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Verification of Tropical Cyclone Operational forecast in 2017

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CONTENTS

1. Introduction

An important key to making better predictions is having an understanding of the errors in current predictions. Subjective and objective verification of tropical cyclone (TC) forecasts give evidence regarding the accuracy and performance characteristics of TC forecasts and warnings. Verification analyses diagnose and quantify the systematic and random errors so that improvements can be made to operational forecasting methodologies and to the underpinning numerical models. This process also provides users of TC forecasts with information on the reliability of the forecasts, so that they can make better decisions accordingly. Particularly, forecasters need the verification results for different numerical weather prediction (NWP) models in order to use the multiple sources of guidance in an optimal fashion.

This report is primarily about *verification of tropical cyclone operational forecast in 2017*. As the conclusion of the typhoon season, forecast results are evaluated by comparing the projected positions and intensities to the corresponding post-storm derived “best track” positions and intensities for each TC. A forecast is included in the verification only if the system is classified in the final best track as a tropical cyclone at both the forecast’s initial time and at the projection’s valid time. In this report, we start with a short discussion of best track datasets, which are the first requirement for verifying TC forecasts. The next section describes deterministic forecast methods, which will be evaluated here including official forecast guidances, global models and regional models, and ensemble prediction systems will also be depicted. Last and most important, we will evaluate the tropical cyclone track, intensity forecast, which will include deterministic and ensemble predictions.

2. Best track

With the development of modern meteorological techniques, an increasing amount of observational data became available for creating a specialized tropical cyclone database. Currently, four agencies provide their own TC best track analyses for the WNP region: 1) Shanghai Typhoon Institute of China Meteorological Administration, 2) the Japan Meteorological Agency (JMA) Regional Specialized Meteorological Center (RSMC) in Tokyo, 3) Joint Typhoon Warning Center, 4) Hong Kong Observatory. Table 1 provide the data period, characteristics and wind averaging time information of these four best track datasets. It should be noted that the TC position, intensity and structural information usually differ among those agencies due to the lack of sufficient surface observations for TCs, as well as the different techniques used to estimate the position and intensity of a TC. Thus, differences in TC forecast performance may be obtained, depending on the best-track dataset used as a reference. As the typhoon center in RSMC-Tokyo is the regional center that carries out specialized activities in analysis and forecasting of WNP TCs within the framework of the World Weather Watch (WWW) Program of WMO, in this verification report, we used RSMC-Tokyo best track-dataset as the reference.

Table 1. Descriptions of western North Pacific best-track datasets.

Agency	Period	Characteristics	Wind
RSMC Tokyo	1951 to present	Includes extratropical cyclone stage, longitude, latitude, MCP and TS markers since 1951; MSW and typical severe wind radii since 1977 (without TD cases).	10 min
CMA	1949 to present	Includes sub-centers, some double eyewall cases/coastal severe wind of landfalling TCs (until 2004); includes TD cases; extratropical cyclone stage; longitude, latitude, MSW and MCP since 1949.	2 min
HKO	1961 to present	Includes TD cases; longitude, latitude, MSW and MCP since 1961 (extratropical cyclone stages are not marked).	10 min
JTWC	1945 to present	Includes TD cases; extratropical cyclone stage since 2000; longitude, latitude, and MSW since 1945; MCP and TC size parameters since 2001.	1 min

3. TC position and intensity forecast data

In this report, TC position and intensity forecast results from 5 official guidances, 6 global models and 6 regional models are evaluated. These totally 17 methods are deterministic forecast guidance, detail explanations including their abbreviations, short description and source agencies are listed in Table 2. Additional verification on position forecast of ensemble prediction system will also be show in this report. The ensemble prediction systems (EPSs) include ECMWF-EPS, NCEP-GEFS, UKMO-EPS, JMA-GEPS, KMA-GBEPS and MSC-CENS, the TC EPS forecast data are downloaded from http://tparc.mri-jma.go.jp/cxmldata/dat/ensemble/.

Table 2. Details of deterministic forecast guidance

Category	Abbreviation	Full name or short description	Source agency
Official guidance (5)	**CMA**	*China Meteorological Administration*	CMA
	JMA	*Japan Meteorological Agency*	JMA
	JTWC	*Joint Typhoon Warning Center*	JTWC
	KMA	*Korea Meteorological Administration*	KMA
	HKO	*Hong Kong Observatory*	HKO
Global model (6)	**CMA-T639**	*Global spectral model of CMA at a resolution of T639L60*	CMA
	ECMWF-IFS	*Integrated Forecasting System of ECMWF*	ECMWF
	JMA-GSM	*Global Spectral Model of JMA*	JMA
	NCEP-GFS	*Global Forecast System of NCEP*	NCEP
	KMA-GDAPS	*Global Data Assimilation and Prediction System of KMA*	KMA
	UKMO-MetUM	*Unified Model system of UKMO*	UKMO
Regional model (6)	**BoM-ACCESS-TC**	*Tropical cyclone model in the Australian Community Climate and Earth-System Simulator Numerical Weather Prediction systems*	BoM
	GRAPES-TCM	*Regional TC-forecasting model based on the Global/Regional Assimilation and PrEdiction System*	STI/CMA
	GRAPES-TYM	*Regional TC-forecasting model based on the Global/Regional Assimilation and PrEdiction System*	CMA
	CMA-TRAMS	*Tropical Regional Atmosphere Model for the South China Sea based on GRAPES GRAPES*	ITMM/CMA
	HWRF	*The atmosphere-ocean coupled Hurricane Weather Research and Forecast modeling system*	NCEP/EMC
	SHANGHAI-TCM	*Regional tropical cyclone prediction model based on WRF*	STI/CMA

4. Performance of TC track forecast

TC position error or track error is defined as the great-circle difference between a TC's forecast center position and the best track position at the verification time. TC position errors typically are presented as mean errors for the samples of entire typhoon season. Table 3 shows the mean position errors for each of the examined TC forecast methods at the lead times of 24, 48, 72, 96 and 120 h in 2017.

