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Tropical cyclone track and intensity prediction skill of GFS model over NIO during 2019 & 2020

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Abstract

The Tropical Cyclone (TC) track prediction using different NWP models and its verification is the critical task to provide prior knowledge about the model errors, which is beneficial for giving the model guidance-based real-time cyclone warning advisories. This study has attempted to verify the Global Forecast System (GFS) model forecasted tropical cyclone track and intensity over the North Indian Ocean (NIO) for the years 2019 and 2020. GFS is one of the operational models in the India Meteorological Department (IMD), which provides the medium-range weather forecast up to 10 days. The forecasted tracks from the GFS forecast are obtained using a vortex tracker developed by Geophysical Fluid Dynamics Laboratory (GFDL). A total of 13 tropical cyclones formed over the North Indian Ocean, eight during 2019 and five in 2020 have been considered in this study. The accuracy of the model predicted tracks and intensity is verified for five days forecasts (120 h) at 6-h intervals; the track errors are verified in terms of Direct Position Error (DPE), Along Track Error (ATE) and Cross-Track Error (CTE). The annual mean DPE over NIO during 2019 (51–331 km) is lower than 2020 (82–359 km), and the DPE is less than 150 km up to 66 h during 2019 and 48 h during 2020. The positive ATE (76–332 km) indicates the predicted track movement is faster than the observed track during both years. The positive CTE values for most forecast lead times suggest that the predicted track is towards the right side of the observed track during both years. The cyclone Intensity forecast for the maximum sustained wind speed (MaxWS) and central mean sea level pressure (MSLP) are verified in terms of mean error (ME) and root mean square error (RMSE). The errors are lead time independent. However, most of the time model under-predicted the cyclone intensity during both years. Finally, there is a significant variance in track and intensity errors from the cyclone to cyclone and Bay of Bengal basin to the Arabian Sea basin.

Keywords: Tropical cyclone; Track prediction; GFS; NWP; Global model; GFDL

1. Introduction

India Meteorological Department (IMD) has been designated by World Meteorological Organisation (WMO) as Regional Specialised Meteorological Center (RSMC) responsible for monitoring and forecasting Tropical Cyclones (TCs) formed over the North Indian Ocean (NIO). TCs are one of the natural hazards that cause strong winds, heavy rainfall, and coastal inundation, leads to loss of lives and property. So the accurate prediction of cyclone track and intensity is of utmost

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importance for cyclone early warning. Chen et al. (2013) assessed the forecast of TC tracks from six global models (CMA-T213; CMA-T639; ECMWF-IFS; JMA-GSM; NCEP–GFS; UKMO-MetUM) during 2010 and 2012 over Western North Pacific. The authors found that the National Centre for Environmental Prediction (NCEP) Global Forecast System (GFS) and China Meteorological Administration (CMA) -T639 performs better than the other four models considered in the study. One of the important findings from this study was that the models perform better for initially large TCs or the systems with weak vertical wind shear at forecast lead times below 48hr. Authors concluded that forecast errors largely depend on the TCs initial characteristics and its environmental conditions. Hamill et al. (2011) verified the performance of two experimental numerical weather prediction (NWP) ensemble prediction system (EPS) forecasts of Northern hemisphere summer TCs during 2009. The first model was a high-resolution T382L64 NCEP GFS and the second model was a 30 km version of NOAA Earth System Research Laboratory's flow following finite volume Icosahedral Model (FIM). Both models are initialized with the first 20 members of a 60 members Ensemble Kalman filter (EnKF) using the T382L64 GFS. The forecast from two experimental ensembles was compared against four operational EPS's from the European Center for Medium-Range Weather Forecast (ECMWF), NCEP, the Canadian Meteorological Center (CMC), and the Met Office (UKMO). The authors found that the experimental EPS had much lower errors than the operational NCEP, UKMO, and CMC EPS, but the FIM-EnKF tracks were less accurate than the GFS-EnKF. Chen et al. (2019) evaluated the performance of TCs forecasts in the 13-km fvGFS globally, based on 363 daily cases of 10 day forecasts in 2015. The track and intensity errors of TCs in fvGFS were compared with those from the operational GFS (opGFS). The authors found that the fvGFS outperforms the opGFS in TC intensity prediction for all basins. For TC track prediction, the fvGFS forecasts are substantially better over the northern Atlantic basin and the northern Pacific Ocean than the opGFS forecasts. An updated version of the fvGFS with the GFDL 6-category cloud microphysics scheme is also investigated based on the same 363 cases. The upgraded microphysics scheme, fvGFS, shows much improvement in TC intensity prediction over the operational GFS. Hazelton et al. (2018) evaluated the finite-volume dynamical core (FV3) with GFS physics (fvGFS) with the 2-km resolution for simulating the TC track, intensity and fine-scale structure of seven TCs occurred during 2010–2016. The predicted TC structure is evaluated with three-dimensional Doppler radar from P-3 flights by NOAA's Hurricane Research Division (HRD). The structural metrics evaluated include the 2-km radius of maximum wind (RMW), slope of the RMW, depth of the TC vortex, and horizontal vortex decay rate. Authors found that the fvGFS model successfully predicts RMWs in the 25–50 km range but tends to have a small bias at very large radii and a large bias at minimal radii. Elsberry et al. (2020) analyzed the Marchok vortex tracker outputs from the ECMWF ensemble (ECEPS) and NCEP Global ensemble prediction system (GEFS). Authors found that the Time to Formation (T2F) forecast of the ECEPS and GEFS for pre-Hurricane Lorenzo in the eastern Atlantic has been predicted up to 5 days in advance that the precursor African wave will become a Tropical Storm off the west coast and will likely become a hurricane.

Many authors have been evaluated the performance of NWP models in prediction of the TC track and intensity over the NIO. Prasad et al. (2013) assimilated the India Ocean surface wind vector data from Scatterometer (OScat) on-board India's Oceansat-2 satellite into T574L64 Global Data Assimilation and Forecasting (GDAF) system at NCMRWF and found improvement in location of the centre of the cyclone and a reduction in the mean position error of the cyclone with respect to IMD's best track. The study by Routray et al. (2019) found that the NCUM forecasts at 25 km resolution are slower compared to the actual translation speed of the system over the NIO for all forecast lengths; the landfall prediction also delayed and for the intense storms the intensity prediction skill is also low. Deshpande et al. (2021) evaluated the skill of the GEFS for TC forecast over NIO by considering 13 cyclonic storms. The results indicated that the track error for ensemble mean (ENS mean) are comparable with control run up to 48 h and thereafter track error is less for ENS mean. Authors also found that the cyclone intensity in terms of Maximum sustained wind speed (MSW) is under-estimated and the error in control run is less than the ENS mean.

Kotal et al. (2014) developed and implemented an objective NWP based Genesis Potential Parameter (GPP), Multi-Model Ensemble (MME) technique for track prediction and Statistical Cyclone Intensity Prediction (SCIP) models over the NIO. The author's verification results show that the GPP had a higher probability of detection (0.98) and lower false alarm ratio (0.27) with a higher critical success index (0.72); the mean track errors range from 74 km at 12 h to 200 km at 72 h. Also, the mean landfall position errors range from 56 km at 24 h to 137 km at 72 h and landfall time error ranges from 3.6 h at 24 h–6.1 h at 72 h. The mean intensity errors of SCIP are 5.4 kt at 12 h to 16.9 kt at 72 h. Malakar et al. (2020) evaluated Six reanalysis data sets, and found the slightest error in the position of the TCs center, MSLP, and maximum wind speed in GFS analysis followed by ERA5 and Climate Forecast System Reanalysis (CFSR), respectively. The authors concluded that the GFS analysis represents early intensification and, in some cases, over-prediction of the category of TCs, especially during the most intensified stages (beyond cyclonic storms).

In order to improve the model forecast, number of satellite radiance observations from different sensors has been assimilated into the operational global NWP models. Christophersen et al. (2017) observed a positive impact of Global Hawk (GH) dropwindsondes on TC analyses and forecasts. Authors found that GH dropwindsondes may have greater relative contribution in the near-storm environment but have limitations in representing the inner-core complex structures compared to the P-3 aircraft equipped with the tail Doppler radar (TDR) capability. The Doppler Wind Lidar (DWL) complements the existing P3 Doppler radar, in that it collects wind data in rain-free and low-rain regions where Doppler radar is limited for wind observations (Zhang et al., 2018; Bucci et al., 2018). Gao et al. (2021) proposed methodologies to retrieve TC intensity parameters like, surface maximum wind speed, TC fullness (TCF) and central surface pressure from the European Space Agency Sentinel-1 Extra Wide swath mode cross-polarization data. Authors observed that the space borne synthetic aperture radar (SAR) retrieved maximum wind speeds were showing better results. Kumar and Gairola (2021) study, emphasizes the importance of the winds from L-band radiometric measurements from Soil Moisture Active Passive (SMAP) satellite compared to the operational Advanced Scatterometer (ASCAT) (C-band) and SCATSAT-1 (Ku-band) scatterometers, NCEP final analysis, and ERA5 reanalysis wind products. Authors found that at global scale except SMAP, no other selected data are able to capture wind speed more than 56 m s^{-1}, and large under-estimations are observed in the presently available scatterometers and reanalysis. Abhineet and Neerja (2018) utilized the L-band (1.4 GHz) microwave radiometric observations to derive high wind speeds (WS) of tropical cyclones and observed that the spatial variations of brightness temperature (BT) well captured with high WS conditions.

