REVISITING TROPICAL CYCLONE ACTIVITIES OVER NORTH INDIAN OCEAN BASED ON MULTIPLE NUMERICAL WEATHER PREDICTION MODELS OUTPUT

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ABSTRACT: The present study examines the cyclonic activities that have occurred in North Indian Ocean (NIO) during the period 1997 to 2019. Moreover, the performance of four Numerical Weather Prediction (NWP) models, namely, India Meteorological Department-Global Forecast System (IMD-GFS), United Kingdom Meteorological Office (UKMO), European Centre for Medium Range Weather Forecasts (ECMWF) and IMD Multi-Model Ensemble (IMD-MME) have been also analysed based on annual average track forecasts error of tropical cyclones which formed during the period 2015-19 over the North Indian Ocean. For this purpose, 12-hourly annual average track forecasts errors have been taken up to 120 hours. Present studies elucidate the trend of the occurrence of number of tropical disturbances based on its stages and inter annual variation of track forecasts error (i.e., direct position error) of four NWP models. Present results show that 94 tropical cyclones were formed during 1997-2019, out of which 61 (around 65%) were in Bay of Bengal and 33 (around 35%) were in Arabian Sea. This shows that the number of tropical cyclones formation in Bay of Bengal was higher than the Arabian Sea. However, last ten years (from 2010-19) analysis shows that the percentage contribution of Arabian Sea tropical cyclones has been increased by 5%. Furthermore, the overall track forecast error analysis during 2015-19 reveals that the Multi-Model Ensemble (MME) consensus forecast was outperformed among the four models.

1. INTRODUCTION

Tropical cyclones (TCs) are extreme synoptic weather systems that originate from the world's warm oceans and grow into large vortices made up of swirling winds, dense clouds and torrential rains by drawing energy from the oceans. They cause large-scale devastation of life and property around the world's coastal areas as they pass across land. India is vulnerable to the destructive features associated with landfalling North Indian Ocean (NIO) basin TCs consisting of the Bay of Bengal (BoB) and the Arabian Sea (AS) with an extensive coastline of about 7500 km (Mohapatra *et al*, 2017). Regional Specialised Meteorological Centre (RSMC) of India Meteorological Department (IMD), New Delhi is involved in the tracking and prediction of tropical cyclones (TC) across the NIO basin consisting of the AS and the BoB. TC forecasts and alerts provided by RSMC, New Delhi include prediction genesis of TC and location (in terms of latitude and longitude), movement, intensity with reference to Maximum Sustained Surface Wind Speed (MSW), time and location of landfall and detrimental weather condition corresponding the landfall due to TCs. The basic observations for these forecasts come from the automatic weather stations (AWS), conventional surface and upper air station networks, automatic rain gauge stations (ARG), ships, ocean buoys, satellite data and products, high wind speed recorders (HWSR) and doppler weather radars (DWR) installed along the Indian coastal belt. Numerical Weather Prediction (NWP) guidance from various models such as IMD-Global Forecast System (IMD-GFS), United Kingdom Meteorological Office (UKMO), European Centre for Medium Range Weather Forecasts (ECMWF),IMD-Multi Model Ensemble(IMDMME),and many more are used for forecast guidance up to 5 days. A sophisticated weather forecasting tool and a tropical cyclone module developed by Meteo France International (MFI) are used to evaluate multi-platform observations and products synergistically and to improve forecast products(Mohapatra, 2014). The parameters such as the location, date and time of formation of tropical cyclone, and the subsequent intensity and positions are generated for various intensity stages of: depression (D, Maximum Sustained Wind (MSW) : 17-27 knots (kts)), deep depression (DD, MSW: 28-33 kts), cyclonic storm (CS, MSW: 34-47 kts), severe cyclonic storm (SCS, MSW: 48-63 kts), very severe cyclonic storm (VSCS, MSW: 64-89 kts), extremely severe cyclonic storm (ESCS, MSW: 90-119 kts) and super cyclonic storm (SuCS, MSW:≥120 kts). The forecast is issued based on observations at 00, 03, 06, 12 and 18 UTC during D/DD stages and 3-hrly observation at 00, 03, 06, 09, 12, 15, 18 and 21 UTC during the stages of CS and above (Mohapatra, 2014).The findings at this time are summarized as Best Track data for the specific TC by IMD and archived year-wise from the year 1990 (Mohapatra, 2014). Since 2009, TC track forecast for 12, 24, 36, 48, 60,72-hr is issued by RSMC New Delhi from the deep depression stage onwards and from 2013 onwards the forecast is made available up to 120 hours. The forecasts are verified as per the standard practices adopted by various national meteorological agencies and recommended by the World Meteorological Organisation (World Meteorological Organization, 2013). Observations of TCs and the associated weather with them over the NIO region come from a variety of sources, including buoys, ship logs, radiosondes , surface networks, radar, and meteorological satellites. Such findings and their accuracy are critically significant in the assessment of TC predictions and their impacts – and also a limiting factor. Uncertainties in these measurements lead to uncertainties in the results of the predictions for verification; as this uncertainty is often unknown, it is difficult to incorporate it into the predictions for TC evaluation.(Mohapatra *et al*, 2012) addressed limitations of best track parameters in relation to the NIO. The TC track verification is carried out for 6-hrly forecasts issued at 00, 06, 12 and 18 UTC from the stage of DD and is continued till the TC dissipates into D(Mohapatra *et al.*, 2013). Calculating the latitudinal error, longitudinal error, along track error and cross track error will determine the bias in track forecast error. The DPE is decomposed into track and cross-track error components with respect to the best track observed. Along the track errors are important indicators of whether a forecasting system moves a storm too slowly or too fast, whereas the cross-track error indicates a displacement to the right or left of the track observed. Also, the two components can be interpreted as errors in where the TC heads (cross-track error) and when it arrives (track error) IMD's best operational track data is considered as TC's actual track/position for the purpose of forecast verification. For forecast verification, the actual position from the DD stage to the TC maximum intensity during the intensification phase and from the maximum intensity to the D stage during the weakening process is taken into account. Direct position error (DPE) or absolute track error, which is the most commonly used measure for verification of the track forecast is determined by RSMC, New Delhi. The DPE is the great circle distance between the expected position of a TC and the position observed at the time of the predicted verification. The average DPE for a given TC is the average of all DPEs determined on the basis of 00, 06, 12 and 18 UTC predictions during the TC's lifetime.

