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Forecasting of tropical cyclone using global and regional ensemble prediction systems of NCMRWF : A review

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सार – वर्ष 2016 के बाद से उष्णकटिबंधीय चक्रवातों (TC) के प्रचालनात्मक पूर्वानुमान के लिए NCMRWF की वैश्विक एनसेम्बल पूर्वानुमान प्रणाली (NEPS-G) का उपयोग किया जा रहा है। NEPS-G का उन्नयन किया गया और वर्ष 2018 में इसके क्षैतिज विभेदन को 33 कि.मी. से बढ़ाकर 12 कि.मी. कर दिया गया। उन्नत NEPS-G ने उत्तर हिंद महासागर (NIO) के ऊपर उष्णकटिबंधीय चक्रवातों के पूर्वानुमान में बेहतर प्रदर्शन दिखाया है। 2019 के छह उष्णकटिबंधीय चक्रवातों और 2020 के चार उष्णकटिबंधीय चक्रवातों के लिए NEPS-G की औसत ट्रैक पूर्वानुमान त्रुटियां क्रमशः 250 कि. मी. और 220 कि. मी. हैं। NCMWRF (NEPS-R) की क्षेत्रीय एनसेम्बल पूर्वानुमान प्रणाली का क्षैतिज विभेदन 4 कि.मी. है। 72 घंटे के अग्रिम पूर्वानुमान समय के लिए NEPS-R की औसत ट्रैक पूर्वानुमान त्रुटि NEPS-G की तुलना में कम है। NEPS-G द्वारा दिए गए पूर्वानुमान की विश्वसनीयता अच्छी है और इसके प्रचालनात्मक क्षेत्र के अंतर्गत 2020 के चार उष्णकटिबंधीय चक्रवातों के लिए विशेषता वक्र 0.5 से अधिक है। उष्णकटिबंधीय चक्रवातों की चरम तीव्रता का पूर्वानुमान करने में NEPS- R बेहतर है। यह 'फॉनी' और 'अम्फन' जैसे चक्रवातों की तीव्रता का भी पूर्वानुमान कर सका है। NEPS-G चरम तीव्रता का पूर्वानुमान करने में असमर्थ रहा। चरम तीव्रता के समय का पूर्वानुमान करना अभी भी एक मुद्दा है। NEPS-G और NEPS-R दोनों ने ही उष्णकटिबंधीय चक्रवात 'निसर्ग' की चरम तीव्रता का आकलन अधिक किया है। NEPS-R के पूर्वानुमान में आकलन अधिक हुआ है।

ABSTRACT. NCMRWF global ensemble prediction system (NEPS-G) is being used for operational forecasting of tropical cyclones (TC) since the year 2016. The NEPS-G was upgraded and its horizontal resolution was increased from 33 km to 12 km in the year 2018. The upgraded NEPS-G has shown improved performance in forecasting tropical cyclones over the North Indian Ocean (NIO). The average 120 hours track forecast errors of NEPS-G for six TCs of 2019 and four TCs of 2020 are about 250 km and 220 km, respectively. The regional ensemble prediction system of NCMWRF (NEPS-R) has 4 km horizontal resolution. Average track forecast error of NEPS-R at 72 hours forecast lead time is less than that of NEPS-G. The strike probability forecast of NEPS-G shows good reliability and the area under the relative operating characteristic curve is greater than 0.5 for four TCs of 2020. The forecasting of peak TC intensity is better in NEPS-R. It could also predict the rapid intensifications of the TCs 'Phani' and 'Amphan'. NEPS-G was unable to predict rapid intensifications. The prediction of time of peak intensity is still an issue with the models. Both NEPS-G and NEPS-R overestimate peak intensity of TC 'Nisarga'. The overestimation is more in NEPS-R forecast.

Key words – Tropical cyclones, Ensemble prediction system, Strike probability, Forecast verification.

1. Introduction

The coastal regions of Indian subcontinent witness tropical cyclones (TC) that originate over the North Indian Ocean (NIO) during pre- and post-monsoon seasons. Accompanied by the strong wind, torrential rainfall and high tides, these storms create huge impact on the lives and economy of the regions along the coastline. While a reliable forecast at a longer lead time helps administrators to initiate timely measures, an accurate short-range prediction of intensity and track helps in avoiding unnecessary evacuations. Weather forecasting centres around the world, including the Regional Specialized Meteorological Centres (RSMCs), provide intensity and track forecasts of the cyclones. India Meteorological Department (IMD) issues forecasts of tracks and intensity for the TCs that originate over the NIO based on synoptic and numerical model guidance (Kotal *et al*., 2014). The TC track is determined by the location of the centre and the intensity is measured by either maximum sustained surface wind speed or minimum surface pressure at the cyclone centre.

Numerical Weather Prediction (NWP) model is an essential tool for operational forecasting of tropical cyclones. Operational NWP modelling centres provide the forecasts of the TCs around the globe from their respective NWP models. Since 1991 the TC track forecasts from operational NWP models have been evaluated on a regular basis under the Working Group on Numerical Experimentation (WGNE). Twelve NWP centres participate in this evaluation process and the intercomparison of the performances indicates significant improvements in TC track forecasts by operational global models during this period (Yamaguchi, 2017). In spite of the consistent incremental improvements in accuracy deterministic model forecasts of TC tracks and intensities are still associated with great deal of uncertainty. An erroneous deterministic forecast may mislead the decision makers and cause losses of life and property due to the lack of appropriate action at proper location and time. Unnecessary evacuations along the coastlines can be avoided and lives and property can be saved if a deterministic forecast is accompanied by reliable uncertainty information. In general, users are interested to know the uncertainty in the forecast and prefer it to deterministic forecast (Morss *et al*., 2008) because it helps them in taking better decisions (Joslyn *et al*., 2007; Nadav-Greenberg and Joslyn, 2009).

