 onwards, COU in the 72 h track forecast is also being depicted IMD in its graphical warning product according to international practice<sup>6</sup>. Until 2013, this COU was based on five-year average errors of official track forecasts of IMD for 12 and 24 h forecasts. For 36–72 h forecasts, five-year average track forecast error of Quasi Lagrangian Model (QLM) run in IMD was used, as 36–72 h forecast was introduced only in 2009 (ref. 6). The COU forecast has been extended to 120 h since 2013 (ref. 9).

### Current cone of uncertainty

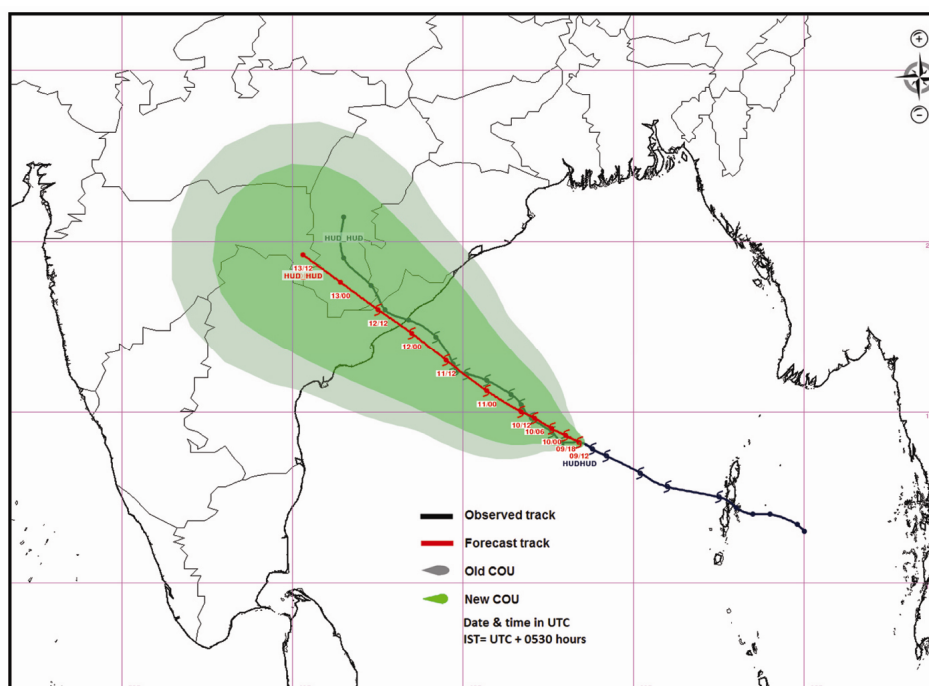
From the post-monsoon season (October–December) of 2014, the radius of the COU has been re-determined based on the official track forecast errors during the period 2009–2013. Table 1 shows the operational track forecast errors and the skill of the forecasts of IMD against the climatology and persistence (CLIPER) method forecasts during the period 2009–2013 for lead times 12–72 h. As TC forecasts were issued every 6 h up to 24 h and every 12 h thereafter up to 72 h during 2009–2012, the radii of the circles used to construct the COU were the same as the average track forecast errors (DPEs) for 6, 12, 24, 36, 48, 60 and 72 h track forecasts. Detailed methodology used to calculate the track forecast errors for the NIO has been discussed by Mohapatra *et al.*<sup>5</sup>. As IMD extended the forecast lead time from 72 to 120 h only in 2013, long-period average errors of 84–120 h forecasts are not available and hence the radii for 84, 96, 108 and 120 h have been determined by linearly extrapolating the errors

**Table 1.** Mean track forecast errors and skill of India Meteorological Department for tropical cyclones over the north Indian Ocean during 2009–2013

Forecast lead time (h)	Track forecast error (km; 2009–2013)	Forecast skill (%) (2009–2013)
12	68.5	31.2
24	124.1	35.9
36	163.8	43.9
48	202.1	52.6
60	233.8	58.1
72	268.2	61.8