2. DATA AND METHODOLOGY

The data of tropical cyclones from the year 1997 to 2019 are obtained from the records of the IMD best track of the Regional Specialized Meteorological Centre (RSMC), New Delhi, India (http://www.rsmcnewdelhi.imd.gov.in). The Department is recognised by the World Meteorological Organisation for rendering cyclone warning advice for the North Indian Ocean as the RSMC. The data available at the RSMC include position in latitude and longitude ,date, central pressure ,time, pressure drop at center of the cyclone and intensity (Mohapatra *et al.*, 2013).The annual average DPE of the four models viz. IMD-GFS, UKMO,ECMWF and IMD-MME is obtained from the RSMC annual reports for the period 2015 to 2019 that are available at (http://www.rsmcnewdelhi.imd.gov.in).

The geographic distance between the predicted location in each prediction and the corresponding location observed is determined by direct position errors (DPE) which indicates an absolute prediction error (Rao *et al*, 2006). The DPE can be represent by the great-circle distance between two points i.e. the shortest distance "*d*" over the earth's surface between predicted and best track positions is as follows:

$$a = \sin^2(\Delta\varphi/2) + \cos(\varphi 1).\cos(\varphi 2).\sin^2(\Delta\lambda/2)$$
$$c = 2.\tan^{-1}\left(\sqrt{1-a}/\sqrt{a}\right) \quad (1)$$
$$d = R.c$$

where $\Delta\varphi$ is difference between two latitudes $\varphi 1$ and $\varphi 2$, $\Delta\lambda$ is difference between two longitudes $\lambda 1$ and $\lambda 2$ and R is the earth's radius (mean radius = 6,371 km).Depending upon the error statistics for individual TCs, the average error statistics for the season is calculated by taking the sample weighted mean into consideration.(Mohapatra, 2014) described if $x_1, x_2, \ldots, x_n$ are the DPEs for the TCs $1, 2, \ldots n$ with the number of forecasts verified as $i_1, i_2, \ldots, i_n$, then the average DPE for the season/year is given by:

$$DPE_{avg} = \frac{i_1x_1 + i_2x_2 + i_3x_3 + \cdots + i_nx_n}{i_1 + i_2 + i_3 + \cdots + i_n} \quad (2)$$

By determining the minimum/maximum errors and the standard deviation, the inter-annual variation in DPE is analyzed. The annual average DPE is plotted, compared and analysed for the period 2015 to 2019 for four NWP models namely, IMD-GFS, UKMO, ECMWF and IMD-MME.

3. RESULTS AND DISCUSSION

In the present study, cyclonic activities over NIO for the period 1997 to 2019 and 2010 to 2019 are analysed and results are produced in subsection 3.1. In addition, the performance of the four models viz., IMD-GFS, UKMO, ECMWF and IMD-MME based on their annual average DPE for TC are evaluated and results are discussed in subsection 3.2.