Recent times, the NWP forecast has been improved by using new assimilation schemes, high resolution models and combined atmosphere and ocean coupled models. The Ensemble prediction systems are also effective to estimate the uncertainty of the TC forecasts. In turn, the TC track forecasts issued by regional warning centres uses NWP models and other forecasting techniques (Heming et al., 2019); IMD uses synoptic, statistical, satellite and radar guidance for short range (up to 24 h) forecast and NWP guidance for medium range (24–129 h) forecast. The Consensus forecast utilises the NWP forecast tracks, synoptic and statistical guidance to issue the official forecast (IMD, 2013). At present IMD runs the GFS model at 12.5 km resolution on operational mode to provide the medium-range weather forecast. In this study, the GFS model's performance in predicting the TCs formed over the NIO is evaluated. The verification of NWP model TC forecast plays a vital role in the proper application of forecast and further necessary improvements to the model forecast.

2. Data and methodology

2.1. GFS model

The NWP model used in this study is a primitive equation spectral global model with state of the art dynamics and physics. The GFS is a hydrostatic model based on the semi-implicit semi-Lagrangian dynamics (Sela, 2010). The GFS physics includes Simplified Arakawa Schubert (SAS) & Pan and Wu (1995) and with some modifications in Han and Pan (2011) scheme for convection; Improved turbulence mixing in stratocumulus regions (Han and Pan, 2011) for Planetary boundary layer; Solar radiation and Infrared based on RRTM with Monte Carlo Independent Column Approximation (McICA) for Short/Longwave radiation; Noah four-level land model for land surface processes; Large Scale condensation and Precipitation is parameterized following Zhao and Carr (1997) and Sundqvist et al. (1989). This GFS model conforms to a dynamical framework known as the Earth System Modeling Framework (ESMF). Its code was restructured to have many options for updated dynamics and physics. The configurations of the GFS model and GSI (Grid-point Statistical Interpolation) data assimilation component were customized and experimented for operational forecasting after several studies by the researchers (Mukhopadhyay et al., 2019; Sarkar et al., 2021; Prasad et al., 2016, 2021) in India.

The GFS-T1534L64 is run with ~12.5 km horizontal resolution and 64 hybrid sigma-pressure layers in the vertical with the top layer at 0.27 hPa. The initial conditions are generated through Global Data Assimilation System (GDAS) of NCMRWF using GSI (with hybrid Ensemble Variational assimilation). In the present study, the GFS T1534 forecast outputs at 25 km in GRIB format have been utilized.

2.2. GFDL vortex tracker

The forecast tracks predicted by the GFS model have been obtained using a vortex tracker developed by Geophysical Fluid Dynamics Laboratory (GFDL) (Biswas et al., 2018). The GFDL tracker program analyzes the forecast data and estimates the vortex center position, i.e., Latitude & Longitude, and tracks the storm for the duration of the forecast. It also provides the metrics of the forecast storm, such as intensity (10 m maximum sustained wind speed (MaxWS) and minimum mean sea level pressure (MinSLP)), wind structure (wind radii for 34, 50, and 64-knot thresholds in each quadrant), radius of outermost closed isobar (ROCI) and optionally integrated kinetic energy (IKE), storm surge damage potential (SDP) and cyclone thermodynamic phase at each output time. The tracker supports the GRIB (GRIB1 or GRIB2) or NetCDF format model output.

The forecast fields used by the tracker are (1) Relative Vorticity at 10 m, 850 hPa, and 700 hPa levels (2) Mean Sea Level Pressure (MSLP) (3) Geopotential height at 850 and 700 hPa levels (4) Wind speed at 10 m, 850 and 700 hPa levels (5) 200–500 hPa and 500–850 hPa thickness. In the present study, the GFS T1534 forecast outputs at 25 km in GRIB format have been utilized. The output file contains vortex position, intensity, and structure information in Automated Tropical Cyclone Forecast (ATCF) and modified formats. In the present study the GFDL vortex tracker has been run from the Deep Depression (DD) stage during formation to DD stage of the cyclonic storm during dissipation.

2.2.1. Best track data

The RSMC - Tropical Cyclones, IMD, New Delhi monitors and predicts the cyclonic disturbances over the North Indian Ocean and issues the Tropical Cyclone advisories for the benefit of the Economic and Social cooperation for the Asia and the Pacific (ESCAP) Panel member countries. The expert's committee reviews the operationally finalized tracks of the past year in the annual review meeting of IMD. The committee considers all the available surface and upper-air observations from land and ocean, satellite and radar observations

(Mohapatra et al., 2012). The committee finalized tracks are presented in the annual cyclone review meeting and adopted as the best track after the corrections/modifications. The six-hourly best track data sets contain vortex position (Lat/Long), stage of intensity and T/CI number, estimated central pressure, pressure drop at the center, and sustained maximum surface wind speed. The Best track data as shared by RSMC, IMD, New Delhi, is downloaded from http://www.rsmcnewdelhi.imd.gov.in/report.php?internal_menu=MzM.

2.3. Tcvitals file

A tcvital file is a small data file that contains the current operational estimate of the cyclonic storm's such as organization-id, storm-id, Basin identifier, storm name, storm report date, report hour and minute, cyclone's center location (Lat/Long), storm direction (in degrees from North), intensity (storm speed in kt & storm central pressure in mb), storm environmental pressure in mb, the estimated radius of the outermost closed isobar (km), estimated maximum wind speed in kt, estimated radius of maximum wind speed (km), estimated radius of 34 knots winds in 4 (NE, SE, SW, NW) quadrant of the storm (km^2), the indicator for storm depth, estimated radius of 50 knots winds in 4 (NE, SE, SW, NW) quadrant of the storm (km^2), maximum forecast time (hr), etc. created in real-time by storm forecasting centres at synoptic hours (00, 06, 12 and 18 UTC). These tcvital files are provided by RSMC, New Delhi and are used to relocate the TC from the GFS forecast. The complete details about the tcvitals are available at the following link

https://www.emc.ncep.noaa.gov/mmb/data_processing/tcvitals_description.htm.

http://hurricanes.ral.ucar.edu/realtime/index.php#about_tcvitals.http://hurricanes.ral.ucar.edu/realtime/index.php#about_tcvitals.

2.4. TCs track and intensity errors

In this study, the performance of the GFS model in the prediction of TCs formed over the NIO is evaluated using a vortex tracker developed by GFDL. The ‘tcvital’ provided by RSMC, IMD, New Delhi is used to relocate the TCs from the GFS forecast. A total of 13 tropical cyclones formed over the NIO from 2019 to 2020; 8 TCs formed during 2019 and 5 TCs during 2020 are considered in this study. The predicted tracks are evaluated against the Best track data developed by RSMC, IMD, New Delhi. The accuracy of the model predicted tracks had been verified up to 5 days with 6 h intervals, in terms of Direct Position Error (DPE), Along Track Error (ATE), and Cross Track Error (CTE). The predicted cyclone intensity forecast verified for maximum sustained wind speed (MaxWS) and central mean Sea Level Pressure (MinSLP) in terms of mean error (ME) and root mean square error (RMSE).

The average track forecast error, i.e., DPE in km, is calculated based on the arithmetic mean of all the available forecasts for all forecast lead periods (hours) for each cyclone. Along with the DPE, the CTE and ATE (Heming, 2016) were also calculated. The DPE is the great circle distance between the GFS forecasted track position and the RSMC best track position at the corresponding forecast verification time (Mohapatra et al., 2013; 2013a). The Positive/negative values of ATE indicate that the cyclone's movement in the forecasts is faster/slower than the observed best track. The positive/negative values of CTE suggest that the forecast track is right/left of the observed track. The perpendicular distance from the model track forecast position to the observed track is the CTE. The CTE gives the spatial spread of the simulated tracks. The ATE's are defined as the perpendicular distance from the forecast position to the observed track as described in Fig. 2. If the crossing point of the perpendicular meets the observed track ahead (behind) of the observed position, the value of ATE is positive (negative) and indicates the faster (slower) movement of the simulated TC relative to the actual direction of the TC (Fig. 2.). Since CTE and ATE depends on the real-time existence of an observed position 6 h prior to the verification time, they cannot be calculated for the first analyzed position of a TC (Heming, 2016).

The information on CTE and ATE are beneficial for TC disaster management; because the CTE will help determine the span of evacuation area required in case of a land-falling TC. The ATE will help determine the time of evacuation. A relatively lower CTE is desirable for disaster managers because it will lower the cost of evacuation. The average DPE is the average of all DPE's calculated based on 00 and 12 UTC forecasts considered during the life period of the corresponding tropical cyclone. The cyclone track verification is carried out for a 6hourly forecast issued at 0000 and 1200 UTC from the Deep Depression (DD) stage during formation to DD stage of the cyclonic storm during dissipation. The cyclone intensity forecast was also verified in terms of ME and RMSE for MaxWS and MinSLP. The GFS model predicted tracks & observed best track plots, and corresponding error plots for each cyclone during 2019 and 2020 are given in section 4 Results and discussion.

3. TCs over NIO during 2019–2020

3.1. TCs during 2019

During 2019, the cyclone activity over the NIO was very high; eight cyclones formed over NIO. The Arabian Sea (AS) was more active than the Bay of Bengal (BoB). Out of 8 cyclones, five storms formed over AS, and the remaining three cyclones formed over BoB. In terms of seasons, the post-monsoon season is more active than the pre-monsoon. During the -post-monsoon season, the cyclone formation activity is more over the AS (three cyclones formed) than BoB (one cyclone). Out of eight cyclones, land-falling occurred in 5 cyclones, i.e., Pabuk, Fani, Hikaa, Bulbul, and Pawan. The details of the cyclones formed over the North Indian Ocean during 2019 are given as Table 1.