Table 3. Average position error for each method at lead time levels of 24, 48, 72, 96 and 120 h in 2017. Numbers in bracket are sample sizes. (Unit: km)

Method	Lead time	24h	48h	72h	96h	120h
Official guidance	CMA	80.3(326)	139.5(241)	225.8(168)	317.3(122)	423.0(87)
	HKO	83.1(202)	139.0(126)	216.9(74)	295.0(48)	347.2(30)
	JMA	82.3(341)	137.6(238)	222.4(169)	322.6(122)	406.2(90)
	JTWC	86.7(328)	148.3(240)	238.4(168)	330.9(122)	361.0(90)
	KMA	97.3(344)	161.9(254)	261.2(180)	326.5(125)	370.3(87)
Global Model	CMA-T639	101.4(272)	191.8(205)	318.6(146)	469.1(103)	724.9(75)
	ECMWF-IFS	68.9(158)	108.9(118)	203.7(83)	296.8(61)	323.0(42)
	JMA-GSM	78.8(348)	141.3(259)	235.1(184)	/	/
	NCEP-GFS	76.4(180)	126.2(124)	193.9(83)	264.6(56)	370.2(38)
	KMA-GDAPS	79.0(161)	124.8(118)	207.6(86)	515.3(63)	811.5(45)
	UKMO-MetUM	71.7(174)	112.1(127)	183.9(91)	298.3(68)	364.9(47)
Regional Model	BoM-ACCESS-TC	86.5(163)	151.9(120)	254.7(81)	/	/
	GRAPES-TCM	92.3(239)	145.6(172)	250.4(118)	/	/
	GRAPES-TYM	82.6(252)	134.1(182)	248.4(117)	474.8(75)	695.5(44)
	CMA-TRAMS	64.9(75)	111.7(55)	212.8(39)	/	/
	HWRF	89.5(153)	151.4(98)	223.8(57)	312.8(31)	368.5(22)
	SHANGHAI-TCM	90.8(235)	153.1(180)	230.0(127)	/	/

4.1 Subjective deterministic forecasts

Normally, the subjective deterministic forecasts issued by official typhoon prediction agencies. In 2017, position errors from 5 official typhoon prediction agencies are 80.3-97.3km, 137.6-161.9km, 216.9-261.2km, 295.0-330.9km and 347.2-423.0km at the lead time level of 24, 48, 72, 96 and 120 h, respectively. The mean position errors for each agency are a little larger than last two years as showing in the track forecast trend diagrams (Fig.1).

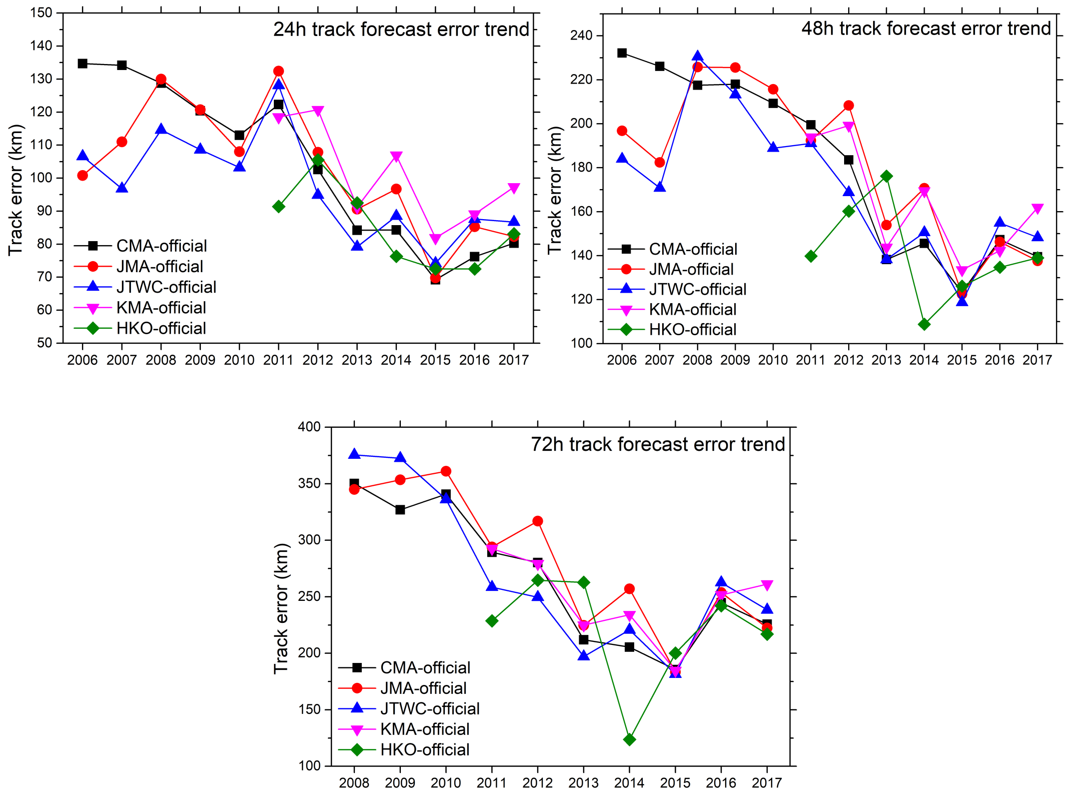


Fig.1 Track error trends for each official typhoon prediction agencies at the lead time of 24, 48 and 72 h.

To assess subjective track forecast skills, the track forecast error was compared to the error of a persistent climatology model with no information on the state of the atmosphere during the storm. Fig.2 shows the track forecast skill scores at the lead times of 24 and 48 h for official guidances from 2010 to 2017. All the forecast methods had positive skill scores indicating that over the past eight years, these forecast accuracies were better than the climatic persistence method.

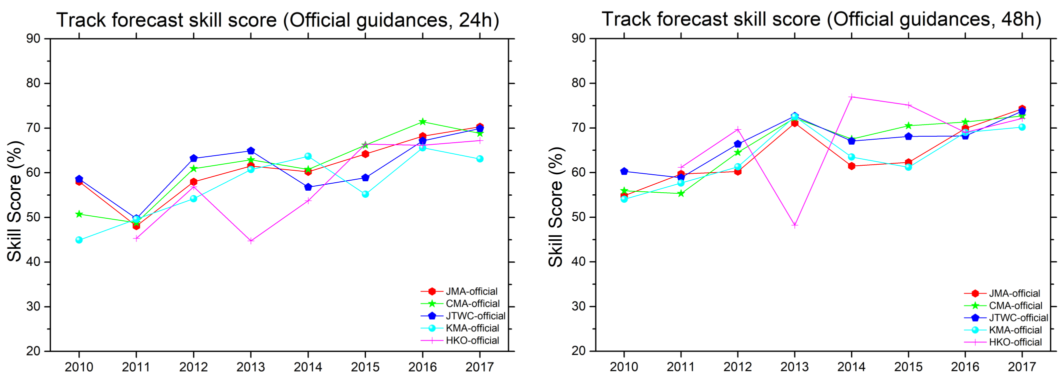


Fig.2 Track forecast skill scores at the lead times of 24 h (left) and 48 h (right) for official guidances.

The along-track and cross-track bias of official guidances from 24 to 120 h are given in Fig.3. The figures show that with increased forecast lead times, the forecasted TCs propagated, on average, too slow for most official guidances. There are not obvious leftward or rightward biases for official guidances at the lead time levels less than 96 h.