In order to provide reliable uncertainty information, the operational NWP centres around the globe use ensemble prediction systems of varied resolutions, sizes and perturbation methods for initial condition and model physics. Global medium range ensemble forecasts of major operational NWP centres are available at The Observing System Research and Predictability Experiment (THORPEX) Interactive Grand Global Ensemble (TIGGE; Bougeault *et al*., 2010; Swinbank *et al*., 2015) for research purpose. NCMRWF also contributes its global ensemble forecasts to TIGGE. Yamaguchi *et al*. (2015) have verified the TC forecasts of European Centre for Medium-Range Weather Forecasts (ECMWF), Japan Meteorological Agency (JMA), National Centers for Environmental Prediction (NCEP) and the Met Office, UK (UKMO) global medium range ensemble prediction systems for 7 TC basins around the world using the data obtained from TIGGE portal. The study reveals that though the operational global models provide skilful medium range TC forecasts the Multicentre Global Ensembles (MCGEs) have more skill than the best single model which, in most of the cases, is the ECMWF ensemble. Heming *et al*. (2019) have recently presented an overview of the operational NWP models used for deterministic and probabilistic TC forecasting and their performance statistics. Magnusson *et al*. (2019) have reviewed recent changes in ECMWF operational forecasting systems and highlighted the future challenges in improving the TC intensity forecast skill for all the global and regional prediction systems, using the example of ECMWF system.

Like other major operational NWP centres, NCMRWF also uses its global and regional ensemble prediction systems (NEPS-G and NEPS-R, respectively) for probabilistic TC forecasting. These ensemble prediction systems are based on Met Office Global and Regional Prediction Systems (MOGREPS) of Met Office, UK. In the present paper the performance of NEPS-G and NEPS-R in forecasting tropical cyclones over the North Indian Ocean in recent past has been reviewed. Brief descriptions of NEPS-G and NEPS-R are given in section 2. The performances of NEPS-G and NEPS-R in forecasting track and intensity of tropical cyclones are discussed in section 3 and the summary is presented in section 4.

2. Ensemble Prediction System of NCMRWF

2.1. *NCMRWF Global Ensemble Prediction System (NEPS-G)*

NCMRWF Global Ensemble Prediction System is based on the global version of the MOGREPS (Bowler *et al*., 2008). It was first operationally implemented in the year 2015 with 45 ensemble members (1 control + 44 perturbed), 33 km horizontal resolution (0.45° along latitudinal circle and 0.30° along longitudinal line) and 70 vertical levels upto a height of about 80 km (N400L70). The initial condition perturbations of horizontal wind components, potential temperature, specific humidity and exner pressure are generated by Ensemble Transform Kalman Filter Method (Bishop *et al*., 2001). The initial condition perturbations are added to the deterministic global model analysis generated by 4D Var data assimilation method using Incremental Analysis Update (IAU) method to obtain 44 perturbed initial conditions. The model uncertainties are represented by Stochastic Kinetic Energy Back Scattering (SKEB) and Random Parameter (RP) Schemes (Tennant *et al*., 2011). A detailed description of the operational implementation of NEPS-G is available in Sarkar *et al*., 2016. NCMRWF started using NEPS for probabilistic forecasting of tropical cyclones over the NIO in the year 2016. The bivariate approach (Vitart and Stockdale, 2001; van der Grijn, 2002) adopted by the TC tracker developed at Met Office, UK (Heming, 2017) is used for this purpose. In this approach TC is identified by examining the relative vorticity field at 850 hPa pressure level but TC centre is then fixed at nearest mean sea level pressure (MSLP) minimum. Chakraborty *et al*. (2020) have investigated the TC forecasts by NEPS-G off our tropical cyclones of 2016 namely ‘Roanu’, ‘Kayant’, ‘Nada’ and ‘Vardah’. The results of their study indicate that in most of the cases the ensemble with larger size provides better uncertainty information in terms of TC tracks, strike probability and intensity errors. It was also found that at longer forecast lead time the mean track forecasts by an ensemble of larger size (22 or 44 members) had less error than the forecast error of the ensemble of smaller size (11 members) and control member.

The horizontal resolution of NEPS-G was increased to about 12 km (0.18° along the latitudinal circle and 0.12° along longitudinal line; N1024L70) in the year 2018. In order to address the issue of lack of ensemble spread in the near surface variables initial condition perturbations are also added to Sea Surface Temperature (SST), Soil Moisture Content (SMC) and Deep soil temperature in this upgraded version of NEPS-G. Also, more observations have been included in the ETKF data assimilation system. In the meantime, the deterministic data assimilation system was upgraded to Hybrid-4D Var data assimilation system which uses input from NEPS-G to make its background covariance matrix flow dependent. The high resolution (12 km) NEPS-G has 23 ensemble members (1 control + 22 perturbed). Out of the 22 perturbed members, 11 members run from 0000 UTC of the current day and the remaining 11 members run from 1200 UTC of the previous day to generate the 22 members ensemble forecast. The forecast of deterministic global model running from 0000 UTC of the current day is used as the control forecast. Generally, the resolutions of the global ensemble prediction systems of other operational NWP centres are less than that of the corresponding deterministic models but the NEPS-G has the same resolution as the operational global deterministic model of NCMRWF, *i.e*., NCUM. The implementation and preliminary verification details of this upgraded NEPS-G are available in Mamgain *et al*. (2019). Dube *et al*. (2020) have carried out a comparative study on the skills of old and upgraded NEPS-G in forecasting TCs over the NIO. The forecasts of the cyclones occurred between 2016 and May 2018 by old NEPS-G and that occurred between June and December of 2018 by the upgraded NEPS-G were considered for the comparison. The study reveals that the upgraded NEPS-G shows better skill in predicting tracks, strike probability and intensity.