**Table 2.** Radii of circles used to construct cone of uncertainty in track forecast during 2009–2013 and 2014–2015

Forecast lead time (h)	Radius of the circle used to construct cone of uncertainty in track forecast (n mile)		Reduction in radius of circle (%)
	During 2009–2013	Since 2014	
00	10	10	0
06	20	20	0
12	40	35	12.5
18	60	50	16.7
24	80	65	18.9
36	115	85	26.1
48	135	105	22.2
60	165	125	24.2
72	185	140	24.3
84	205	155	24.3
96	235	170	27.7
108	265	185	30.2
120	285	200	29.8



**Figure 1.** Observed and forecast tracks along with the old and new cones of uncertainty (COUs) in respect of tropical cyclone Hudhud (7–14 October 2014) based on 1200 UTC of 9 October 2014.

of 60 and 72 h. The new radii of circles determined to construct the COU are shown in Table 2 along with the percentage of reduction in the respective radius of COU from the old COU. The new COU has been made operational by IMD from post-monsoon season (October–December) in 2014. Figure 1 presents sample TC track forecasts along with the forecasts up to 120 h for the old and new COUs for the TC Hudhud based on 1200 UTC of 9 October 2014. It may be mentioned that the TC Hudhud which developed over the Bay of Bengal on 7 October

2014, crossed Andhra Pradesh coast near Visakhapatnam around 0700 UTC on 12 October 2014 (ref. 7).

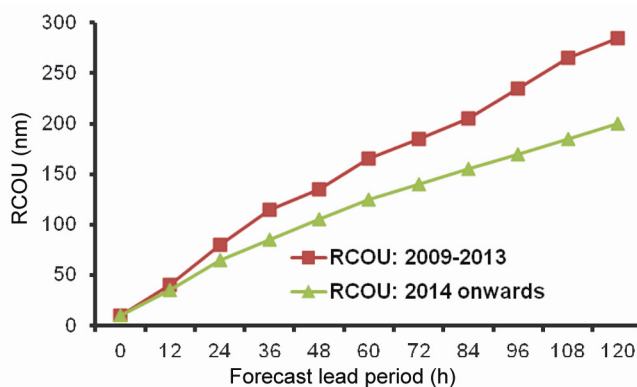
The present radii of the COU for 24, 48, 72, 96 and 120 h lead times are 81%, 78%, 76%, 72% and 70% of the corresponding radii of COU during the period 2009–13 (Figure 2). Improvement in TC track forecasting during the period 2009–2013 has enabled this shrinking of the radius of COU in TC track forecasts over NIO by about 20–30% in 24–120 h track forecasts with effect from October 2014 (Table 2). This has been mainly due

to the various initiatives taken by IMD towards improvement of TC forecasting<sup>11</sup>.

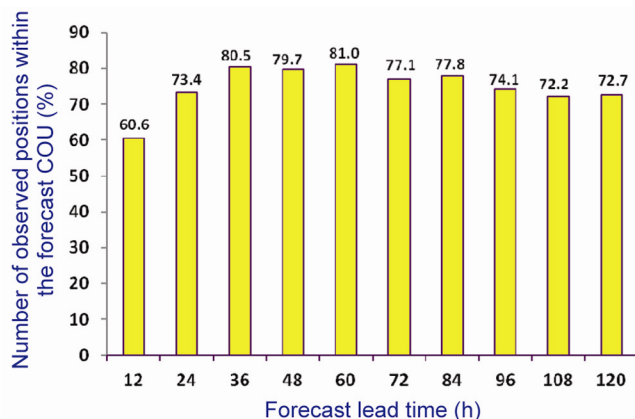
### Accuracy of cone of uncertainty forecast

Based on forecast tracks of TCs over NIO during 2009–2011, Mohapatra *et al.*<sup>6</sup> have noted that the observed track lies within the forecast COU in about 60% of the cases. It varies from 57% to 63% for different forecast lengths (12–72 h). On a sub-basin scale, the accuracy of COU forecast for the Bay of Bengal and the Arabian Sea is about 64% and 52% respectively, and on a seasonal scale, it is about 66% for the primary cyclone season (post-monsoon season) and about 50% for the secondary cyclone season (pre-monsoon season, i.e. March to May)<sup>6</sup>. It has also been pointed out in this study that the low accuracy in the forecast COU is a manifestation of large DPEs associated with recurring TCs, and this warrants use of a dynamical COU.