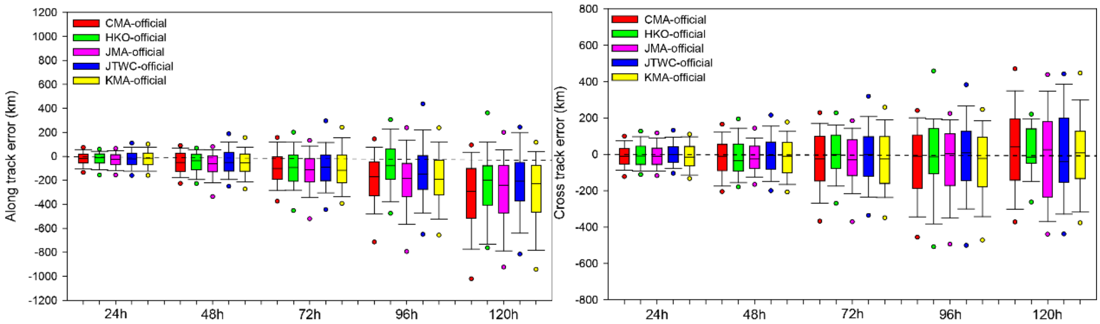


Fig.3 Along-track (left) and cross-track (right) biases for official guidances. The bar in the middle of the plot represents the median values of errors, the lower and upper ends of the boxes represent the 25th and 75th quantile values. The bars below and above the box represent the non-outlier extreme values, and the upper and lower circles represent the 95% and 5% quantile values.

Fig.4 shows a useful tool to evaluate the systematic bias of a track forecast method which called track error rose (TER). TER uses the same concept as a "wind rose" diagram. Fig.4 shows TER representations of the distributions of direction and magnitude position-errors for the five official guides at 72 h lead time in 2017. In the TER diagrams, each color bar represents a different magnitude of position error, and the length of each alignment of the color bars represents the proportion for each azimuthal angle. The TER diagram reveals the position error distribution (both error magnitude and percentage of sample size) for each azimuthal angle. Take JTWC as an example, their forecasted TC positions most concentrate on northeast at 72 h. The percentage of sample size at northeast direction is close to 22%, with the dominant position error range at 100 – 200km, 200 – 300km and 300 – 400km are about 7% (yellow), 6% (red) and 4% (blue), respectively.

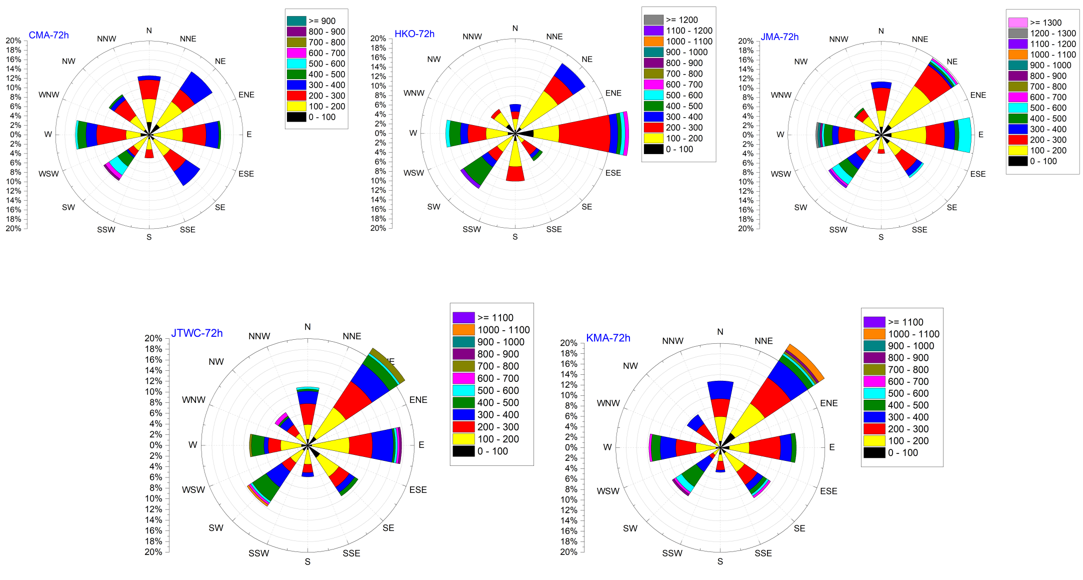


Fig.4 Position error rose (TER) diagrams of the distribution of direction and magnitude position errors for official guidances at the lead time of 72 h.

Generally, due to the limitations of different technologies, there are large variations in TC center position estimates from different operational agencies. In order to draw out how different reference TC data, which called TC "true" position may influence verification results. This report uses difference TC best tracks (RSMC-TOKYO and CMA-STI) or real-time operational TC position (JTWC, HKO and KM) as reference data to recalculate the track errors of all above 5 official guidances at lead time levels of 24, 48, 72, 96 and 120 h (Fig.5). The solid lines with different colors and symbols indicate the mean track errors by referring to different best track or operational TC position. The upper and lower shaded areas indicate the maximum and minimum track errors by referring to different best track or operational TC position. Fig.5 shows that there exist 5% - 10% track error varieties while using different observation data as reference.

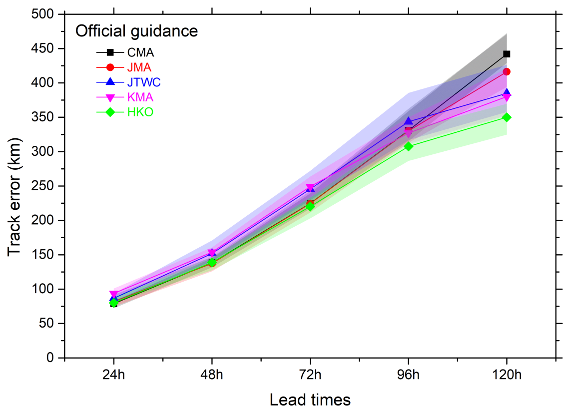
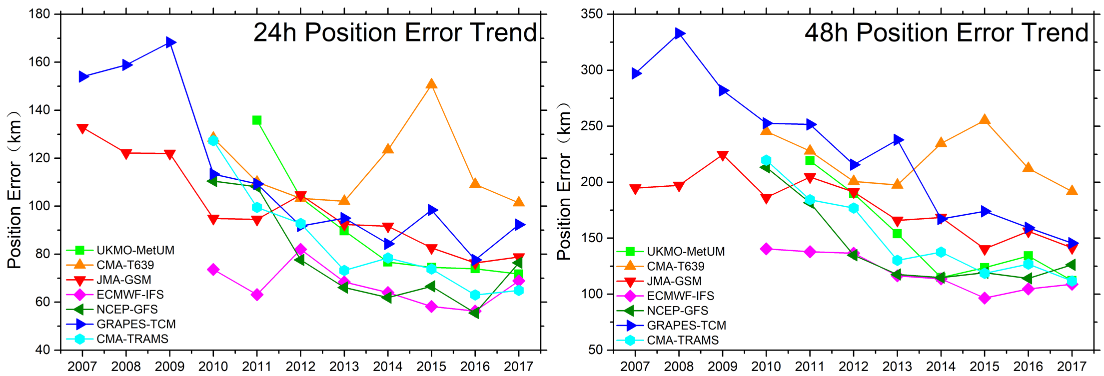


Fig.5 Variation intervals of track errors for official guidances by referring to different TC best tracks or real-time operational position.