2.2. *NCMRWF Regional Ensemble Prediction System (NEPS-R)*

Regional ensemble prediction system of NCMRWF was successfully tested in the year 2018 and first implemented as an on-demand model in the year 2019. Due to the lack of available computational resources, the model was used for short range probabilistic forecasting of extreme events if any signal was received from the medium range forecasting of the operational global ensemble prediction system. It was used for on-demand probabilistic forecasting of Tropical Cyclone 'Phani' which hit the Odisha coast in May 2019. There are 12 ensemble members which include 1 control and 11 perturbed members. The horizontal resolution of the model is 4 km and it has 80 vertical levels which extend up to a height of about 38.5 km. The initial and boundary conditions are obtained from NEPS-G. Convection is treated explicitly in NEPS-R instead of using parameterized convection. The parameterized physical processes include long- and short-wave radiation, a ten-tile surface exchange scheme, mixed phase cloud microphysics, a boundary-layer turbulence scheme and a random parameters stochastic physics scheme (McCabe *et al*., 2016; Bowler *et al*., 2008). A detailed description of the implementation of this convective scale ensemble prediction system at NCMRWF is available at Prasad *et al*. (2019). NEPS-R was implemented operationally in July 2019 and was running daily from the initial condition of 0000 UTC to provide 75 hours forecast over the domain extending from 67° E to 98° E and from 7° N to 38° N. The model uncertainties are addressed by Random Parameter scheme. Tropical Cyclones 'Amphan' and 'Nisarga' were forecasted using this operational NEPS-R.

NEPS-R has recently been subjected to major changes in its initial condition and science configurations. In the new version of NEPS-R the perturbations generated by Ensemble Transform Kalman Filter (ETKF) of NEPS-G are added by IAU method to the analysis prepared by the regional 4D Var data assimilation system to provide the perturbed initial conditions. The deterministic operational regional model running from the regional 4D Var analysis is used as the control member. This upgraded version of NEPS-R has been used for forecasting the most recent tropical cyclones 'Nivar', Gati and 'Burevi'.

3. Performance of NEPS-G and NEPS-R in forecasting track and intensity

The performances of NEPS-G and NEPS-R in forecasting the tropical cyclones over the NIO during 2019 and 2020 are discussed in the present study using the examples of tropical cyclones 'Phani', 'Amphan', 'Nisarga', 'Nivar' and 'Burevi'. Prediction of TC tracks and intensities will be considered for analyzing the forecast performances. Verification has been done against the best track data of IMD.

TC 'Phani' originated as a low-pressure system over the east equatorial Indian Ocean and the neighbouring south east Bay of Bengal on 25th April, 2019. The low-pressure system moved north westward and intensified into Cyclonic Storm 'Phani' on 27th April. It became a very severe cyclonic storm (VSCS) in the morning of 30th April and an extremely severe cyclonic storm (ESCS) in the evening on the same day. Then it recurved in the

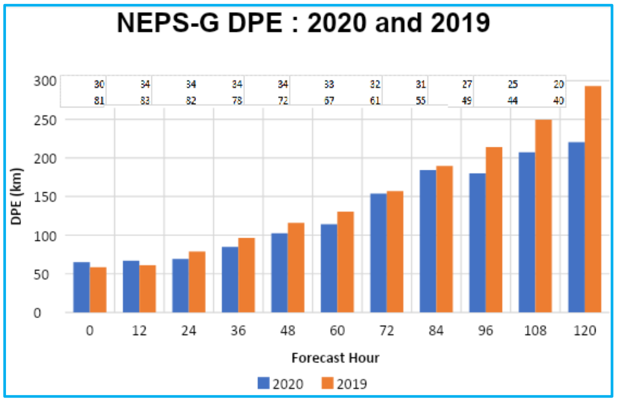


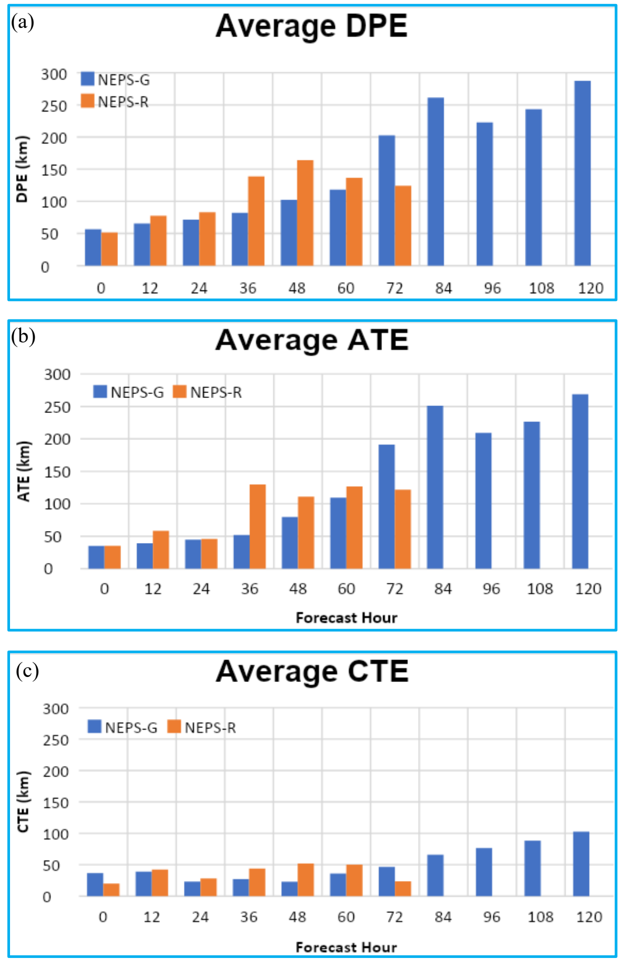
Fig. 1. Variation of average NEPS-G forecast track error (DPE) with time for 6 TCs of 2019 and 4 TCs of 2020. The numbers in the upper and lower rows at the top of the figure indicate the number of forecast points for the years 2020 and 2019, respectively over which the validation has been carried out

north-northeastward direction and reached its peak intensity in the night of 2nd May and early morning of 3rd May. It crossed Odisha coast as an ESCS with maximum sustained wind speed of about 100 knots between 8-10 am on 3rd May, 2019.