3.1. Study of Cyclonic Activities in Bay of Bengal and Arabian Sea (1997-2019)

On an average, there were 94 cyclones from 1997 to 2019 out of which 61(around 65%) were in BoB and 33(around 35%) were in AS (Figure 1 and Figure 2). Also, for the period 1997 to 2019, there is no cyclone in AS in the year 2000, 2005, 2013, 2016 and 2017. So we can derive from this that there were about twice as much cyclonic activity in BoB compared to the AS, which is probably due to the fact that BoB gets higher rainfall and because the slow winds around it hold temperatures fairly high: about 28 degrees a year. Warm air currents increase the surface temperature and aid cyclone formation. Moreover, the Bay receives higher rainfall and constant freshwater inflow from the rivers Brahmaputra and the Ganges. This ensures that the surface water of the Bay needs to be drained, making it difficult for the warm water to combine with the colder water below, making it suitable for depression. At the other side, the AS experiences stronger winds that help dissipate the heat and the lack of continuous supply of fresh water helps the warm water combine with the cool water to minimize the temperature. But not every cyclone is developed in the BoB. The basin also hosts cyclones that are formed elsewhere but move towards the body of water, especially those formed in the Pacific Ocean. Cyclones typically weaken when facing a large mass of land. Because of the lack of any such presence between the Pacific and the BoB, cyclonic winds pass easily into the BoB, whereas, the winds hit the Western Ghats and the Himalayas, either weakening or being blocked in the BoB, but never touching the AS.

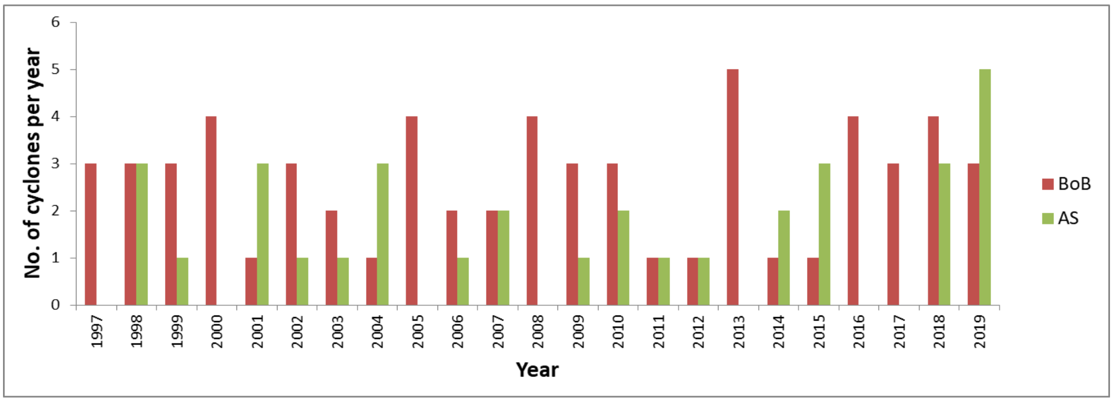

Figure 1: Cyclonic activities in Bay of Bengal (BoB) and Arabian Sea (AS) from 1997 to 2019

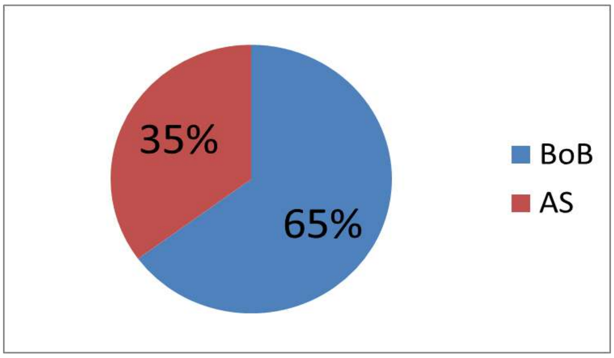

Figure 2: Cyclonic activity (in %) from 1997 to 2019 in Bay of Bengal (BoB) and Arabian Sea (AS)

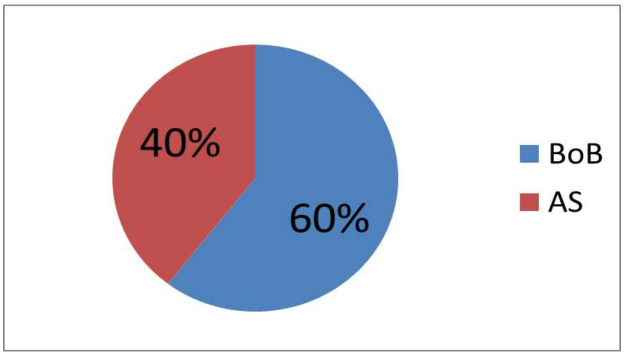

Figure 3: Cyclonic activity (in %) from 2010 to 2019 in Bay of Bengal (BoB) and Arabian Sea (AS)

From 1997 to 2019, the percentage contribution of tropical cyclone over AS was about 35% and over BoB it was around 65%. However, in last ten years (from 2010 to 2019), the percentage contribution of tropical cyclone over AS is recorded as 40% and over BoB, it is found as 60%. Therefore, figure 2 and figure 3, elucidates that for last ten years (from 2010-19) the percentage contribution of AS tropical cyclones has been increased by 5%.