4.2 Objective deterministic forecasts

In 2017, position errors for 6 global models are on intervals of 68.9 – 101.4km, 108.9 – 191.8km, 193.9 – 318.6km, 264.6 – 515.3km and 323.0 – 811.5km, and for 6 regional models are on intervals of 64.9 – 92.3km, 111.7 – 153.1km, 212.8 – 254.7km, 312.8 – 474.8km and 368.5 – 695.5km at the lead time level of 24, 48, 72, 96 and 120 h, respectively. Fig.6 shows track error trends for most of the global and regional models at the lead time of 24, 48 and 72 h.



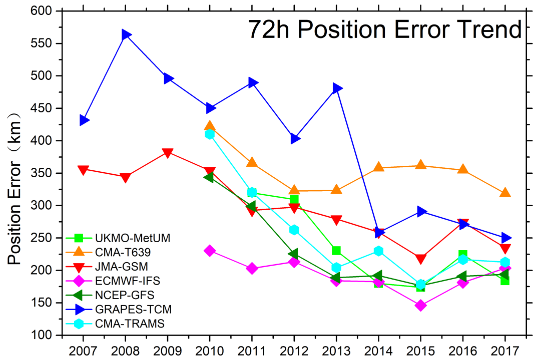


Fig.6 Same as fig.1 but for objective deterministic forecasts.

Fig.7 shows the track forecast skill scores at the lead times of 24 and 48 h for regional and global models from 2010 to 2017. Delightedly, all the models had positive skill scores. The overall tendency of models' skill score is generally going up during last eight years.

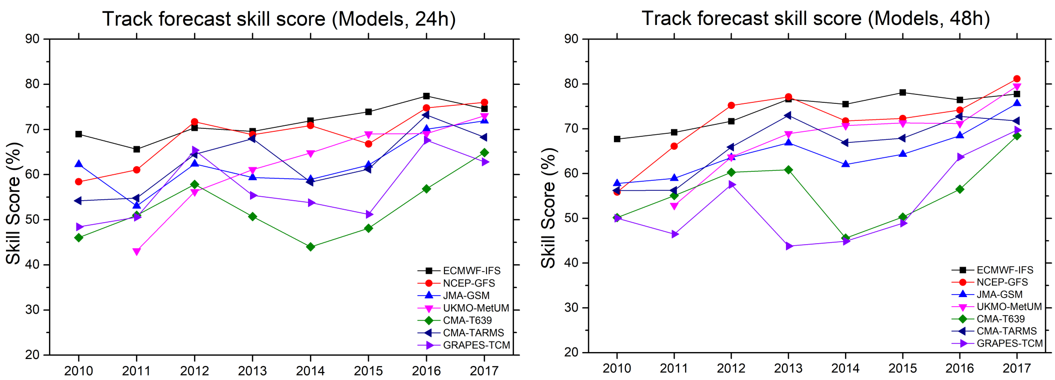


Fig.7 Track forecast skill scores at the lead times of 24 h (left) and 48 h (right) for global and regional models.

An alternative approach for examining average error is to consider the distributions of errors, as shown in Fig8. In this example, box plots summarize the distribution of errors for track forecasts from 2010 to 2017 for three global models. This analysis approach not only shows the entire performance of each model's track forecast at each lead time but also provides a straightforward method of understanding the annual improvements of each global model. This methodology was developed to evaluate the uncertainty in verification measures with confidence intervals and paired statistical tests, and to provide a consistent set of results to allow forecasts from the various models to be compared and fairly evaluated. Fig.8 clearly shows that for each lead time, decreases occur in the values of each quantile from 2010 to 2015, and the forecast accuracies at 72, 96, and 120 h in 2015 were nearly the same or better than the forecast accuracies in 2010 at 24, 48 and 72 h, respectively. However, this progress in forecasts stagnated or regressed in 2016 and 2017, especially for long lead times.

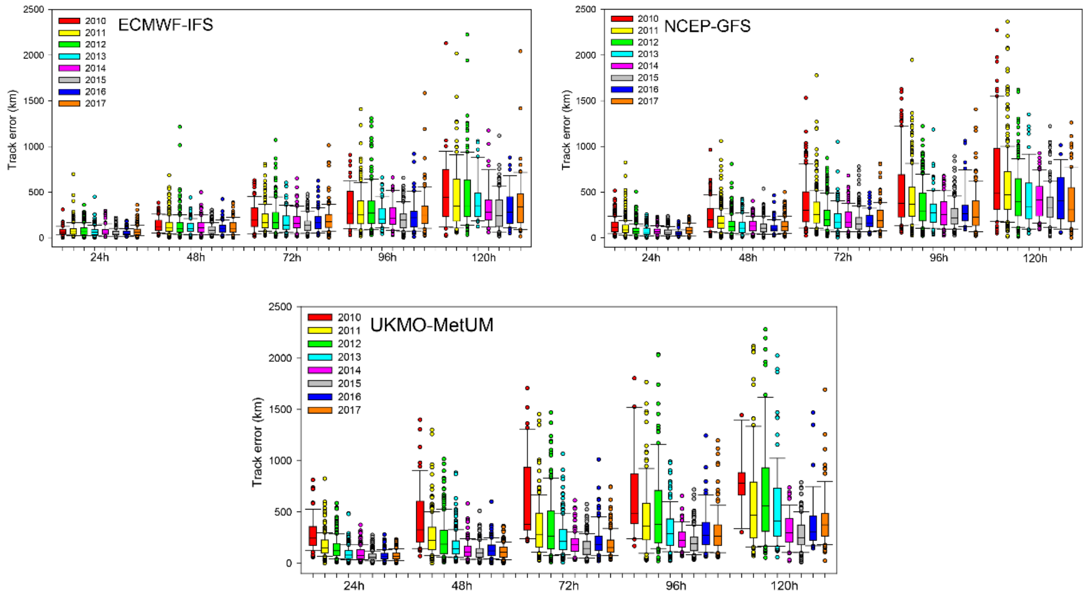


Fig.8 Box plots of position errors for ECMWF-IFS, NCEP-GFS and UKMO-MetUM in TC track forecasts from 2010 to 2017. The bar in the middle of the plot represents the median values of errors, the lower and upper ends of the boxes represent the 25th and 75th quantile values. The bars below and above the box represent the non-outlier extreme values, and the circles represent the outliers.