TC 'Amphan' originated as a low-pressure area over the south-eastern Bay of Bengal on 15th May, 2020. It intensified to cyclonic storm on 16th May, 2020 after moving in the north north-westward direction. It turned into a severe cyclonic storm in the morning of 17th May and underwent rapid intensification in next 24 hours. It intensified to a super cyclonic storm on 18th May, 2020. Then it weakened into an ESCS and later crossed West Bengal Coast between 1530 and 1730 IST on 20th May, 2020 as a VSCS.

Severe Cyclonic Storm (SCS)'Nisarga' originated as a depression in the Arabian Sea near coast of Kerala and Karnataka around 1st June, 2020 and moved generally northward. The low-pressure system intensified into a CS on 2nd June and subsequently to a severe cyclonic storm (SCS) on 3rd June. It then turned to the northeast to make landfall approximately 95 km south of Mumbai. 'Nisarga' rapidly weakened after landfall and dissipated on 4th June. This was the strongest tropical cyclone to strike the Indian state of Maharashtra in the month of June since 1891. Heavy rains and winds gusting up to 120 km per hour were reported as the cyclone crossed the coast near the city of Alibagh. It was also the first cyclone to impact Mumbai since Cyclone 'Phyan' of 2009.

VSCS 'Nivar' originated as a low-pressure system on 22nd November, 2020 in the Bay of Bengal near the coast of Tamil Nadu. It intensified to a depression on 23rd November and to a CS on 24th November. The cyclone



Figs. 2(a-c). Variation of (a) DPE, (b) ATE and (c) CTE of NEPS-G and NEPS-R forecast track errors with time for TC 'Nisarga'

moved north-westward and made a landfall over north coastal Tamil Nadu between Puducherry and Chennai in the midnight of 25th November. After landfall it first moved north northeastward and then towards west.

TC 'Burevi' was a comparatively weak cyclonic storm. It originated from a low-pressure area developed on 28th November, 2020 near the coast of Aceh. The system gradually became a depression on 30th November and intensified to cyclonic storm on 1st December. It made landfall in Srilanka on 2nd December and entered the Gulf of Manner on the next day. 'Burevi' dissipated into an area of low-pressure on 5th December, 2020.

3.1. *TC track forecast of NEPS-G and NEPS-R*

A mean of TC forecast positions of the ensemble members provides the ensemble mean track which can be used as a deterministic TC forecast track. Direct position

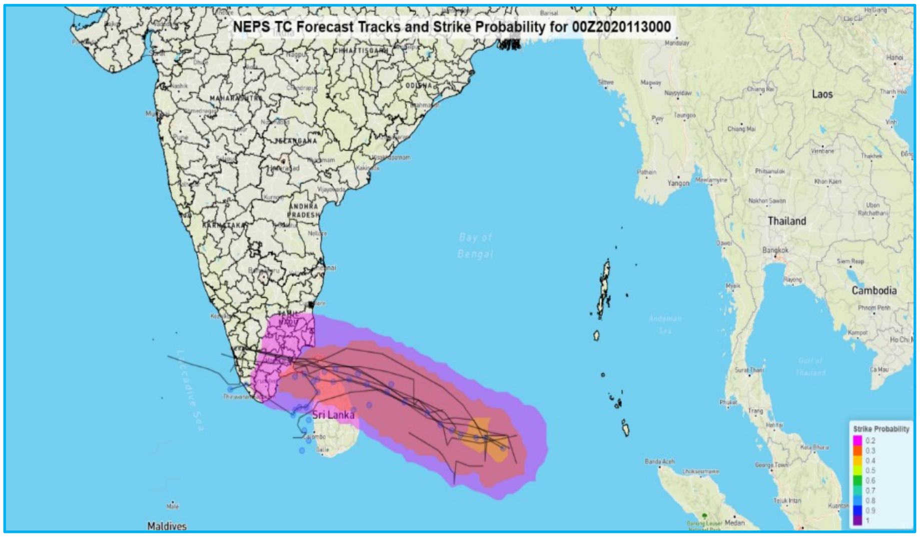
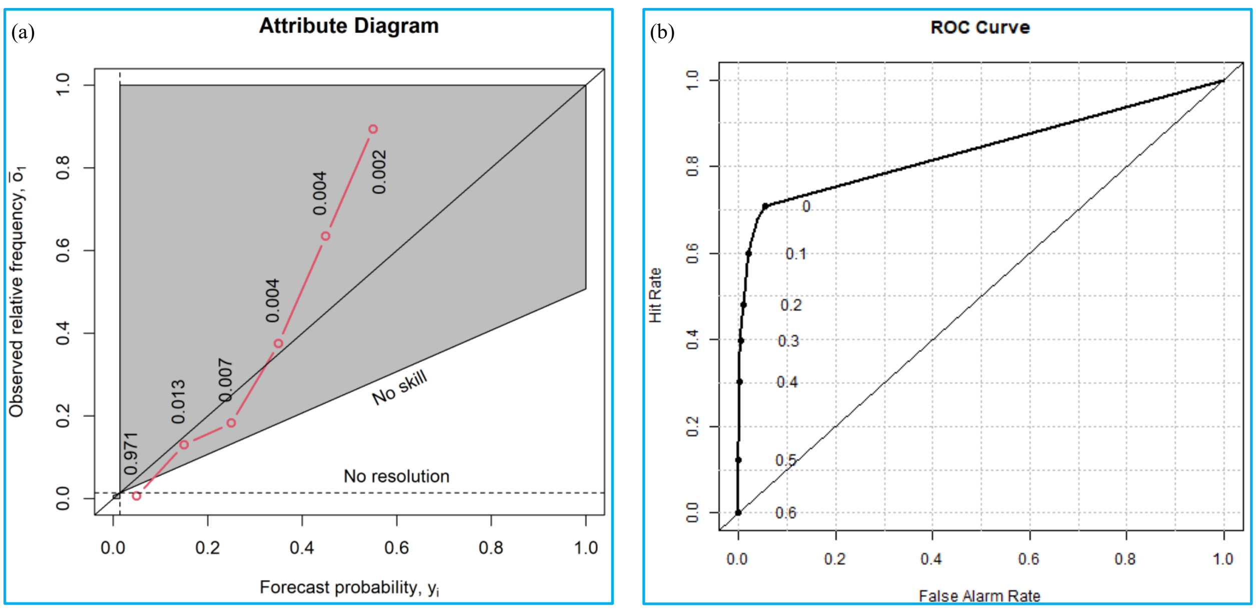