3.2. TCs during 2020

In 2020, the cyclone activity over the NIO was significantly less. There were only five cyclones formed over the NIO. Out of

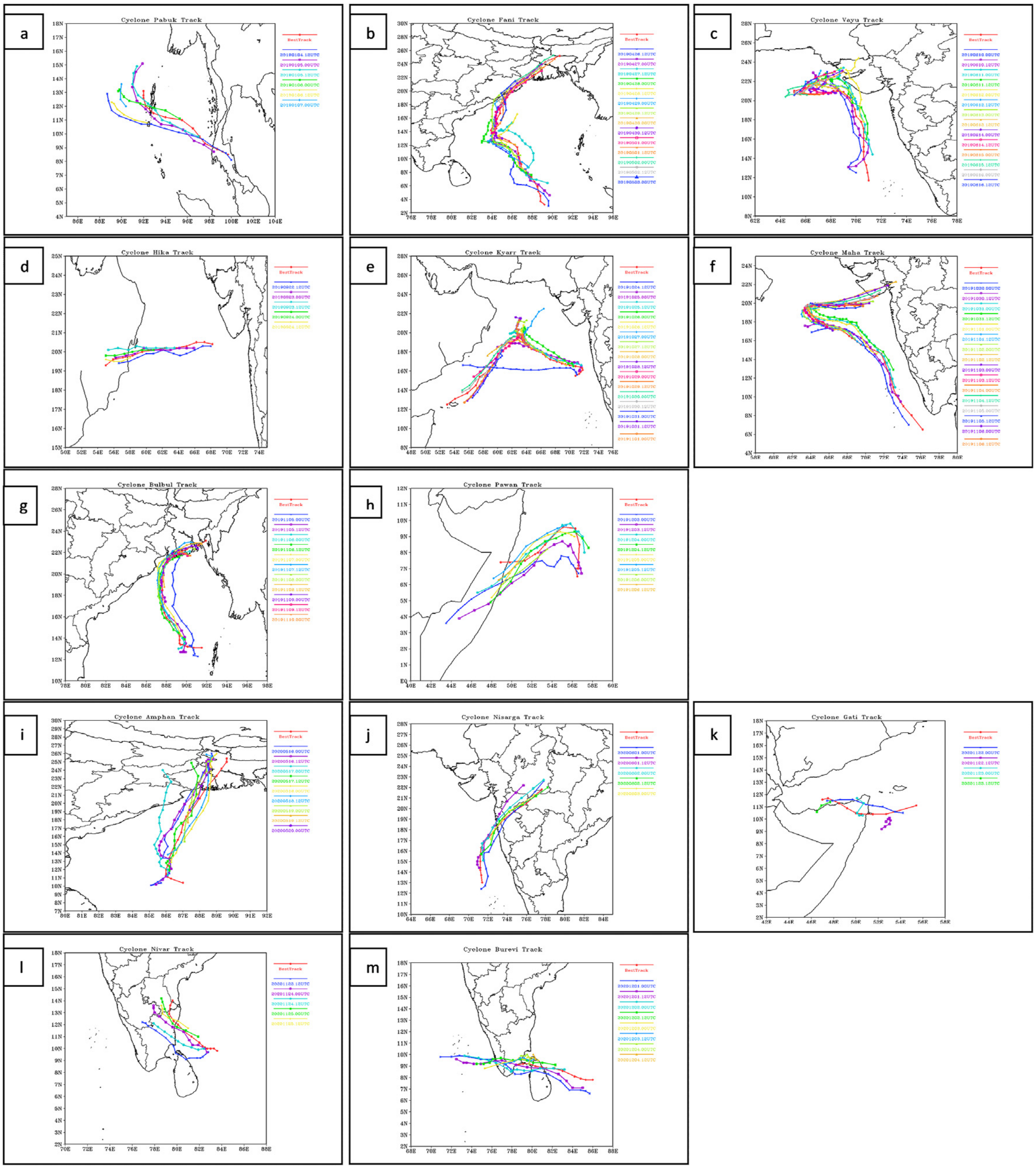

Fig. 1. The observed and GFS model predicted track positions of Cyclonic Storms formed over NIO (a) Pabuk (b) Fani (c) Vayu (d) Hikaa (e) Kyarr (f) Maha (g) Bulbul (h) Pawan; during 2019 and (i) Amphan (j) Nisarga (k) Gati (l) Nivar (m) Bureviduring 2020 at different initial times (different colours) and the Red colour line is the IMD best track.

five cyclones, two cyclones formed over AS and three formed over BoB. Two cyclones formed in the pre-monsoon and three cyclones in the post-monsoon season. The Super Cyclonic Storm Amphan, Nivar, and Burevi developed over BoB, and the Severe Cyclonic Storm Nisarga and Very Severe Cyclonic Storm Gati formed over the AS. The details of the cyclones formed over the NIO during 2020 are given as Table 2.

4. Results and discussion

The GFS model predicted tracks and observed best tracks at different initial conditions are shown in Fig. 1 for the TCs developed over the NIO during 2019 and 2020. The GFS simulated tracks are matching with the observed best track for most of the cycles. The cyclone annual mean track errors are calculated in terms of DPE, ATE, and CTE. The corresponding track errors along with standard deviation (SD) (vertical line on error bar) and the number of cycles considered for each forecast hour (red line on secondary Y-axis) are plotted in Figs. 3, 5 and 7. The forecasted Intensity errors over NIO for the MaxWS and MinSLP are verified interms of ME and RMSE, and the basin-wise annual mean errors are shown in Figs. 4, 6 and 8. The corresponding average track and intensity errors for all the individual cyclones during 2019 and 2020 over NIO are

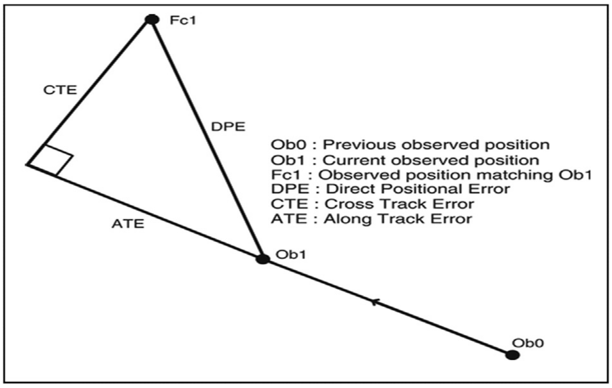

Fig. 2. Predicted cyclone track errors i.e., Direct Position Error (DPE), Along Track Error (ATE) and Cross Track Error (CTE) (Adopted from Heming 2016).

calculated. But for brevity, the annual mean errors over BoB, AS, and NIO are discussed.

4.1. Annual mean track and intensity errors over BoB

The mean track and intensity errors for the BoB basin are calculated by considering the 31 cases of total three cyclones during 2019 and 22 cases of 3 cyclones during 2020. The mean track errors are calculated in terms of DPE, ATE, and CTE. The corresponding track errors along with standard deviation (SD) (vertical line on error bar) and the number of cycles considered for each forecast hour (red line on secondary Y-axis) are shown in Fig. 3 and Table 3. The mean DPE (SD) during 2019 varies from 70 (65) to 288 (132) km, and the DPE is less than 160 km up to the 78 h. The positive ATE (SD) varies from 62 (47) to 189 (110) km indicates that the predicted track moves faster than the observed. The mean CTE (SD) ranges from −50 (91) to 40 (68) km, and the positive CTE values indicate that the predicted track is at the right side of the observed track up to 90 h further the negative CTE for 96, 102, 108, and 114 h shows the expected track is at the left side of the observed track. Whereas during 2020, the mean DPE (SD) varies from 73 (54) to 359 (216) km, and the DPE is less than 150 km up to 42hr and further increased. The mean ATE (SD) varies from 83 (47) to 332 (158) km, and the positive ATE indicates the predicted track moves faster than the observed. The mean CTE (SD) ranges from 2.8 (78) to 243 (279) km, and the positive CTE indicates that the predicted track is to the right side of the observed track. There are several marked differences seen between the track statistics over BOB for the years 2019 and 2020. The DPE range is more in 2020 than in 2019, even though the cyclones had an extended life period in 2019 compared to 2020, as seen from the average number of cases available for 114 h forecast duration. Therefore, in general, the GFS forecast for DPE was better in 2019 than in 2020. Also, it is noticed that the mean CTE did not have any negative values in 2020, and therefore, the GFS track forecast in 2020 seems to be showing the forecast track in general to the right of the observed track. However, in 2019, there was no such one-sided bias towards the right side of the observed track. The variation in mean ATE for 2019 and 2020 showed a similar pattern with a slight reduction in the mean ATE values during 0–90 h forecasts. However, the reduction is more noticeable during 2019 as compared to 2020.