Fig.9 shows the along-track and cross-track biases of global and regional models from 24 to 120 h. Fig.9 shows that with the lead time increasing, the forecasted TCs from both regional and global model propagated slower than observations. There are not obvious leftward or rightward biases for global models. However, for regional models, forecasted TCs propagated, on average, a little leftward.

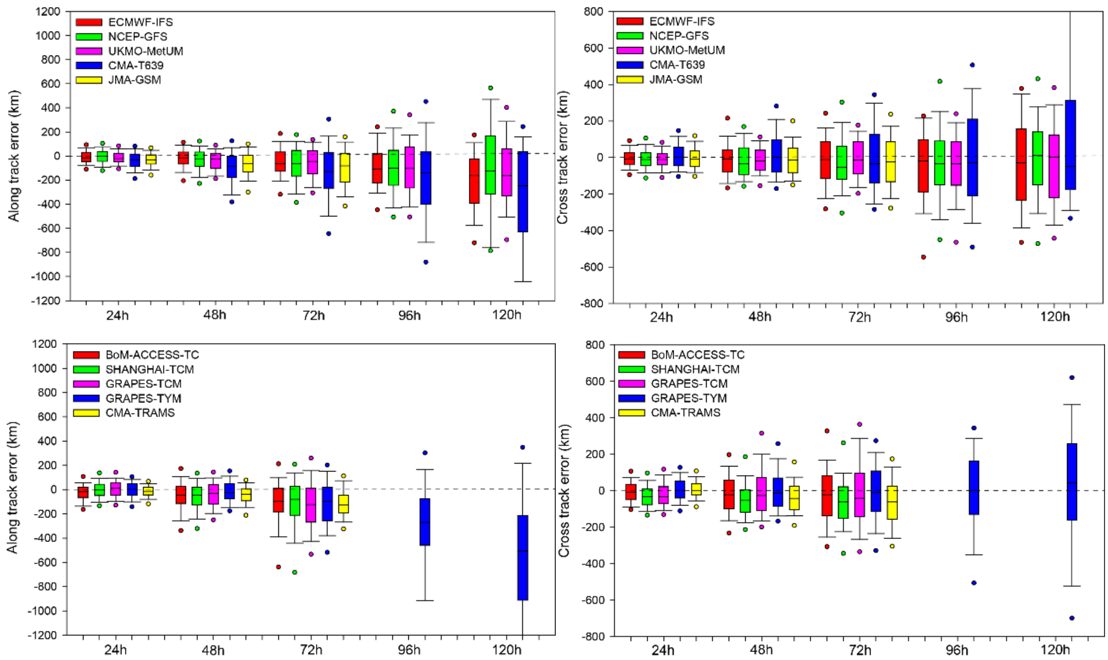


Fig.9 Along-track and cross-track biases for global and regional models.

Fig.10 presents polar scatter plots of the mean combined direction and magnitude error relative to the actual storm locations for global and regional models at different lead times in 2017. Each models' systematic track forecast bias is clearly shown in Fig.10. The placement of lead time labels with different text colors for different models denotes the annual mean locations relative to the actual typhoon locations obtained from the best-track dataset. Fig.10 shows that the systematic bias of each global model is obviously different. With the forecast lead time increasing, the systematic biases of NCEP-GFS, ECMWF-IFS, UKMO-MetUM, JMA-GSM and CMA-T639 tend to southeastward, west, northeast, east, southeast and southwest, with the values of systematic bias reach 60km at 120 h, respectively. For regional models, the systematic biases of GRAPES-TCM and SHANGHAI-TCM tend to north and southwest. The systematic bias of GRAPES-TYM is separated, it tends to north within 48 h, then turn to southwest when lead time more than 48 h. However, HWRF, CMA-TRAMS and BoM-ACCESS-TC show insignificant systematic bias. Plots like those in fig.10 provide information that is useful for the pre-estimation of the bias of a certain method.

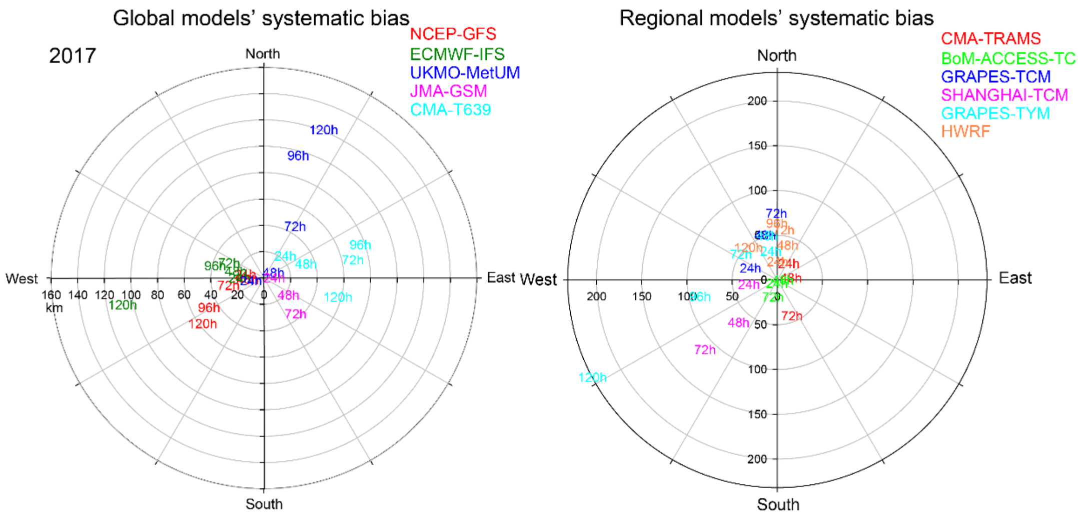
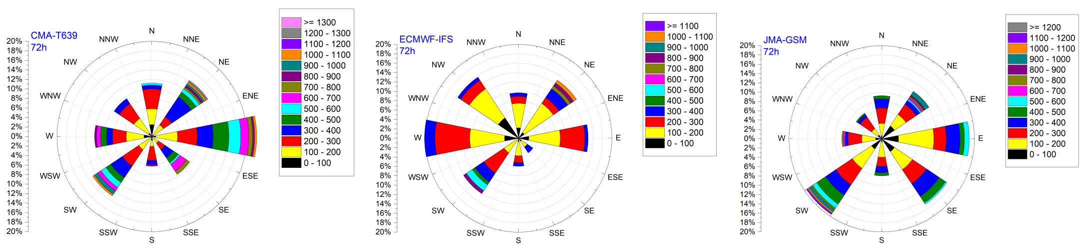


Fig.10 Polar scatter plots depicting the mean combined direction and magnitude errors relative to the actual storm location for each model at different lead times in 2017.