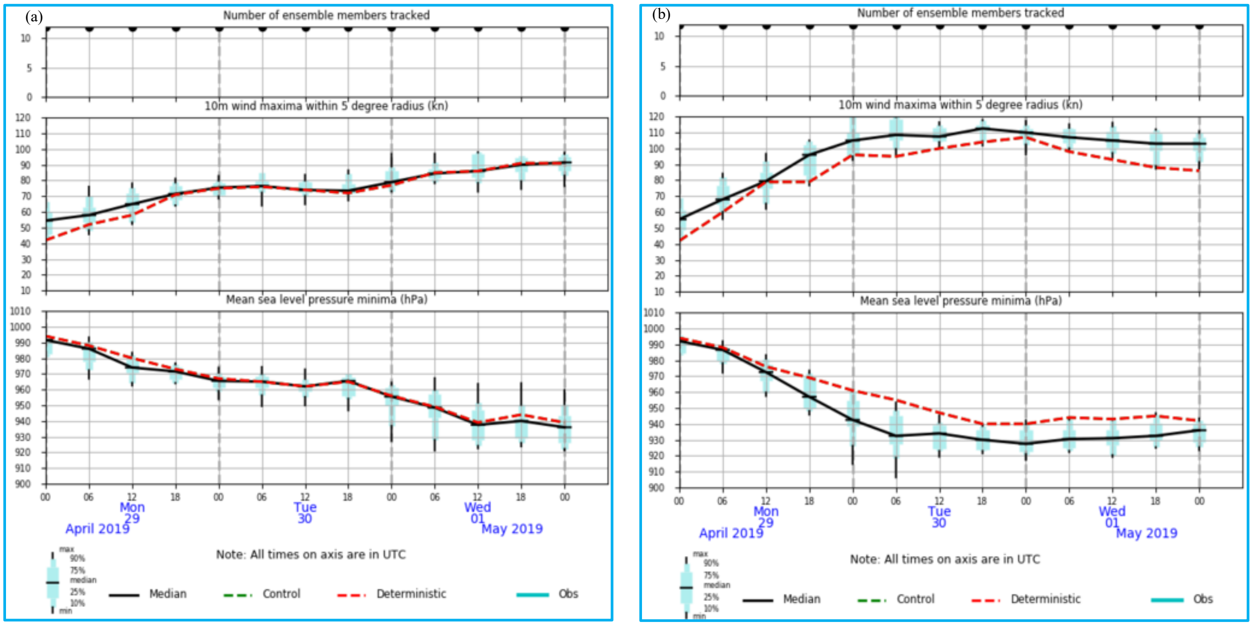
Fig. 3. Strike probability forecast of NEPS-G for TC 'Burevi' based on initial condition of 0000 UTC 30th November, 2020



Figs. 4(a&b). (a) Reliability diagram and (b) ROC curve of strike probability forecast by NEPS-G for TC 'Burevi'

error (DPE) is the great circle distance between the observed and ensemble mean forecast positions of the TC at the same forecast validity time (Heming, 2017). The position error in the direction perpendicular to the observed track is called the cross-track error (CTE). The component of the position error along the observed track which occurs due to the difference in speeds of the observed and forecasted systems is called along-track error (ATE).

The comparative study between the performances of older (44 km horizontal resolution) and the upgraded (12 km horizontal resolution) version of NEPS-G carried out by Dube *et al.* (2020) shows that the average DPE has decreased from 560 km to 260 km in day 5 forecast which is about 53% reduction in the error. The reduction in ATE was noted to be much more significant than that in CTE. Across all lead times the average decrease in ATE, CTE and DPE are about 48%, 15% and 38% respectively.