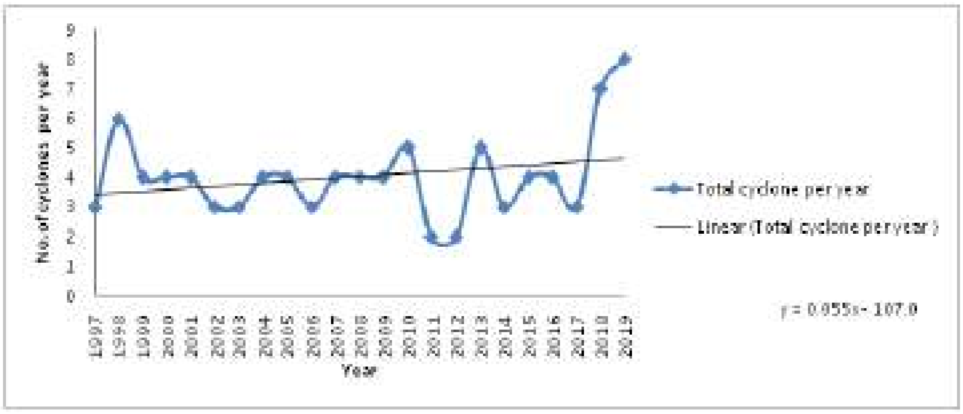

Figure 4: Overall trend of total number of cyclones per year (1997-2019)

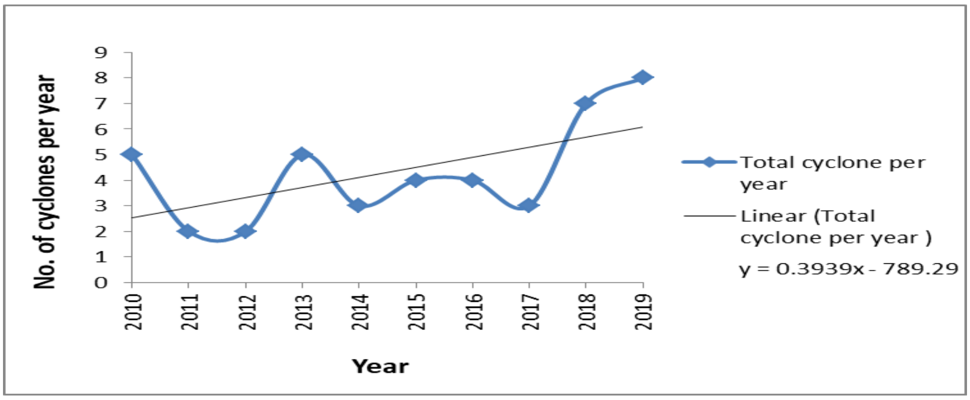

Figure 5: Overall trend of total number of cyclones per year (2010-2019)

The trend analysis of cyclonic activity over NIO during the period 1997 to 2019 shows that per year cyclonic activity is increasing about 0.06 (shown in figure 4), whereas, for the period 2010 to 2019 it is found to be 0.4 (shown in figure 5). This implies that the occurrence of tropical cyclones over the last ten years has increased.

3.2. Comparing Numerical Weather Prediction Model: IMDGFS, UKMO, ECMWF, IMD-MME on the basis of annual average DPE

A comparison of four Numerical Weather Prediction(NWP) model namely, IMD-GFS, UKMO,ECMWF, IMD-MME at 12, 24, 36, 48, 60,72, 84, 96, 108 and 120-hr lead time from year 2015 to 2019 is performed on the basis of DPE.