Similar as fig.4, fig.11 show the position error rose diagrams of the distribution of direction and magnitude position errors for global and regional models at the lead time of 72 h. It is useful for model developer to further understanding the model's forecast characteristic combined using fig.10 and fig.11.



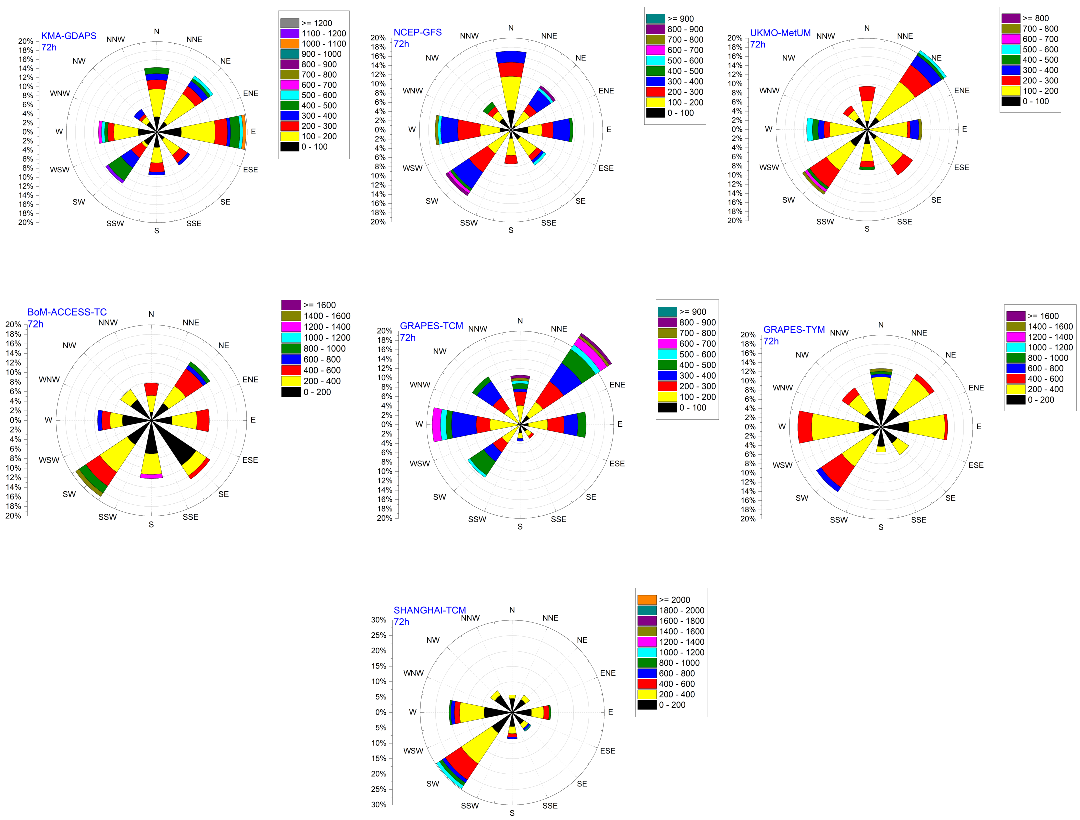


Fig.11 Position error rose diagrams of the distribution of direction and magnitude position errors for global and regional models at the lead time of 72 h.

Fig.12 shows the variation intervals of track errors for global (left) and regional (right) models by referring to different TC best tracks or real-time operational position. It can be found from fig.12 that, by using different observation data as reference, both global and regional models exist 4% - 6% track error varieties with the lead time levels less than 72h, and will increase to 12% - 19% at 120 h, especially for CMA-T639 and KMA-GDAPS.

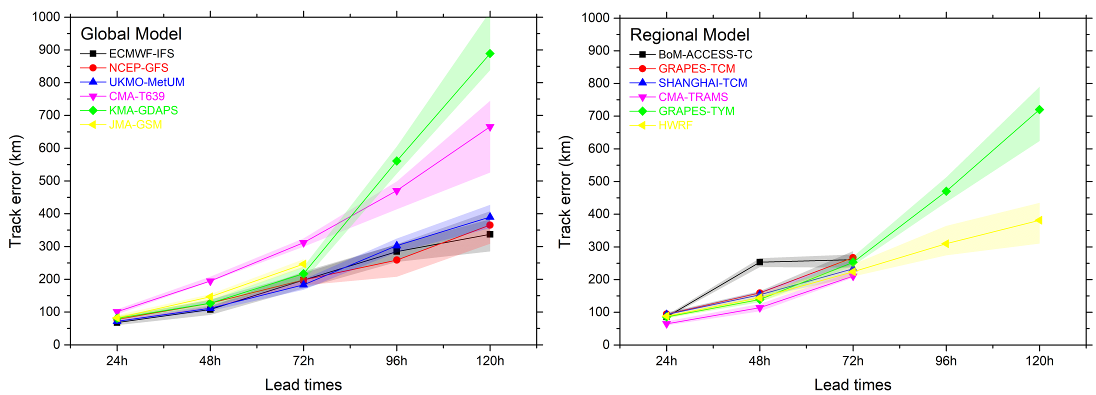


Fig.12 Same as fig.5 but for global models (left) and regional model (right).

4.3 Ensemble prediction systems

To evaluate the performance of the TC track forecasts of each EPS which mentioned in section

2, we first treate the ensemble forecasts as deterministic by summarizing the ensembles using the mean applied to the members. Fig.13 shows the ensemble mean track errors for six EPSs and detail values of errors at each lead time levels for those six EPSs are listed in table 4. Fig.13 and table 4 indicate that ECMWF-EPS was the best system for the lead time less than 72 h. However, for the lead time equal to or larger than 72 h, NCEP-GEFS became the best ensemble system. The ensemble mean position error at the lead time of 120 h was less than 400 km for both NCEP-GEFS and UKMO-EPS.