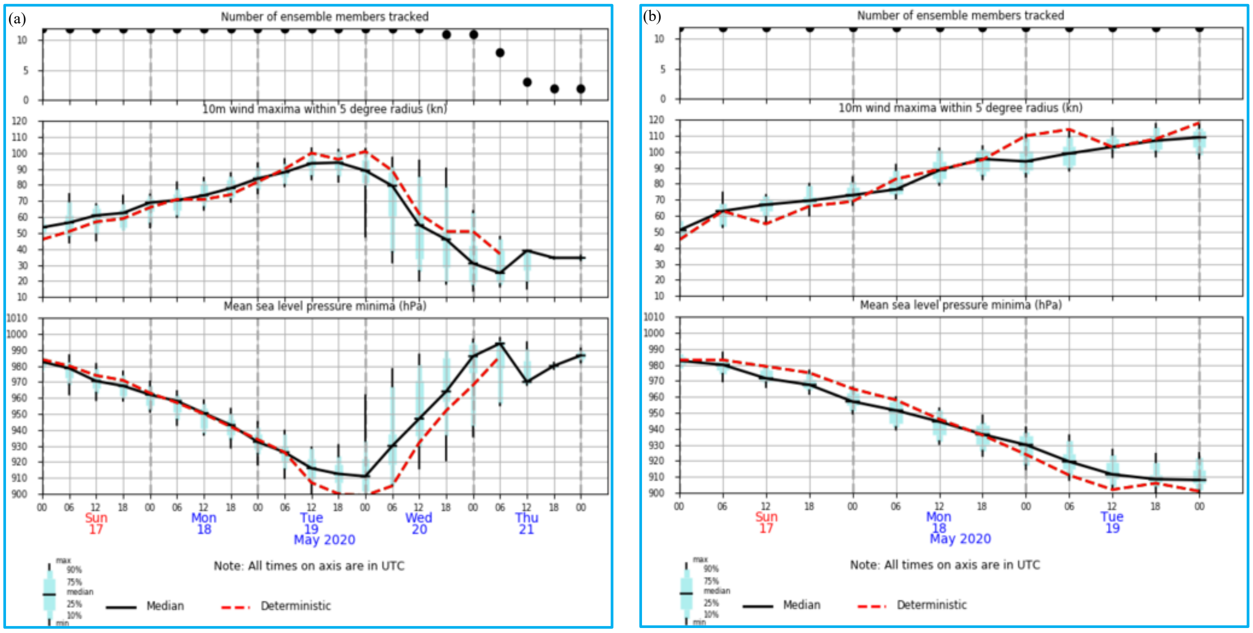


Figs. 5(a&b). Storm following EPS grams of (a) NEPS-G and (b) NEPS-R from the initial condition of 0000 UTC, 29th April, 2019 for TC 'Phani'. The black line denotes the median and the red dashed line denotes the deterministic forecast

The DPE of NEPS-G forecast for the TCs of 2019 and 2020 over NIO is smaller than that for the TCs of 2018. Fig. 1 shows the average values of the DPE of 6 TCs of 2019 ('Bulbul', 'Phani', 'Hikaa', 'Kyarr', 'Maha' and 'Vayu') and 4 TCs of 2020 ('Amphan', 'Nisarga', 'Nivar' and 'Burevi'). The numbers in the upper and lower rows at the top of the figure indicate the number of forecast points for the years 2020 and 2019, respectively over which the validation has been carried out. The improvement in forecasting TC track with every passing year may be due to the continuous improvement in modelling and observing systems. The figure shows that the average track forecast error of 6 TCs of 2019 is about 250 km and that of 4 TCs of 2020 in day 5 forecast is about 220 km which is approximately 12% reduction in DPE. The comprehensive analysis of TC track forecast error of NEPS-R for the cyclones of 2019 and 2020 has not yet been carried out. Figs. 2(a-c) shows the variations of DPE, ATE and CTE of NEPS-G and NEPS-R track forecasts with time for the TC 'Nisarga'. It can be noted that the major contribution to this error is from ATE, *i.e.*, the difference between the predicted and observed TC speeds. In case of 'Amphan' DPE of NEPS-R was lower than that of NEPS-G at all forecast lead times till 72 hours. DPE of NEPS-R at 72 hours forecast lead time for 'Amphan' was about 170 km. In case of TC 'Phani', track error of NEPS-R was initially larger than that of NEPS-G but after 30 hours DPE of NEPS-R was lower. On an average NEPS-R track forecast error at 72 hours forecast lead time is smaller than that of NEPS-G.

The main objective of TC track forecasting by an ensemble prediction system is quantifying the uncertainty associated with the deterministic track forecasting. This uncertainty is expressed in the form of TC strike probability. Strike probability at a location is the probability of passing the centre of cyclone within 120 km distance from that location in next few days. IMD and most of the RSMCs issue uncertainty information associated with the official track forecasts in the form of cone of uncertainty (COU) which is based on the predictive skill of the recent past (Mohapatra *et al.*, 2012). While uncertainty information from COU is almost static in nature the flow dependent uncertainty information is provided by TC strike probability.

The strike probability forecast of NEPS-G for the TC 'Burevi' is shown in Fig. 3. Verification of strike probability is presented in Figs. 4(a&b) using Reliability diagram and Relative Operating Characteristic (ROC) curve. The Reliability diagram [Fig. 4(a)] gives a comparison of forecast probability against the observed relative frequency. A perfect probabilistic forecast will show all points along the diagonal. Points above diagonal suggest underestimation (lower forecast probabilities) while points below the diagonal suggest overestimation (higher forecast probabilities). Figure shows that the reliability curve lays in the skillful region and very close to the diagonal line of perfect reliability for the lower values of probability. However, for higher probability values NEPS-Gunder-forecasted the strike probabilities. The