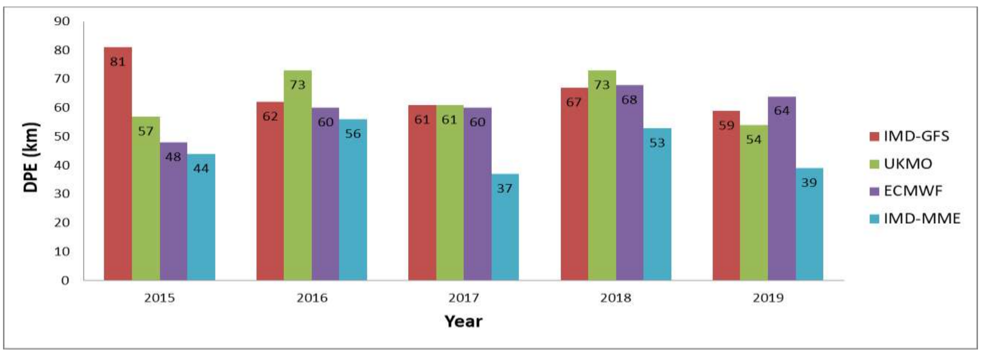

Figure 6: Annual average track forecast errors (Direct Position Error (DPE)) at 12-hr

From figure 6, it has been observed that for the period 2015 to 2019, the annual average DPE for 12-hr was observed minimal for the NWP model IMD-MME among all models. Also, figure 6 shows that IMD-MME had the minimum DPE (around 37 km) on 2017 and maximum DPE (around 56 km) on 2016.

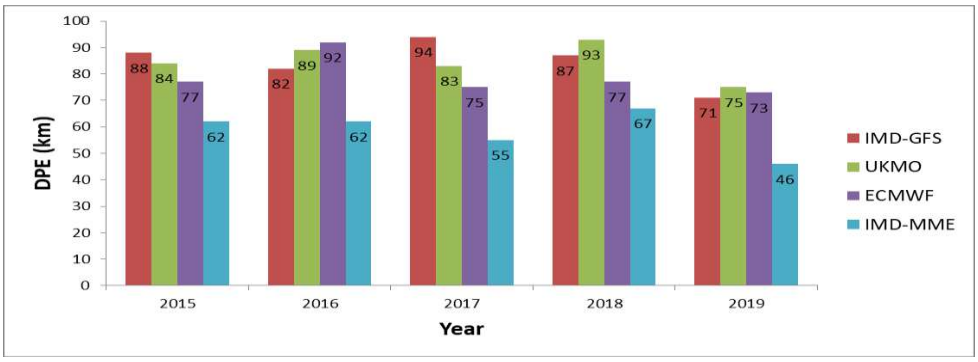

Figure 7: Annual average track forecast errors (Direct Position Error (DPE)) at 24-hr

Figure 7 illustrates that the annual average 24-hr DPE for the NWP model IMD-MME was found to be minimal for the period 2015 to 2019. IMD-MME had the minimum DPE (about 46 km) on 2019 and the maximum DPE (about 67 km) on 2018.

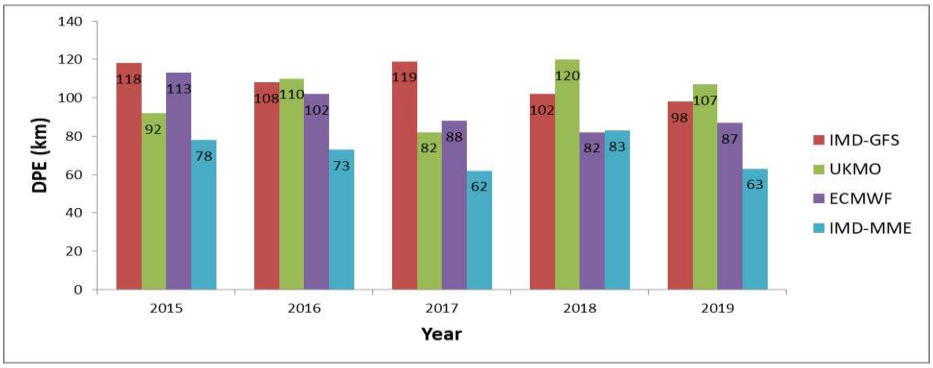

Figure 8: Annual average track forecast errors (Direct Position Error (DPE)) at 36-hr

Figure 8 illustrates that the annual average 36-hr DPE for the NWP model IMD-MME was found to be minimal for the period 2015 to 2019 .IMD-MME had the least DPE (about 62 km) on 2017 and the most DPE (about 83 km) on 2018.