The mean Intensity forecast errors over the BoB basin during 2019 and 2020 are shown in Fig. 4 and Table 4. During 2019, the wind speeds ME shows under-prediction of 1.6–12 kt, and the mean RMSE for MaxWS is 14–24 kt for 6–114 h. The ME for MinSLP shows over-prediction of 0.2–2.8 hPa for 6, 12, 18, 54, 60, 66, 72, 78, 84, 90, 96 and 108 h; under-prediction of 1.5, 0.2, 1.2, 0.1, 0.3, 3.4 and 3 hPa for 24, 30, 36, 42, 48, 102 and 114 h respectively. The mean RMSE for MinSLP varies from 8 to 20 hPa for 6–114 h of forecast lead times. Whereas during 2020, the average wind speed ME shows under-prediction of 1.8–26 kt, and the mean RMSE for MaxWS varies from 8.7 to 31 kt. The average ME for MinSLP shows under-estimation of −1.6 to 14.4 hPa for 6–96 h; and over-prediction of 1.6, 5 and 4 hPa for 102, 108 and 114 h respectively. The mean RMSE for MinSLP varies from 2 to 22 hPa for 6–114 h of forecast lead times. The mean intensity errors for 2019 and 2020 cyclones over NIO show that the mean intensity errors are more in 2020 than in 2019. This can also be correlated with the fact that the mean DPE in 2020 was more than 2019. Therefore, if the model track errors

Table 2
List of Cyclones formed over the NIO during the year 2020.

Basin	Cyclone-Name	Severity-Class	Cyclone Period
BoB	Amphan	SupCS	16th to 21st May 2020
AS	Nisarga	SCS	1st to 4th June 2020
AS	Gati	VSCS	21st to 24th November 2020
BoB	Nivar	VSCS	22nd to 26th November 2020
BoB	Burevi	CS	30th November to 5th December 2020

Table 1
List of Cyclones formed over the NIO during the year 2019.

Basin	Cyclone-Name	Severity-Class	Cyclone Period
BoB	Pabuk	Cyclonic Storm (CS)	4th to 8th January
BoB	Fani	Extremely Severe Cyclonic Storm (ESCS)	26th April to 4th May
AS	Vayu	Very Severe Cyclonic Storm (VSCS)	10th to 17th June
AS	Hikaa	VSCS	22nd to 25th September
AS	Kyarr	Super Cyclonic storm (SupCS)	24thOct to 2nd November
AS	Maha	ESCS	30th October to 7th November
BoB	Bulbul	VSCS	5th to 11th November
AS	Pawan	CS	2nd to 7th December

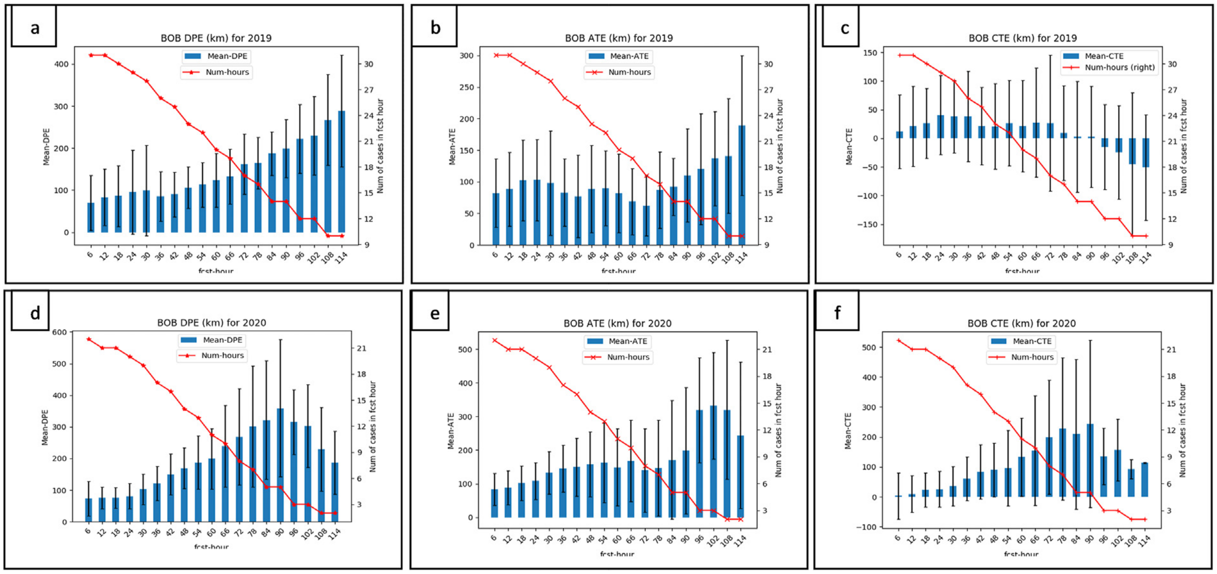

Fig. 3. Predicted Track mean errors (km) along with standard deviation (SD) (vertical line on error bar) and the number of cases considered for each forecast hour (red line on secondary Y-axis) for a 6 hourly time interval up to 114 h, for the Tropical cyclones formed over BoB, in terms of (a, d) Direct Position Error (b, e) Along Track Error (c, f) Cross Track Error for the years 2019 (upper panel) and 2020 (lower panel).

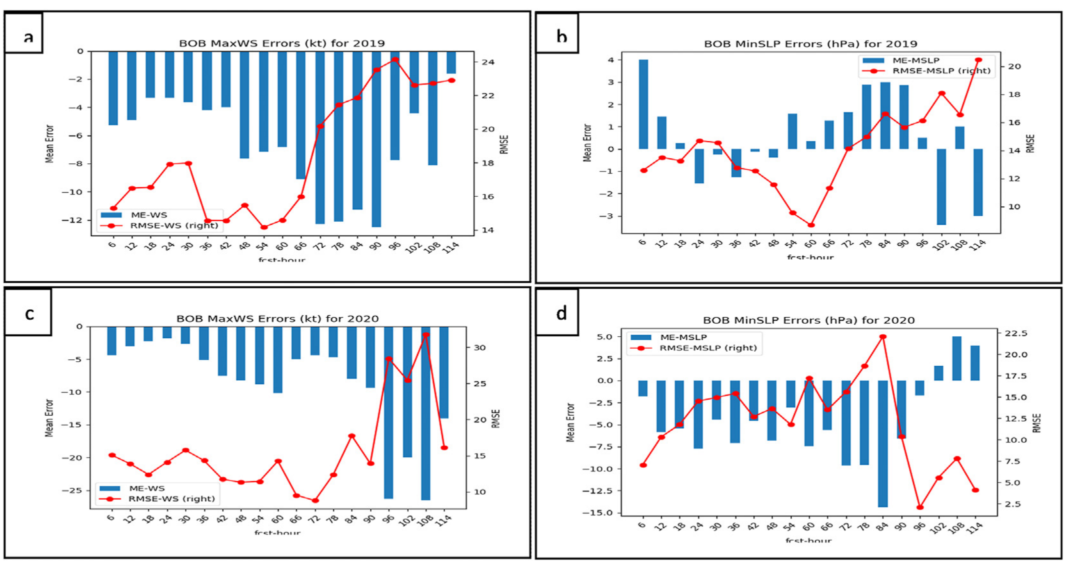

Fig. 4. Average Intensity errors for 6 hrly time interval up to 114 h, for the tropical cyclones formed over BoB, in terms of Mean Error (shaded bars) and Root Mean Square Error (red line on secondary Y-axis); (a, c) maximum Wind Speed (kt) (b, d) minimum MSLP (hPa); for the years 2019 (upper panel) and 2020 (lower panel).

are more, then the position of the cyclone is displaced over the sea to a larger extent. Therefore, the intensity, which is also affected by sea surface properties, shows more errors.

4.2. Annual mean track and intensity errors over AS

The annual mean Track errors for the AS basin are calculated by considering the 55 cases of 5 cyclones formed during 2019 and 9 cases of 2 cyclones formed during 2020 and are shown in Fig. 5 and Table 5. During 2019, the mean DPE (SD) varied from 40 (35) to 449 (346) km, and the DPE is less than 150 km up to 54 h. Whereas during 2020, the mean DPE along with standard deviation (SD) varied from 84 (53) to 164 (226) km, and the DPE is less than 165 km for all the forecast lead times (6–72 h). The range of DPE for cyclones of 2019 is more as compared to the cyclones observed in 2020. The variance in errors is because the forecast hours for which the GFS forecast was available in 2020 were only up to 72 h, whereas, for 2019, the GFS based DPE is available for 114 h. Therefore, the cyclone formed over the AS during 2019 had a longer life period than cyclones of 2020. The mean ATE (SD) for 2019 varied from 63 (58) to 331 (288) km, whereas the mean ATE

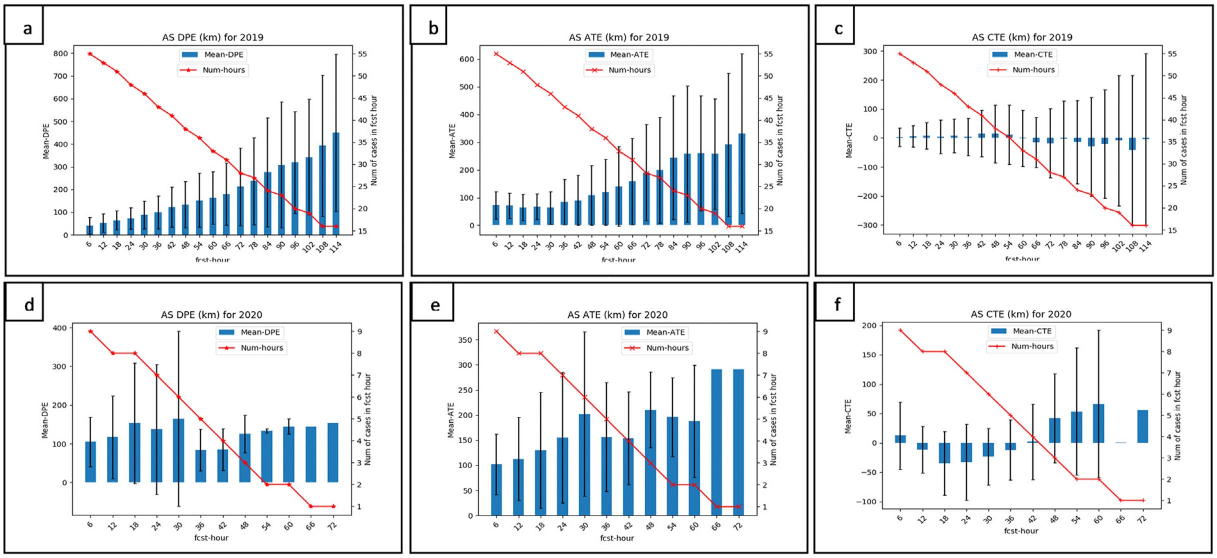

Fig. 5. Predicted track mean errors (km) along with standard deviation (SD) (vertical line on error bar) and the number of cases considered for each forecast hour (red line on secondary Y-axis) for 6 hourly time interval up to 114 h and 72 h, for the Tropical cyclones formed over AS, in terms of (a, d) Direct Position Error (b, e) Along Track Error (c, f) Cross Track Error; for the years 2019 (upper panel) and 2020 (lower panel).