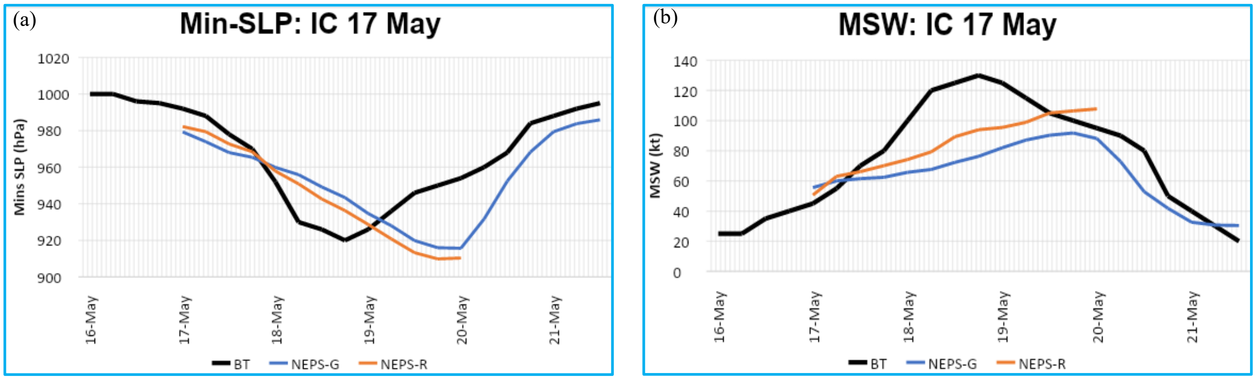
Figs. 6(a&b). Storm following EPSgrams of (a) NEPS-G and (b) NEPS-R from the initial condition of 0000 UTC 17th May for the SuCS 'Amphan'. The black line denotes the median and the red dashed line denotes the deterministic forecast

reliability diagram is conditioned on the forecast while ROC is conditioned on the observations. Fig. 4(b) shows the ROC curve which plots the variation of false alarm rate (FAR) against hit rate (HR) with changing values of threshold probability that distinguishes events from non-events. As the probability threshold increases both HR and FAR decreases. If the HR decreases slower than the FAR, the curve lies above the diagonal and the forecasting system is considered to have skillin discriminating events from non-events. In that case, the area under the ROC curve (AUC) is greater than 0.5.The AUC of NEPS-G for TC 'Burevi' is 0.83 which shows reasonable discrimination skill. NEPS-G shows similar skill in forecasting the recent TCs 'Amphan', 'Nisarga' and 'Nivar' also. The AUC for 'Amphan', 'Nisarga'and 'Nivar are 0.866, 0.95 and 0.9, respectively. The figures showing ROC curves for these cyclones are not shown here for brevity.

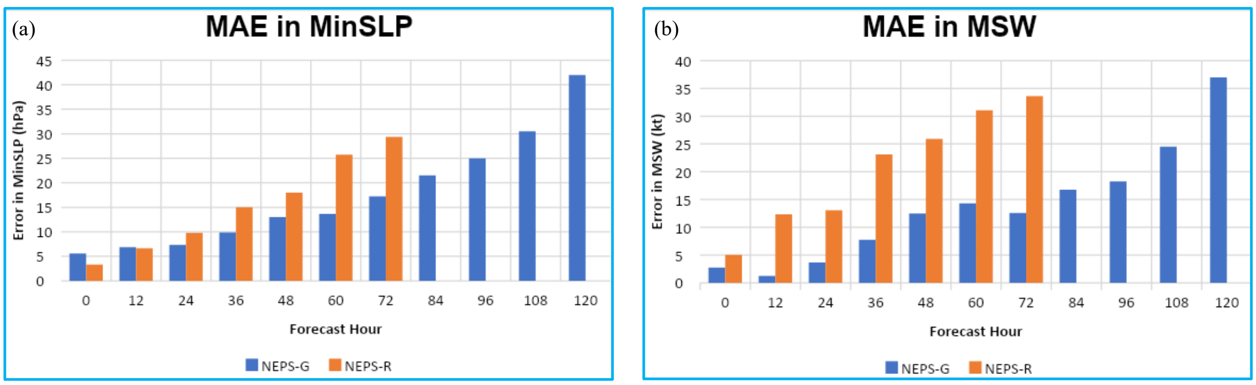
3.2. *TC intensity forecast*

At the start of this century the ensemble forecasting of TC intensity was at its preliminary stage(Cheung, 2001). Though there is remarkable improvement in skill of TC track forecasts in recent times the skill in intensity forecast has increased comparatively at slower rate (Rappaport, 2009; Emanuel and Zhang, 2016; Yamaguchi *et al*., 2017). Dube *et al*. (2020) considered maximum wind speed for verifying the intensity predicted by NEPS-G before and after the upgradation of the forecasting system. They found that on an average there is 30% reduction in root mean square error (RMSE) of the ensemble mean maximum surface wind speed across all forecast lead times due to the upgradation of NEPS-G. Though main reason behind this improvement can be attributed to the increase in horizontal resolution of the model, inclusion of more observations in the ETKF assimilation system may also have significant contribution. The paper mentioned above shows that RMSE of maximum wind speed predicted by upgraded NEPS-G increases from 10 to16 kts in five days forecast lead times.