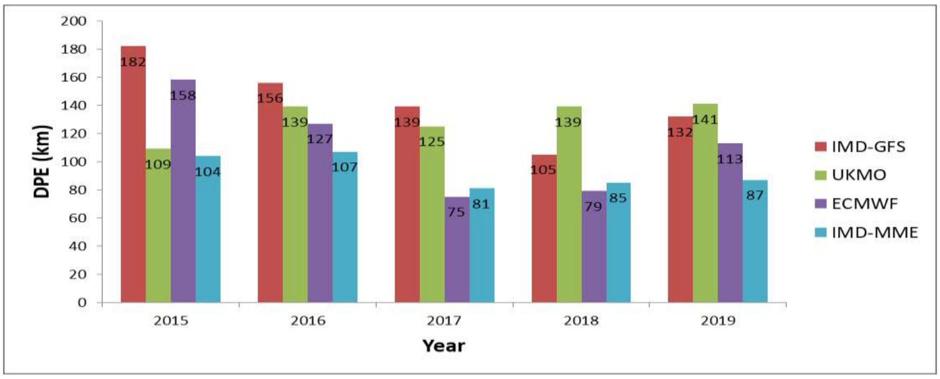

Figure 9:Annual average track forecast errors (Direct Position Error(DPE)) at 48-hr

Figure 9 shows that the annual average 48-hr DPE for the NWP model IMD-MME was found to be minimal for the period 2015 to 2019.Though, ECMWF forecast was better on 2017 and 2018; where IMD-MME had the minimum DPE (about 81 km) ECMWF had minimum DPE (about 75 km) on 2017.

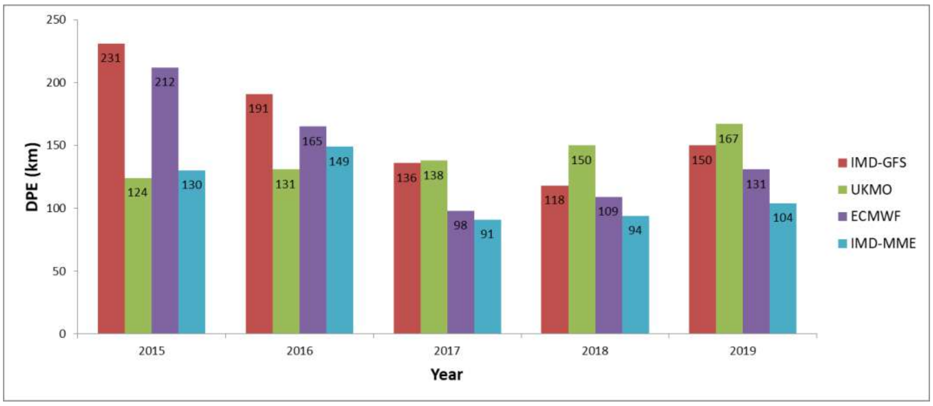

Figure 10: Annual average track forecast errors (Direct Position Error (DPE)) at 60-hr

It has been observed from figure10 that the annual average 60-hr DPE for the NWP model IMD-MME was found to be minimal for the period 2015 to 2019. However, UKMO forecast was better on 2015 and 2016 (DPE: 124 km and 131 km respectively) again IMD-MME forecast was better from 2017 onwards.

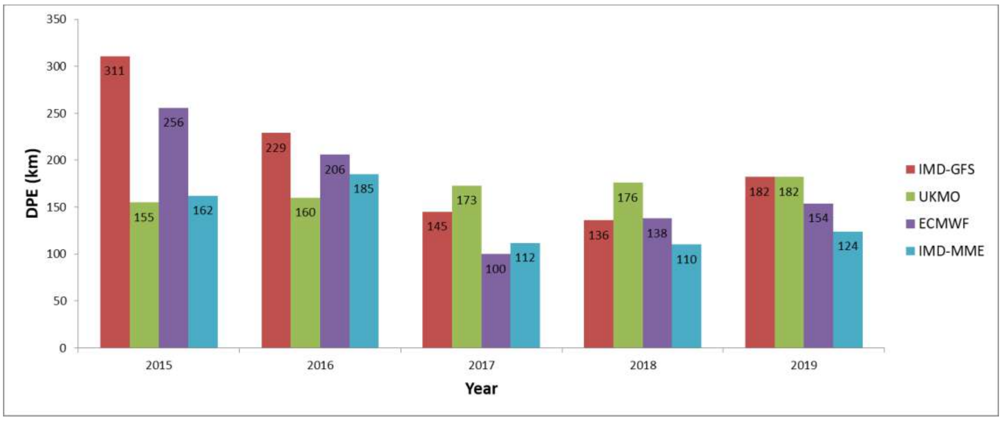

Figure 11: Annual average track forecast errors (Direct Position Error (DPE)) at 72-hr

The annual average 72-hr DPE for the NWP model IMD-MME was found to be minimal on 2015, 2018 and 2019. Whereas, UKMO had least DPE on year 2015 and 2016 and ECMWF had minimum DPE value on year 2017(shown in figure 11).