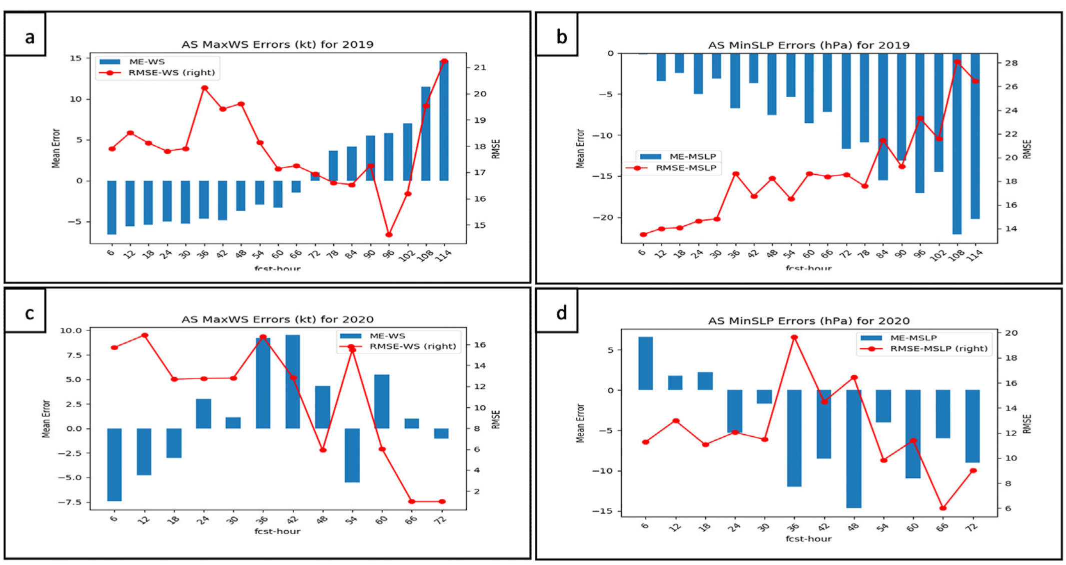

Fig. 6. Average Intensity Errors for 6 hrly time interval up to 114 h and 72 h, for the Tropical cyclones formed over AS, in terms of Mean Error (shaded bars) and Root Mean Square Error (red line on secondary Y-axis); (a, c) maximum Wind Speed (kt) (b, d) minimum MSLP (hPa); for the years 2019 (upper panel) and 2020 (lower panel).

(SD) for 2020 varied from 102 (60) to 291 km, and the positive ATE indicates the predicted track moves faster than the observed. On comparing the ATE for 2019 and 2020, it is seen that the ATE is lesser for 2019 as compared to 2020 for initial forecast hours. Thus, as predicted by GFS for initial forecast hours, the cyclone tracks showed slow movement than the observed track in 2019 than in 2020. For 2019, the mean CTE (SD) ranges from −41 (257) to 15 (80) km; the negative CTE for 60–114 h shows the predicted track is left side of the observed and for the remaining times, the positive CTE values indicate that predicted track is to the right side of the observed. The mean CTE (SD) in 2020 for the AS basin ranges from −34 (54) to 66 (125) km, and the negative CTE for 12, 18, 24, 30, and 36 h shows the predicted track is to the left side of the observed, and for the remaining times the positive CTE values indicate that predicted track is to the right side of the observed track. If the mean CTE is compared for 2019 and 2020, it is seen that the track was in general to the right of the observed track during the first 54 h in 2019, whereas it was to the left of the observed track during the initial 36 h in 2020. The situation gets reversed after these initial hours, and the track is seen to be on the left of the observed track in 2019 and to the right of the

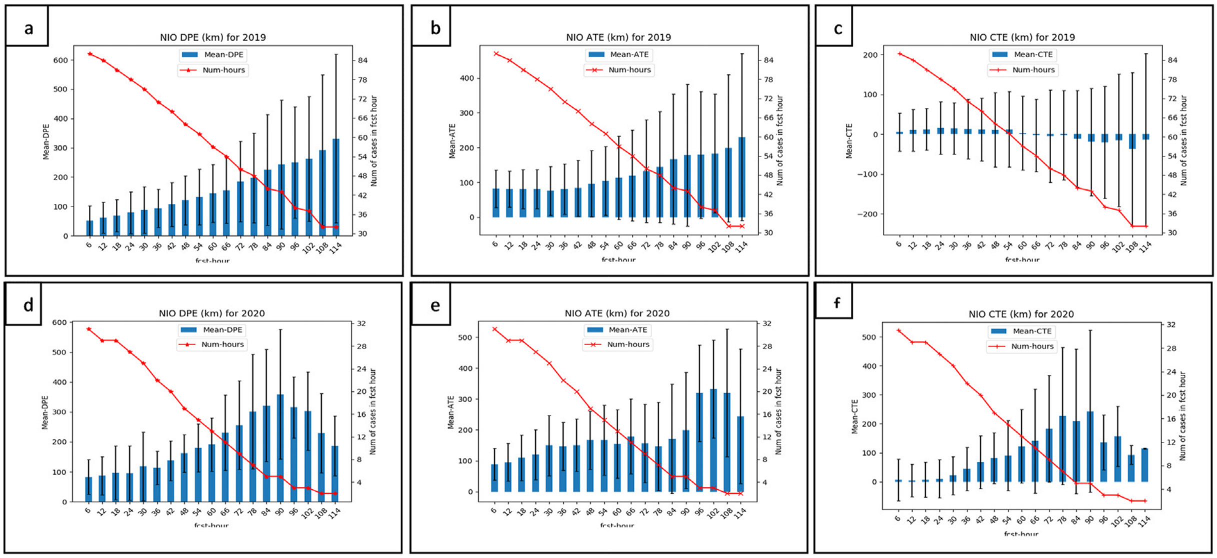

Fig. 7. Predicted Track errors (km) along with standard deviation (SD) (vertical line on error bar) and the number of cases considered for each forecast hour (red line on secondary Y-axis) for 6hourly time interval up to 114hr, for the Tropical cyclones formed over NIO, in terms of (a, d) Direct Position Error (b, e) Along Track Error (c, f) Cross Track Error; for the years 2019 (upper panel) and 2020 (lower panel).

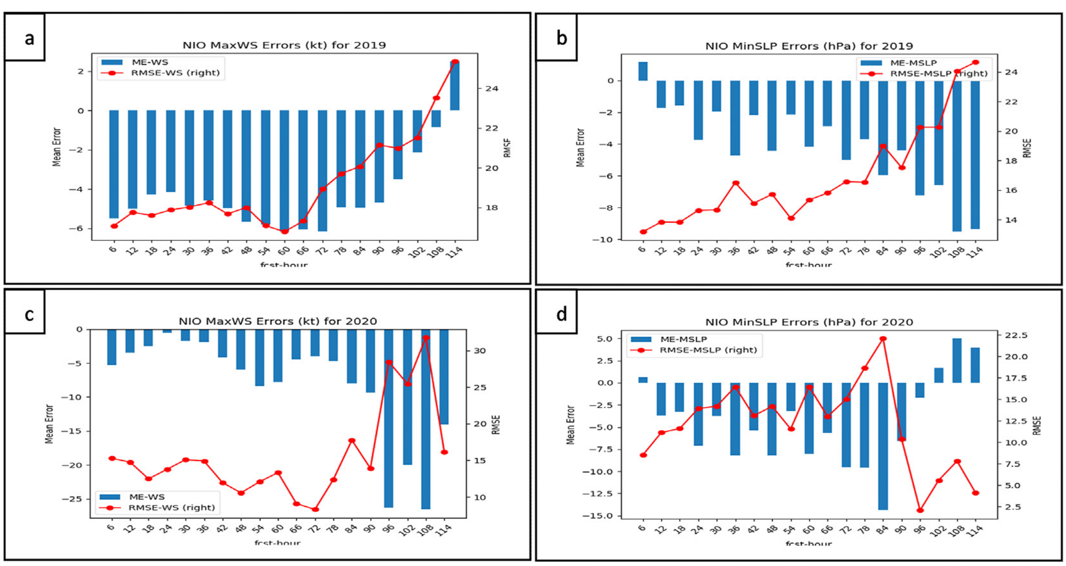

Fig. 8. Average Intensity Errors for 6 hrly time interval up to 114 h, for the Tropical cyclones formed over NIO, in terms of Mean Error (shaded bars) and Root Mean Square Error (red line on secondary Y-axis); (a, c) maximum Wind Speed (kt) (b, d) minimum MSLP (hPa); for the years 2019 (upper panel) and 2020 (lower panel).

observed track in 2020 for the rest of the forecast hours. Therefore, there was no systematic mean CTE bias seen when the 2019 and 2020 years are considered.