Figure 3 shows the accuracy in the present COU based on forecasts for TCs during 2014 (post-monsoon season) and 2015. The observed track lies within the forecast COU in about 73%, 80%, 77%, 74% and 73% cases for



**Figure 2.** Radii of circles for construction of cone of uncertainty (RCOU) during 2009–2013 and 2014–2015.



**Figure 3.** Accuracy of cone of uncertainty forecasts during 2014–2015 over the North Indian Ocean.

24, 48, 72, 96 and 120 h forecast respectively. Hence, there has been a significant improvement in COU forecast from 2009–2013 to 2014–2015 due to various initiatives taken by IMD for improving TC forecasting<sup>11</sup>.

The accuracy in the present forecast COU for NIO is at par with other leading TC forecasting centres of the world. While 70% of the TC tracks fall within the COU for the northwest Pacific, 60–70% lie within the COU for north Atlantic and northeast and northcentral Pacific basins. Over the southern hemisphere, 75% and 70% of the TC tracks fall within the COU for the south Indian and the Australian basins respectively<sup>7</sup>.

The circle radii defining the new COU based on track forecast errors of IMD during 2014–15 are 65, 105, 140, 170 and 200 n miles for 24, 48, 72, 96 and 120 h forecasts respectively, against 52, 90, 122, 170 and 225 n miles respectively, for the Atlantic (based on 2010–14 track forecast errors; [www.nhc.noaa.gov/aboutcone.shtml](http://www.nhc.noaa.gov/aboutcone.shtml)). Thus the 24, 48 and 72 h forecast radii for NIO are still higher than those for the Atlantic by about 15–25%. The 96 and 120 h radii are almost the same and less than those for the Atlantic. Hence, there is scope for further improvement in the track and uncertainty forecasts of TCs over NIO.

### Conclusion

Over the NIO basin, the uncertainty in track forecast is depicted by constructing a COU around the forecast for the benefit of disaster managers in decision-making, especially with respect to area of evacuation. The COU is constructed by drawing a tangent to the circles with the radii equal to average track forecast errors during the past five years for the forecast times of 12, 24, 36, ..., up to 120 h. The COU is revised periodically, preferably once a year, to reflect the track forecast accuracy. The COU was revised recently by IMD from the post-monsoon season of 2014.

The revised radii used to construct the COU have shrunk by 20–30% for 24–120 h forecast period due to improved TC track forecast errors during the recent years (2009–2013). For the newly constructed COU, the radii of circles pertaining to 24, 48, 72, 96 and 120 h forecasts are 65, 105, 140, 170 and 200 nm respectively, against 80, 135, 185, 235 and 285 nm respectively, for the previous COU (2009–2013). The accuracy of the newly constructed forecast COU is 70–80% and is comparable with those of other leading TC forecasting centres of the world. However, the present radii of circles used to construct the new COU are 15–25% higher than those for the Atlantic for 24–72 h lead period. Hence, there is still scope for further improvement.

There is a need for development of COU forecast using dynamical model forecasts of the track of TCs. IMD is utilizing the global EPS products through TIGGE

database (THORPEX Interactive Grand Global Ensemble) with the help of Japan Meteorological Agency and WMO. The National Centre for Medium Range Weather Forecasting (NCMRWF), Noida, is running a 20-member ensemble of global forecast system model and also developing a 40-member ensemble based on NCMRWF-UK Meteorological Office Unified model. These ensemble predication products could be utilized for dynamical COU forecast.

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