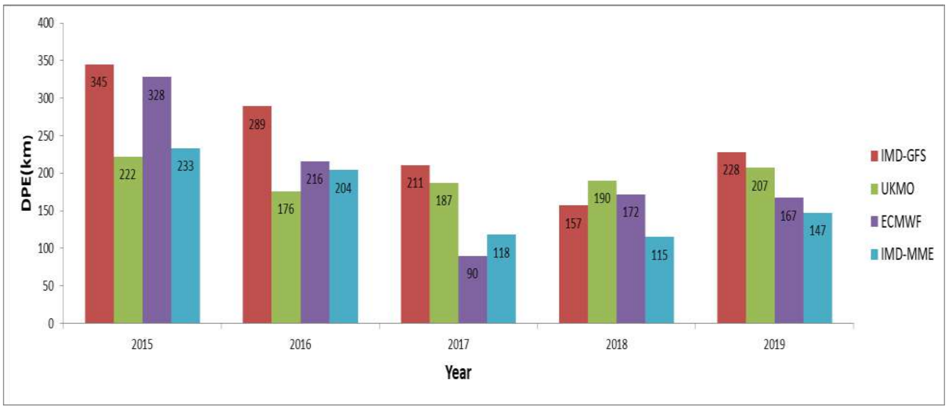

Figure 12: Annual average track forecast errors (Direct Position Error (DPE)) at 84-hr

The 84-hr forecast was better performed by IMD-MME on 2018 and 2019 only. The forecast of UKMO was found best on 2015 and 2016 and ECMWF performed better on 2017(shown in figure 12).

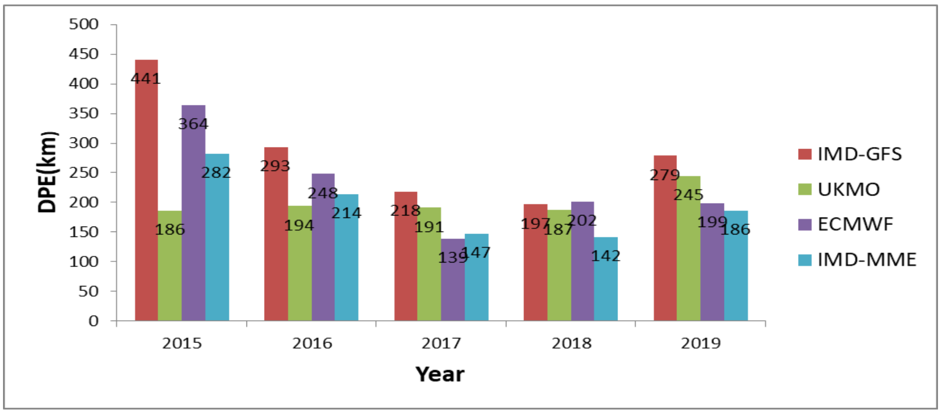

Figure 13: Annual average track forecast errors (Direct Position Error (DPE)) at 96-hr

Similarly, 96-hr IMD-MME forecast was better than other three models except for 2015 when UKMO performed better with an average DPE of 186 km followed by IMD-MME with an average DPE of 282 km (shown in figure 13).

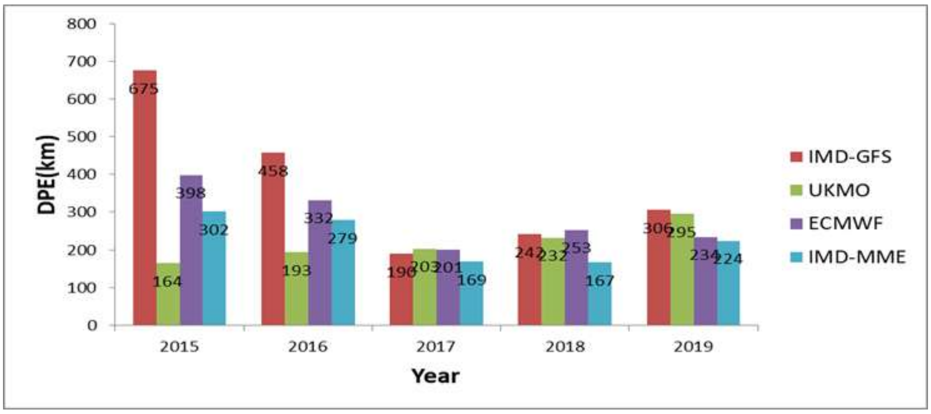

Figure 14: Annual average track forecast errors (Direct Position Error (DPE)) at 108-hr

At 108-hr lead time, IMD-MME forecast performed better than other three models on 2017 (DPE=169 km), 2018 (DPE =167 km) and 2019 (DPE =224 km), whereas UKMO performed better on 2015 (DPE=164 km) and 2016(DPE =193 km) (shown in figure 14).