The mean Intensity forecast errors over the AS during 2019 and 2020 are shown in Fig. 6 and Table 6. During 2019, the MaxWS ME shows under-prediction of 1–6 kt for 6–66 h and over-prediction of 1–14 kt for 72–114 h. Whereas during 2020, the MaxWS ME shows under-prediction of 7.4, 4.7, 3, 5.5, and 1 kt for 6, 12, 18, 54, and 72 h; and over-prediction of 1–9 kt for 24–66 h. Therefore, cyclone intensity was under-predicted in terms of MaxWS ME during the first half of forecast hours (approximately up to 66 h) in 2019 and was over-predicted for the rest of the forecast hours. No definite pattern was seen during the 2020 cyclones intensity prediction. In 2019, the mean RMSE for MaxWS varied from 14 to 21 kt in 2019 and 1 to 16 kt in 2020. In 2019, the average ME for MinSLP showed under-estimation of 0.1–22 hPa for 6–114 h, and the mean RMSE for MinSLP varies from 13.5 to 28 hPa for 6–114 h of forecast lead times. Whereas for 2020, the average ME for MinSLP shows an over-estimation of 6.5, 1.7, and 2 hPa for 6, 12 and 18 h respectively, and under-estimation of 5–14 hPa for 24–72 h respectively. The mean RMSE for MinSLP varies from 6 to 19 hPa for 6–72 h of forecast lead times. The average ME for MinSLP showed negative values for all the forecast

Table 3
The annual (2019 and 2020) mean track errors along with Standard deviation (SD) for different TC categories at various forecast lead times formed over the Bay of Bengal.

Forecast length	Track errors (km) during 2019				Track errors (km) during 2020			
	Num Cases	DPE (SD)	CTE (SD)	ATE (SD)	Num Cases	DPE (SD)	CTE (SD)	ATE (SD)
6	31	70 (65)	11 (64)	82 (54)	22	73 (54)	3 (78)	83 (47)
12	31	83 (67)	21 (70)	88 (58)	21	76 (35)	10 (61)	88 (51)
18	30	86 (72)	26 (61)	102 (64)	21	76 (33)	23 (57)	102 (51)
24	29	95 (99)	40 (68)	103 (64)	20	81 (41)	25 (60)	108 (54)
30	28	99 (108)	38 (63)	98 (83)	19	103 (48)	36 (65)	133 (63)
36	26	85 (59)	38 (79)	83 (53)	17	122 (54)	61 (73)	144 (70)
42	25	90 (53)	22 (68)	77 (65)	16	150 (64)	84 (91)	149 (86)
48	23	106 (50)	20 (74)	89 (69)	14	169 (65)	90 (89)	157 (97)
54	22	113 (54)	26 (74)	90 (59)	13	188 (84)	96 (126)	162 (119)
60	20	123 (64)	21 (80)	82 (62)	11	199 (96)	133 (131)	149 (115)
66	19	133 (65)	28 (95)	69 (52)	10	239 (130)	155 (183)	167 (121)
72	17	160 (71)	26 (119)	62 (47)	8	269 (152)	200 (190)	139 (125)
78	16	161 (61)	9 (82)	87 (60)	7	301 (191)	227 (237)	146 (143)
84	14	187 (51)	3 (97)	92 (45)	5	322 (188)	209 (250)	170 (177)
90	14	199 (69)	2 (88)	110 (74)	5	359 (216)	243 (279)	198 (188)
96	12	222 (82)	−15 (74)	120 (87)	3	315 (102)	136 (94)	319 (157)
102	12	230 (93)	−24 (82)	137 (75)	3	303 (131)	156 (104)	332 (158)
108	10	267 (108)	−45 (125)	140 (91)	2	229 (133)	93 (33)	320 (206)
114	10	288 (132)	−50 (91)	189 (110)	2	187 (100)	115 (2)	244 (218)

Table 4
The annual (2019 and 2020) mean intensity errors for different TC categories at various forecast lead times formed over the Bay of Bengal.

Forecast length	Intensity errors during 2019				Intensity errors during 2020			
	MaxWS (kt)		MinSLP (hPa)		MaxWS (kt)		MinSLP (hPa)	
	ME	RMSE	ME	RMSE	ME	RMSE	ME	RMSE
6	−5	15	4	13	−4	15	−2	7
12	−5	16	1	14	−3	14	−6	10
18	−3	17	0	13	−2	12	−5	12
24	−3	18	−2	15	−2	14	−8	15
30	−4	18	0	15	−3	16	−4	15
36	−4	15	−1	13	−5	14	−7	15
42	−4	15	0	13	−8	12	−5	13
48	−8	15	0	12	−8	11	−7	14
54	−7	14	2	10	−9	11	−3	12
60	−7	15	0	9	−10	14	−7	17
66	−9	16	1	11	−5	10	−6	13
72	−12	20	2	14	−4	9	−10	16
78	−12	21	3	15	−5	12	−10	19
84	−11	22	3	17	−8	18	−14	22
90	−13	24	3	16	−9	14	−7	10
96	−8	24	1	16	−26	28	−2	2
102	−4	23	−3	18	−20	25	2	6
108	−8	23	1	17	−27	32	5	8
114	−2	23	−3	20	−14	16	4	4

hours in 2019, implying that the GFS predicted lower central pressure for the cyclones in general for 2019. In contrast, a similar pattern was observed for the GFS prediction of cyclones in 2020 for forecast hours starting from 24 h and more. In general, the average ME for MinSLP showed over-prediction by the GFS model for 2020 cyclones during initial hours.

4.3. Mean track and intensity errors over NIO

The annual mean track errors for NIO calculated by considering the 86 cases of 8 cyclones during 2019 and 31 cases of 5 cyclones during 2020; the corresponding errors are shown in Fig. 7. During 2019, the mean DPE (SD) varied from 51 (50) to 331 (287) km, and the DPE is less than 150 km up to 66 h and further increased. Whereas during 2020, the mean DPE (SD) for the NIO varies from 82 (58) to 359 (216) km, and the DPE is less than 150 km up to 48 h and further increased gradually with forecast lead time. Considering the entire NIO, the DPE showed better results for 2019 with errors within 150 km up to 66 h, whereas, for 2020, they are 150 km by 48 h forecast of GFS. The mean ATE for 2019 varied from 76 (69) to 230 (239) km, and for 2020, it varied from 89 (51) to 332 (158) km. The positive ATE suggests that the predicted track moves faster than the observed. Therefore, the GFS predicted a more rapid cyclone movement in 2020 than in 2019. The mean CTE in 2019 ranged from −37 (192) to 15 (65) km; the negative CTE for 66–114 h shows the predicted track is to the left side of the observed track, and for the remaining hours, the positive CTE values indicate that predicted track is to the right side of the observed track. For 2020, the mean CTE (SD) ranges from 4 (56) to 243 (279) km, and the positive CTE values indicate that the predicted track is the right side of the observed for all the forecast lead times. It is seen with the mean CTE scores that the GFS model predicted the track to the right of the observed track for the initial forecast hours (up to 60 h). Then the predicted track shifted to the left of the observed track, whereas for 2020, the GFS constantly predicted the track to be to the right of the observed track.

Table 5
The annual (2019 and 2020) mean track errors along with Standard deviation (SD) for different TC categories at various forecast lead times formed over the Arabian Sea.

Forecast length	Track errors (km) during 2019				Track errors (km) during 2020			
	Num Cases	DPE (SD)	CTE (SD)	ATE (SD)	Num Cases	DPE (SD)	CTE (SD)	ATE (SD)
6	55	40 (35)	2 (32)	72 (48)	9	105 (64)	13 (57)	102 (60)
12	53	52 (40)	6 (37)	70 (46)	8	117 (107)	−11 (39)	113 (82)
18	51	64 (42)	8 (46)	64 (47)	8	153 (155)	−34 (54)	130 (116)
24	48	72 (47)	5 (58)	67 (47)	7	137 (168)	−33 (65)	155 (130)
30	46	88 (61)	7 (58)	63 (58)	6	164 (226)	−24 (48)	202 (164)
36	43	100 (72)	4 (65)	84 (81)	5	84 (53)	−12 (52)	156 (109)
42	41	123 (88)	15 (80)	91 (90)	4	86 (54)	2 (64)	154 (92)
48	38	133 (101)	14 (99)	109 (108)	3	126 (48)	42 (76)	210 (75)
54	36	151 (118)	11 (103)	119 (119)	2	134 (6)	54 (108)	197 (78)
60	33	162 (116)	−1 (97)	140 (144)	2	145 (20)	66 (125)	188 (112)
66	31	179 (137)	−15 (87)	158 (156)	1	145	1	291
72	28	212 (170)	−18 (119)	190 (173)	1	154	56	291
78	27	237 (191)	−3 (131)	199 (191)				
84	24	275 (240)	−14 (144)	244 (223)				
90	23	309 (277)	−30 (170)	258 (245)				
96	20	320 (224)	−20 (187)	261 (208)				
102	19	343 (255)	−8 (225)	258 (200)				
108	16	393 (311)	−41 (257)	292 (259)				
114	16	449 (346)	- 5 (296)	331 (288)				

Table 6
The annual (2019 and 2020) mean intensity errors for different TC categories at various forecast lead times formed over the Arabian Sea.