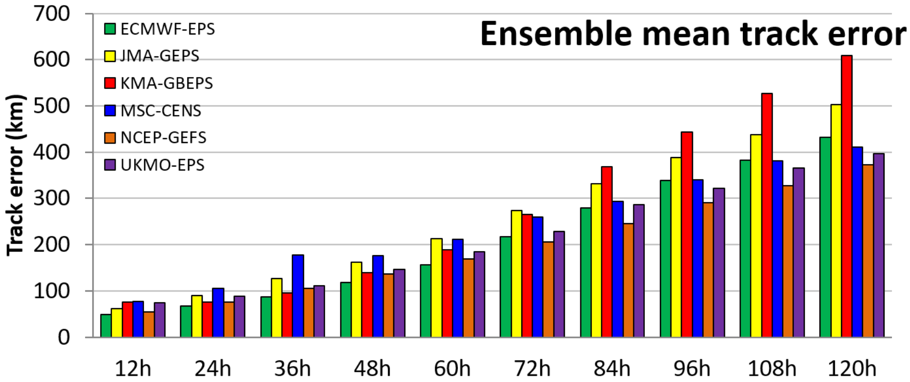


Fig.13 Ensemble mean track errors for six EPSs in 2017.

Table 4. Ensemble mean track errors in 2017. Numbers in bracket are sample sizes. (Unit: km)

EPS	TC No.	12h	24h	36h	48h	60h	72h	84h	96h	108h	120h
JMA-GEPS	1701-1727	61.4(439)	89.2(403)	126.1(363)	161.4(325)	212.5(296)	273.1(266)	332.0(234)	388.8(205)	438.4(182)	502.3(161)
ECMWF-EPS	1701-1727	48.6(203)	67.0(187)	87.4(168)	118.1(154)	155.8(137)	217.0(122)	280.0(110)	338.7(97)	382.6(85)	432.1(75)
MSC-CENS	1701-1727	77.6(152)	105.2(140)	148.0(130)	176.8(117)	211.7(105)	259.2(94)	293.6(82)	340.2(73)	381.2(63)	411.4(55)
KMA-GBEPS	1724-1727	75.2(26)	75.5(24)	94.9(20)	139.6(17)	188.6(14)	265.2(11)	367.9(8)	443.7(7)	526.1(6)	608.0(5)
NCEP-GEFS	1701-1727	54.2(423)	76.2(392)	104.7(360)	136.3(330)	169.6(299)	206.3(268)	245.3(239)	290.9(211)	327.4(185)	372.2(160)
UKMO-EPS	1701-1727	74.9(262)	88.9(239)	111.3(214)	146.1(195)	184.9(175)	228.7(159)	286.3(137)	321.1(116)	365.4(104)	396.5(87)

The ensemble spread is an indicator of forecast uncertainties, which is not linearly related to mean position error. When the spread is large, the mean position error may be small and vice-versa. Traditionally, researchers apply a scatter plot of position error and ensemble spread to analyze the relationship of forecast uncertainty to the error of a particular EPS. A bidirectional scatter plot was adopted in the present report to reanalyze the traditional scatter plot. In the bidirectional scatter plot (Fig.14), the blocks in the middle of the plot represent the mean value of the spread or position error. The lower (left) and upper (right) bars represent the 25th and 75th quantile values. It was found that the median ensemble spreads and position errors were almost the same for lead times from 12 to 240 h for ECMWF-EPS, JMA-GEPS, NCEP-GEFS and UKMO-EPS. However, the median ensemble spreads became larger than position errors with lead time increasing for MSC-CENS. KMA-GBEPS had an opposite result compare to MSC-CENS, which may partly due to lack of sufficient forecast samples for KMA-GBEPS (only 1724-1727 available on http://tparc.mri-jma.go.jp/cxmldata/dat/ensemble/).