Performance of NEPS-R and NEPS-G shows that both 'Phani' and 'Amphan' were well predictable in terms of intensity. According to IMD report 'Phani' reached its peak intensity of maximum surface wind speed (MSW) of about 115 knots and lowest central pressure of 932 hPa between 0900 and 2100 UTC of 2nd May, 2019. Figs. 5(a&b) show the storm following EPSgrams of NEPS-G and NEPS-R for 'Phani' from the initial condition of 0000 UTC 29th April. Though the minimum central pressure was predicted close to 935 hPa by any member of both the EPSs the maximum wind forecasting was better by NEPS-R. This cyclone underwent rapid intensification as its MSW increased from 45 to 95 knots between 0900 UTC of 29th May, 2019 and 1500 UTC of 30th May, 2019. Though neither of these prediction systems could accurately predict the magnitude and the timing of the maximum intensity the rapid intensification was well captured by NEPS-R as the median value of the



Figs. 7(a&b). Variation of ensemble mean forecast of (a) minimum central pressure and (b) Maximum sustained surface wind with forecast lead time from initial condition of 0000 UTC, 17th May, 2020 for SuSC 'Amphan'. The black line is the IMD best track observation



Figs. 8(a&b). Mean absolute errors in (a) minimum central pressure and (b) MSW of NEPS-G and NEPS-R for TC 'Nisarga'

central pressure dropped from 990 hPa to less than 935 hPa between 0600 UTC of 29th April and 0600 UTC of 30th April. The median value of maximum surface wind increased from 70 knots to 110 knots within this period. The rapid intensification is not noticeable in NEPS-G forecast. The coarser resolution of NEPS-G may be the reason behind the large error in predicting the rapid intensification (Magnusson *et al*., 2019). Emanuel and Zhang (2016) noted that errors in prediction of the rapid intensification is large if there is under estimation in initial intensity than the overestimation. Zhang and Tao (2013) and Judt & Chen (2016) experienced low predictability of the timing of the intensification. Rapid intensification was also observed in case of Super Cyclonic Storm (SuCS) 'Amphan'. It intensified from Severe Cyclonic Storm (SCS) in the morning of 17th May, 2020 to VSCS in the afternoon of 17th May, ESCS by the early hours of 18th May and SuCS around noon on the same day. The MSW increased from 50 knots at 0600 UTC on 17th May to 130 knots at 2100 UTC on 18th May. The peak value of MSW was about 130 knots between 1800 UTC of 18th May and 0000 UTC of 19th May. The lowest value of central pressure during this period was about 920 hPa. Figs. 6(a&b) shows that running from the initial condition of 0000 UTC, 17th May many members of NEPS-G predicted the central pressure lower than 920 hPa after 0600 UTC and the median reached its minimum value at 0000 UTC of 20th May. After 0600 UTC of 19th May the control member (denoted by red dashed line) of NEPS-G always predicted lower central pressure than most of the members. The predicted time of minimum central pressure by the median was delayed by about 24 hours. Though the magnitude of minimum central pressure in this case is predicted by more than 75% members of NEPS-G the MSW predicted by any member reached its peak value of about 100 knots. The underestimation of MSW in NEPS-R is less. Many members of NEPS-R could predict the MSW more than 110 knots after 0600 UTC of 19th May. The median reached its peak value of 110 knots at about 0000 UTC of 20th May. In NEPS-R also many members predicted central presser lower than 920 hPa after 0600 UTC of 19th May. It may be noted that the deterministic forecast denoted by the red dashed line in Fig. 6 (b) is not the control member of NEPS-R. It is the forecast of regional deterministic model which runs from the initial condition generated by regional 3D Var data assimilation system.

The variation of ensemble mean forecast of minimum central pressure and MSW with time from the initial condition of 0000 UTC, 17th May also shows [Figs. 7(a&b)] the overestimation in minimum central pressure, underestimation in MSW and delay in maximum intensity predictions. In case of TC 'Nisarga' both the forecasting systems overestimated both the minimum central pressure and MSW but time of maximum intensity prediction was fairly accurate. The overestimation was more in NEPS-R forecast. Figs. 8(a&b) shows the maximum absolute error in minimum central pressure and MSW predictions by NEPS-R and NEPS-G up to forecast lead times of 72 and 120 hours, respectively. In general, NEPS-R predicts higher peak intensity than NEPS-G due to its higher resolution.

4. Summary

Global ensemble prediction system of NCMRWF (NEPS-G) was first operationally implemented in the year 2015 in order to provide probabilistic forecasts of weather events. This 45-member (1 control + 44 perturbed members) ensemble prediction system had 33 km horizontal resolution. This NEPS-G was used for probabilistic forecasting of track and intensity of the tropical cyclones till May 2018. In June 2018 NEPS-G was upgraded and the horizontal resolution was increased to 12 km. Due to limited available computational resources the ensemble size was reduced to 23 (1 control + 22 perturbed members).

A 12 member (1 control + 11 perturbed members) regional ensemble prediction system (NEPS-R) of horizontal resolution 4 km was implemented as an on-demand model for probabilistic forecasting of extreme weather events in the year 2018. The initial and boundary conditions for NEPS-R were provided by NEPS-G. NEPS-R was implemented operationally in July 2019. In the recently upgraded version of NEPS-R, perturbations generated by ETKF method are added to the analysis generated by the regional 4D Var data assimilation system to create perturbed initial conditions.

The performance of NEPS-G in forecasting tropical cyclone has improved after its upgradation in the year 2018. The reduction in DPE was noted to be about 53% in day 5 forecast. The performance has continued improving in the years 2019 and 2020. The average DPE of NEPS-G day-5 track forecast for 4 tropical cyclones of 2020 is about 220 km. The track forecast error of NEPS-R is of the same order. Average NEPS-R track forecast error of 72 hours forecast lead time is less than that of NEPS-G. The strike probability forecast of NEPS-G has good reliability up to day-5 forecast. The area under the ROC curve for NEPS-G is always greater than 0.5 which shows that it has very good discrimination skill.

The peak intensity and the rapid intensification for the stronger cyclones like 'Phani' and 'Amphan' were better predicted by NEPS-R. The prediction of time of peak intensity is still an issue for both the forecasting systems. In case of TC 'Nisarga' both NEPS-G and NEPS-R overestimated the peak intensity though the time of peak intensity was predicted well. The overestimation is more in NEPS-R forecast.

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