Forecast length	Intensity errors during 2019				Intensity errors during 2020			
	MaxWS (kt)		MinSLP(hPa)		MaxWS (kt)		MinSLP(hPa)	
	ME	RMSE	ME	RMSE	ME	RMSE	ME	RMSE
6	−7	18	0	14	−7	16	7	11
12	−6	19	−3	14	−5	17	2	13
18	−5	18	−2	14	−3	13	2	11
24	−5	18	−5	15	3	13	−5	12
30	−5	18	−3	15	1	13	−2	11
36	−5	20	−7	19	9	17	−12	20
42	−5	19	−4	17	10	13	−9	15
48	−4	20	−8	18	4	6	−15	16
54	−3	18	−5	17	−6	16	−4	10
60	−3	17	−9	19	6	6	−11	11
66	−1	17	−7	18	1	1	−6	6
72	1	17	−12	19	−1	1	−9	9
78	4	17	−11	18				
84	4	17	−16	21				
90	5	17	−13	19				
96	6	15	−17	23				
102	7	16	−14	22				
108	12	20	−22	28				
114	15	21	−20	26				

The predicted cyclone Intensity annual mean errors over the NIO during 2019 and 2020 are shown in Fig. 8. During 2019, the MaxWS annual ME showed an under-prediction of 1–6 kt for most of the forecast time (up to 108 h) and 2.5 kt over-prediction for 114 h forecast. The mean RMSE for MaxWS varied from 16 to 25.5 kt. Whereas for 2020, the average wind speed ME shows under-prediction of 0.5 kt to 26 kt, and the mean RMSE for MaxWS varies from 8 to 31.7 kt. The comparison between the 2019 and 2020 scores of MaxWS ME showed that the predicted intensity errors are many times more in 2020 than in 2019. The maximum error score was 6 kt in 2019 against 26 kt in 2020. The annual ME for MinSLP in 2019 showed an under-estimation of - 1 to 9 hPa for 12–114 h. The mean RMSE for MinSLP is 13–24.8 hPa for 6–114 h of forecast lead times. For 2020, the annual ME for central MSLP shows an under-estimation of 1–14 hPa for 12–96 h; over-estimation of 0.6, 1.6, 5 and 4 hPa for 6, 102, 108, and 114 h forecast, respectively. The mean RMSE for central MSLP varies from 2 to 22 hPa for 6–114 h of forecast lead times. Therefore, concerning central MSLP, also the mean errors are more in 2020 than in 2019. Also, for both the years, the general tendency of the model was to under-estimate the MSLP during all the forecast hours in 2019 and up to 96 h forecast in 2020.

4.4. Mean track errors for different TC categories

Table 7 shows the mean track errors along with standard deviation (SD) and the number of cycles (Num Cases) considered for each forecast hour (fcst length) for different TC categories observed over NIO during 2019 and 2020. At the Cyclonic storm stage the errors along with its standard deviation are very high (DPE ~ 87–686 km and SD ~ 64 km). Whereas, the errors are comparatively low for the Severe Cyclonic storms, Very Severe Cyclonic storms and Extremely Severe Cyclonic storms ranging from 65 to 265 km. The errors are a bit higher for the Super Cyclonic storms (DPE ~ 44–520 km and SD ~ 35 388 km). Although, the higher values of the errors are occurring when the number of cases are very less (~10 numbers). Therefore, the mean track errors for different TC categories indicate that the track errors are decreasing with the intensification of TCs up to extremely severe cyclonic storms; but for Super Cyclonic storm again the errors are increasing with forecast lead time with decreasing number of available verification cases.

Table 7
The mean (2019 and 2020) track errors along with Standard deviation (SD) for different TC categories at various forecast lead times formed over the North Indian Ocean.

Fcst length	Mean DPE (SD) km for Tropical Cyclone categories occurred over NIO during 2019–2020									
	Num Cases	CS	Num Cases	SCS	Num Cases	VSCS	Num Cases	ESCS	Num Cases	SupCS
6	22	87 (65)	5	74 (30)	40	56 (49)	30	51 (60)	26	44 (35)
12	21	99 (62)	5	56 (34)	38	72 (61)	29	57 (57)	26	55 (33)
18	19	97 (55)	5	60 (21)	37	84 (84)	29	69 (63)	26	67 (46)
24	18	108 (66)	5	66 (33)	34	83 (83)	28	80 (93)	25	78 (52)
30	16	108 (52)	4	68 (47)	32	95 (106)	28	94 (106)	25	106 (68)
36	15	133 (71)	4	97 (53)	29	83 (50)	26	90 (54)	23	114 (78)
42	13	174 (84)	3	98 (59)	27	94 (54)	26	101 (60)	23	131 (89)
48	12	203 (95)	3	126 (48)	24	112 (56)	24	101 (57)	21	147 (100)
54	10	256 (102)	2	134 (6)	22	112 (55)	24	110 (60)	21	165 (116)
60	9	283 (83)	2	145 (20)	20	129 (65)	22	108 (54)	19	173 (117)
66	7	372 (88)	1	145	18	125 (64)	22	118 (53)	19	198 (133)
72	6	419 (103)	1	154	16	146 (76)	20	138 (57)	17	235 (179)
78	4	532 (46)			15	143 (74)	20	151 (59)	17	268 (200)
84	3	587 (68)			13	160 (91)	18	158 (66)	15	322 (249)
90	2	686 (59)			13	175 (96)	18	169 (95)	15	370 (296)
96	1	655			11	213 (109)	16	166 (113)	13	369 (219)
102					11	225 (137)	16	174 (128)	13	413 (258)
108					9	254 (160)	14	177 (137)	11	460 (332)
114					9	265 (149)	14	206 (145)	11	520 (388)

5. Conclusions

During 2019 and 2020, 13 cyclones formed over the North Indian Ocean. The corresponding vortex center position (track) and intensity (Maximum sustained wind speed (MaxWS) and minimum mean sea level pressure (MinSLP)) of these cyclones are predicted using the GFS model and the predicted tracks are obtained using the GFDL vortex tracker. The corresponding cyclone track positions and intensity are verified against IMD's best track data. The track forecast positions are verified in terms of DPE, ATE, and CTE for all the individual cyclones and the annual errors for BoB, AS and NIO. The intensity forecasts are verified with statistics of ME and RMSE for all the individual cyclones and the annual errors for BoB, AS and NIO.

The cyclone track errors observed over BoB during 2019 (DPE (SD) is 70 (65) to 288 (132) km) is lower than 2020 (DPE (SD) is 73 (54) to 359 (216) km) and the DPE is less than 150 km up to 66 h during 2019 and is up to 42 h in 2020. During both the years, the positive ATE indicates the predicted track movement is faster than the observed for all the forecast lead times (6–114 h). The positive CTE suggests that the predicted track is to the right side of the observed for all the forecast lead times during 2020 and up to 90hr during 2019; further, the negative CTE for 96–114 h shows the predicted track is to the left side of the observed track. The intensity of MaxWS shows under-estimation during both the years, and the under-estimation is high for the year 2020 (1–26 kt) compared to 2019 (1–12 kt). The MinSLP mean error is under-estimated most of the time during both the years and is higher (5 to −14 hPa) during 2020 compared to 2019 (3 to −3.4 hPa).

The track errors for the AS during 2019 (DPE (SD) is 40 (35) to 449 (346) km) is higher than 2020 (DPE (SD) is 84 (53) to 164 (226) km), and the DPE is less than 150 km up to 54 h in 2019 and is less than 165 km during 2020 for all the forecast lead times. The positive ATE during both years indicates that the predicted track is faster than the observed track. The negative CTE for 60–114 h during 2019 and for 12–36 h during 2020 shows the predicted tracks is to the left side of the observed and for the remaining times, the positive CTE values indicate that the predicted track is to the right side of the observed. The intensity forecast shows over/under-estimation for different forecast lead hours during both the years, and the wind speed mean error is high in 2019 (−6 to 14 kt) compared to 2020 (−7.4 to 9 kt). The MinSLP forecast shows an under-estimation of −0.1 to −22 hPa for the 06–114 h during 2019. In contrast, for 2020, the GFS model forecast shows an over-prediction of 2–6.5 hPa up to 18 h and further under-prediction of −5 to −14 hPa for 24–72 h.

The track errors over NIO during 2019 and 2020 vary from 50 (51) to 359 (216) km for the 06–114 h forecast lead times. The DPE during 2019 (51–331 km) is lower than the 2020 (82–359 km), and the DPE is less than 150 km up to 66 h during 2019 and 48 h during 2020. During both the years, the positive ATE (76–332 km) indicates the predicted track movement is faster than the observed track. The positive/negative CTE values (−37 to 15 km) suggest that the predicted track is the right/left side of the observed track for all the forecast lead times (6–114 h) during 2019. During 2020, the positive CTE (4–243 km) values indicate that the predicted track is to the right side of the observed track. During both the years model under-predicted the intensity of MaxWS and MinSLP most of the time. The under-estimation is high for the year 2020, i.e., MaxWS ME varies from −26 to −0.5 kt for 2020, and it varies −6 to −1 kt for the year 2019; and MinSLP ME for 2020 ranges from −14 to −1 hPa, and it varies −9 to −1 hPa for the year 2019.

Overall, the cyclone track errors are low for the Severe, Very Severe, Extremely Severe, and Super Cyclonic Storms, and high for the weaker storms reaching Cyclonic Storm stage. Track errors are higher over the AS than BoB basins. Model under-estimated the intensity of the cyclones, most of the time during both 2019 and 2020. These results are only for the 13 cyclones observed over NIO for the selected two years. Different models and best track data sets may lead to different error statistics results, so in the future more comparative studies may be undertaken using different models and best track data from various sources.