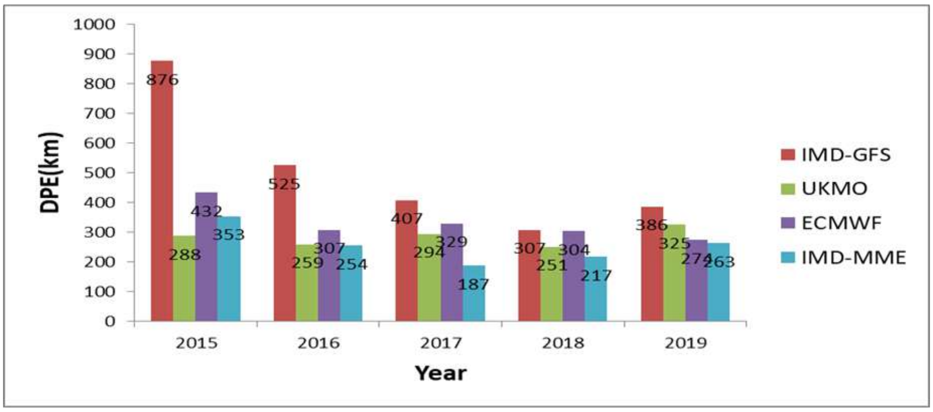

Figure 15: Annual average track forecast errors (Direct Position Error (DPE)) at 120-hr

Again at 120-hr lead time, figure 15 shows that IMD-MME forecast was better than other three models except for 2015 when UKMO performed better with an average DPE of 288 km followed by IMD-MME with an average DPE of 353 km.

Thus, implying the IMD-MME consensus forecast outperformed for all forecasts lead times up to

120 hours during the year 2017-19. Though, UKMO's forecast was better for the years 2015 and 2016 from 60-hrs onwards. Even, at 72-hr and 84-hr lead times, ECMWF forecast was better than the other three models during the year 2017. It has been also observed that for each model the DPE is increasing with increase in lead time period. Thus, it can be inferred that the consensus forecast for the MME is stronger than the forecasts for the remaining three models up to the lead time of 72 hours. The MME technique is based on a statistical linear regression approach (Kotal and Roy Bhowmik, 2011). The predictors chosen for the ensemble technique are latitude and longitude forecasts of five operational NWP models at a 12-hour interval up to 120 hours. In the MME method, the member models' forecast latitude and longitude position are linearly regressed against the observed (track) latitude and longitude position at 12-hour forecast intervals up to 120 hours for each forecast time. Using a cyclone tracking software, the 12 hourly cyclone tracks are then calculated from the respective mean sea level pressure fields. Based on past data, multiple linear regression techniques are used to generate weights (regression coefficients) for each model for each forecast hour (12 to 120-hrs). Then these coefficients are used as weights for the ensemble predictions. Multiple linear regression techniques define the 12-hourly forecast latitude and longitude positions. For the member models GFS (IMD), GFS (NCEP), ECMWF, UKMO and JMA, a collective bias correction is applied in the MME by applying multiple linear regression based minimisation principle. Data from ECMWF are available in 24-hr intervals. Therefore, ECMWF's forecast positions of 12, 36, 60, 84 and 108-hr are determined based on linear interpolation. The annual error analysis of all four models reveals that IMD-MME model predicted the cyclone track with least error. Overall, IMD-MME model outperformed among all models.

4. CONCLUSIONS

The following broad conclusions are drawn from the above results and discussion. It has been observed that on an average, there were 94 cyclones from 1997 to 2019 out of which 61(around 65%) were in BoB and 33(around 35%) were in AS. Also, there is no cyclone in AS in the year 2000, 2005, 2013, 2016 and 2017 (considering from 1997 to 2019). This shows that the number of tropical cyclones formation in BoB was higher than the AS. However, last ten years (from 2010-19) analysis shows that the percentage contribution of AS tropical cyclones has been increased by 5%. From the annual average track forecast, it has been concluded that the IMD-MME consensus forecast outperformed among all models up to 120-hrs during the period 2017-2019. However, for the year 2015-16, annual average track forecast error was found better up to 48-hrs lead times. After 48-hrs lead times in the years 2015-16, UKMO performed better than other three models. Even, at 72-hr and 84-hr of 2017, ECMWF forecast error was found less. It has been noted that the DPE for each model is increasing with increase in lead times. Thus, it can be inferred that the consensus forecast for the MME is stronger than the forecasts of the remaining three models up to the lead time of 72 hours.

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