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References

Abhineet Shyam, Sharma, Neerja, 2018. Ocean surface winds from aquarius L-band radiometer during tropical cyclones: case studies. ISSN 0973-2667 Int. J. Ocean. Oceanogr. 12 (2), 147–158, 2018. http://www.ripublication.com. © Research India Publications.

Biswas, M.K., Stark, D., Carson, L., 2018. GFDL Vortex Tracker Users'Guide V3.9a, 35 pp.

Bucci, L.R., O'Handley, C., Emmitt, G.D., Zhang, J.A., Ryan, K., Atlas, R., 2018. Validation of an airborne Doppler wind lidar in tropical cyclones. Sensors (Basel, Switzerland) 18 (12), 4288. https://doi.org/10.3390/s18124288.

Chen, Guomin., Hui, Yu., Cao, Qing, Zeng, Zhihua, 2013. The performance of global models in TC track forecasting over the Western North pacific from 2010 to 2012. Trop. Cyclone Res. Rev. 2 (3), 149–158. https://doi.org/10.6057/2013TCRR03.02. ISSN 2225-6032.

Chen, Jan-Huey., Lin, Shian-Jiann, Zhou, Linjiong, Chen, Xi, Shannon, Rees, Bender, Morris, Morin, Matthew, 2019. Evaluation of tropical cyclone forecasts in the next generation global prediction system. Am. Meteorol. Soc. 147, 3409–3428. https://doi.org/10.1175/MWR-D-18-0227.1.

Christophersen, H., Aksoy, A., Dunion, J., Sellwood, K., 2017. The impact of NASA Global Hawk unmanned aircraft dropwindsonde observations on tropical cyclone track, intensity, and structure: case studies. Mon. Wea. Rev. 145, 1817–1830. https://doi.org/10.1175/MWR-D-16-0332.1.

Deshpande, Medha., Kanase, Radhika, Phani Murali Krishna, R., Tirkey, Snehlata., Mukhopadhyay, P., Prasad, V.S., Johny, C.J., Durai, V.R., Mohapatra, Sunitha Devi and M., 2021. Global ensemble forecast system (GEFS T1534) evaluation for tropical cyclone prediction over the north Indian ocean. MAUSAM 72 (1), 119–128. https://doi.org/10.54302/mausam.v72i1.123. January 2021.

Elsberry Russell, L., Tsai, Hsiao-Chung, Chin, Wei-Chia, Marchok, Timothy P., 2020. Advanced global model ensemble forecasts of tropical cyclone formation, and intensity predictions along medium-range tracks. Atmosphere 11, 1002. https://doi:10.3390/atmos11091002.

Gao, Y., Zhang, J., Sun, J., Guan, C., 2021. Application of SAR data for tropical cyclone intensity parameters retrieval and symmetric wind field model development. Remote Sens. 13, 2902. https://doi.org/10.3390/rs13152902.

Hamill, T.M., Whitaker, J.S., Fiorino, M., Benjamin, S.J., 2011. Global ensemble predictions of 2009's tropical cyclones initialized with an ensemble Kalman filter. Mon. Wea. Rev 139, 668–688. https://doi.org/10.1175/2010MWR3456.1.

Han, J., Pan, H.L., 2011. Revision of convection and vertical diffusion schemes in the NCEP global forecast system. Weather Forecast. https://doi.org/10.1175/WAF-D-10-05038.1.

Hazelton, A.T., Harris, Lucas, Lin, Shian-Jiann, 2018. Evaluation of tropical cyclone structure forecasts in a high-resolution version of the Multi scale GFDL fvGFS model. Am. Meteorol. Soc. 419–442. https://doi.org/10.1175/WAF-D-17-0140.1.

Heming, J.T., 2016. Tropical cyclone tracking and verification techniques for Met Office numerical weather prediction models. Meteorol. Appl. 24 (1).

Heming, Julian T., Fernando, Prates., Bender, Morris A., Bowyer, Rebecca, John, Cangialosi., Caroff, Phillippe, Coleman, Thomas, Doyle, James D., Dube, Anumeha, Ghislain, Faure., Fraser, Jim, Howell, Brian C., Igarashi, Yohko, McTaggart-Cowan, Ron, Mohapatra, M., Moskaitis, Jonathan R., Murtha, Jim, Rivett, Rabi, Sharma, M., Short, Chris J., Singh, Amit A., Vijay, Tallapragada., Helen, A. Titley., Xiao, Yi, 2019. Review of recent progress in tropical cyclone track forecasting and expression of uncertainties. Trop. Cyclone Res. Rev. 8 (4), 181–218. https://doi.org/10.1016/j.tcrr.2020.01.001. ISSN 2225-6032.

IMD, 2013. Cyclone Warning Services: Standard Operation Procedure. Cyclone Warning Division, IMD, New Delhi.

Kotal, S.D., Bhattacharya, S.K., Roy Bhowmik, S.K., 2014. Development of NWP based objective cyclone prediction system (CPS) for north Indian ocean tropical cyclones evaluation of performance. Trop. Cyclone Res. Rev. 3 (3), 162–177. https://doi.org/10.6057/2014TCRR03.03.

Kumar, P., Gairola, R.M., 2021. Fostering the need of L-band radiometer for extreme oceanic wind research. IEEE Transact. Geo-science Rem. Sens. https://doi.org/10.1109/TGRS.2021.3105333.

Malakar, P., Kesarkar, A.P., Bhate, J.N., Singh, V., Deshamukhya, A., 2020. Comparison of reanalysis data sets to comprehend the evolution of tropical cyclones over North Indian Ocean. Earth Space Sci. 7, e2019EA000978. https://doi.org/10.1029/2019EA000978.

Mohapatra, M., Bandyopadhyay, B.K., Nayak, D.P., 2013. Evaluation of official tropical cyclone intensity forecast over north Indian ocean issued by India meteorological department, natural hazards. J. Earth Syst. Sci. 68, 433–451.

Mohapatra, M., Bandyopadhyay, B.K., Tyagi, 2012. A. Best track parameters of tropical cyclones over the North Indian Ocean: a review. Nat. Hazard. 63, 1285–1317. https://doi.org/10.1007/s11069-011-9935-0.

Mohapatra, M., Nayak, D.P., Sharma, R.P., Bandyopadhyay, B.K., 2013a. Evaluation of official tropical cyclone track forecast over north Indian Ocean issued by India Meteorological Department. J. Earth Syst. Sci. 122, 589–601.

Mukhopadhyay, P., Prasad, V.S., Krishna, R.P.M., Deshpande, M., Ganai, M., Tirkey, S., Sarkar, S., Goswami, T., Johny, C.J., Roy, K., Mahakur, M., Durai, V.R., Rajeevan, M., 2019. Performance of a very high-resolution global forecast system model (GFS T1534) at 12.5 km over the Indian region during the 2016–2017 monsoon seasons. J. Earth Syst. Sci. 128 (6), 155. https://doi.org/10.1007/s12040-019-1186-6.

Pan, H.L., Wu, W.S., 1995. Implementing a mass flux convective parameterization package for the NMC medium range forecast model. NMC Off. Note 409, 40. http://www.emc.ncep.noaa.gov/officenotes/FullTOC.html1990.

Prasad, V.S., Gupta, Anjari., Rajagopal, E.N., Basu, Swati., 2013. Impact of OSCAT surface wind data on T574L64 assimilation and forecasting system - a study involving tropical cyclone Thane. Curr. Sci. 104 (5), 627–632.

Prasad, V.S., Johny, C.J., Sodhi, J.S., 2016. Impact of 3D Var GSI-ENKF hybrid data assimilation system. J. Earth Syst. Sci. 125, 1509–1521. https://doi.org/10.1007/s12040-016-0761-3.

Prasad, V.S., Dutta, Suryakanti, Sujata, Pattanayak., Johny, C.J., George, John P., Kumar, Sumit, Indira Rani, S., 2021. Assimilation of satellite and other data for the forecasting of tropical cyclones over NIO. MAUSAM 72 (1), 107–118. January 2021. 551.515.2: 551.509.32 (267).

Routray, Ashish., Dutta, Devajyoti, George, John, 2019. Evaluation of track and intensity prediction of tropical cyclones over north Indian ocean using

NCUM global model. Pure Appl. Geophys. 176. https://doi.org/10.1007/s00024-018-1924-8.

Sarkar, S., Mukhopadhyay, P., Dutta, S., Phani Murali Krishna, R., Kanase, Radhika D., Prasad, V.S., Deshpande, Medha S., 2021. GFS model fidelity in capturing the transition of low-pressure area to monsoon depression. Q J R Meteor. Soc. 147, 2625–2637. https://doi.org/10.1002/qj.4024.

Sela, J., 2010. The derivation of sigma pressure hybrid coordinate semi-Lagrangian model equations for the GFS. NCEP Off. Note 462, 31.

Sundqvist, H., Berge, E., Kristjansson, J.E., 1989. Condensation and cloud studies with mesoscale numerical weather prediction model. Mon. Wea. Rev. 117, 1641–1757.

Zhang, J.A., Atlas, R., Emmitt, G.D., Bucci, L., Ryan, K., 2018. Airborne Doppler wind lidar observations of the tropical cyclone boundary layer. Remote Sens. 10, 825. https://doi:10.3390/rs10060825.

Zhao, Q.Y., Carr, F.H., 1997. A prognostic cloud scheme for operational NWP models. Mon. Wea. Rev. 125, 1931–1953.