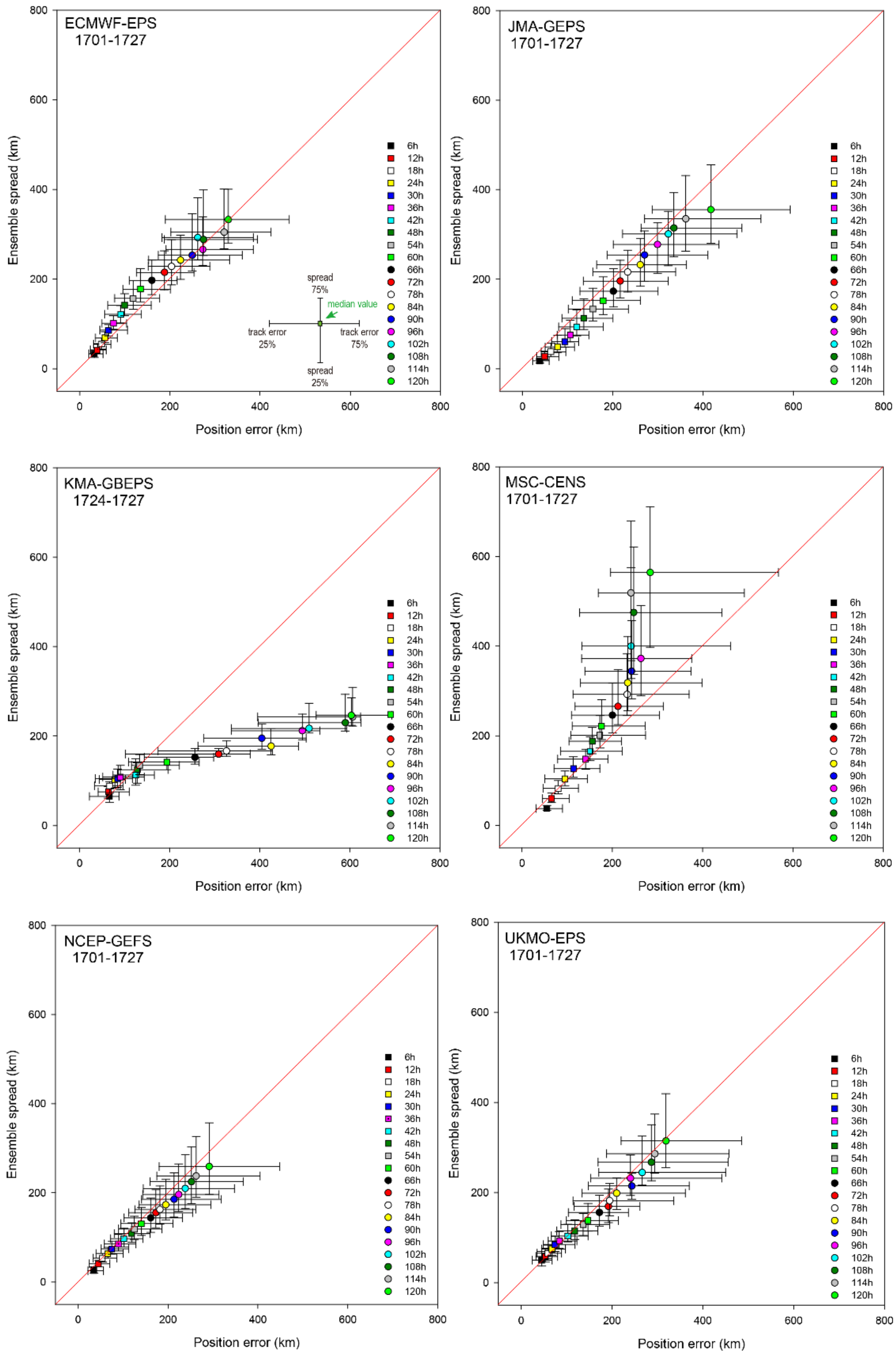


Fig.14 Bidirectional track forecast scatter plot for EPSs. The blocks represent the mean values of spread or position error. The lower (left) and upper (right) bars represent the 25th and 75th quantile values.

5. Performance of TC intensity forecast

Forecast intensity error (i.e., maximum wind speed and minimum pressure) is defined as the mean absolute error or mean relative error of the difference between the forecast and best-track intensity for the time of forecast verification. MAE indicates the average magnitude of the error, whereas MRE measures the bias in the forecast. Table 5 shows the MAE of the maximum wind speed forecast for each method at each lead time in 2017. The wind speeds of all forecast methods are converted to 10-min averages according to the WMO documentation[1].

Table 5. Mean absolute error of maximum wind speed for each forecast method at the lead times of 24, 48, 72, 96 and 120 h in 2017. The numbers in brackets are sample sizes. (Unit: m/s)

Method	Lead time	24h	48h	72h	96h	120h
Official guidance	CMA	5.63(326)	7.41(241)	8.72(168)	9.59(122)	9.37(87)
	HKO	4.91(202)	6.94(126)	7.47(74)	8.41(48)	9.96(30)
	JMA	5.05(341)	7.10(238)	7.39(169)	/	/
	JTWC	5.23(328)	7.29(240)	8.40(168)	8.72(122)	8.90(90)
	KMA	5.73(344)	7.11(254)	7.82(180)	7.53(125)	8.19(87)
Global Model	ECMWF-IFS	6.40(158)	8.45(118)	10.23(83)	11.21(61)	12.65(42)
	JMA-GSM	6.37(348)	9.45(259)	11.49(184)	/	/
	NCEP-GFS	5.92(180)	7.42(124)	10.34(83)	11.65(56)	13.98(38)
	UKMO-MetUM	7.45(174)	8.22(127)	9.32(91)	9.99(68)	11.47(47)
Regional Model	BoM-ACCESS-TC	7.64(163)	9.33(120)	11.11(81)	/	/
	GRAPES-TCM	6.88(239)	8.88(172)	10.15(118)	/	/
	GRAPES-TYM	5.69(252)	7.09(182)	8.35(117)	10.21(75)	12.72(44)
	CMA-TRAMS	7.80(75)	8.85(55)	9.62(39)	/	/
	HWRF	6.57(153)	8.06(98)	9.90(57)	9.86(31)	9.24(22)
	SHANGHAI-TCM	6.36(235)	7.30(180)	8.96(127)	/	/

5.1 Subjective deterministic forecasts

Fig.15 shows the variation intervals of intensity errors for official guidances by referring to different TC best tracks or real-time operational intensity. It can be found from fig.15 that, the verification results may exist a 15% -25% difference by using different observation data as reference. This indicates compare to TC position, the differences of observed TC intensity among the best tracks or real-time operational records even larger.

[1] Guidelines for converting between various wind averaging periods in tropical cyclone conditions. World Meteorological Organization, TCP Sub-Project Report, WMO/TD-No.1555.

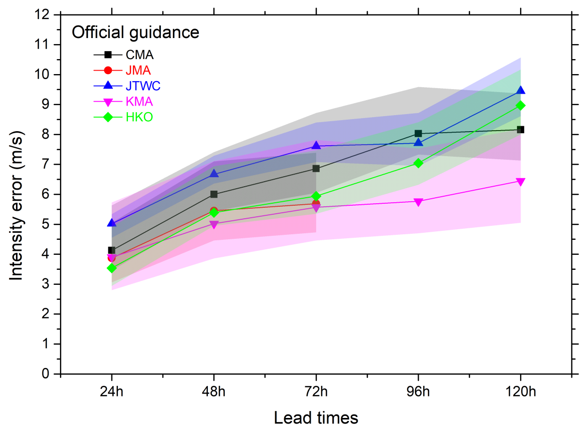


Fig.15 Variation intervals of intensity error for official guidances by referring to different TC best tracks or real-time operational intensity.

In 2017, the intensity forecast skill scores of official guidances were almost positive at the lead time levels of 24 h and 48 h. However, the values of intensity forecast skill scores decreased by 5% - 45% over 2016.

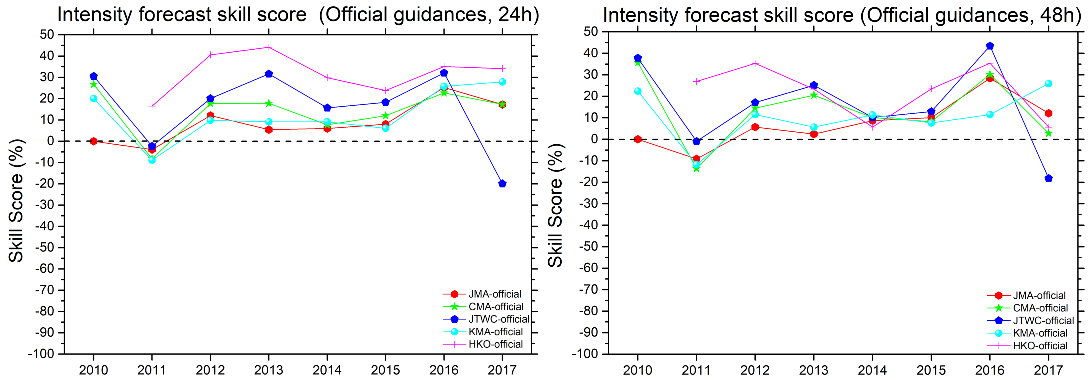


Fig.16 Intensity forecast skill scores at the lead times of 24 h (left) and 48 h (right) for official guidances.

5.2 Objective deterministic forecasts

As fig.15, fig.17 shows the variation intervals of intensity errors for regional (left) and global (right) models by referring to different TC best tracks or real-time operational intensity.

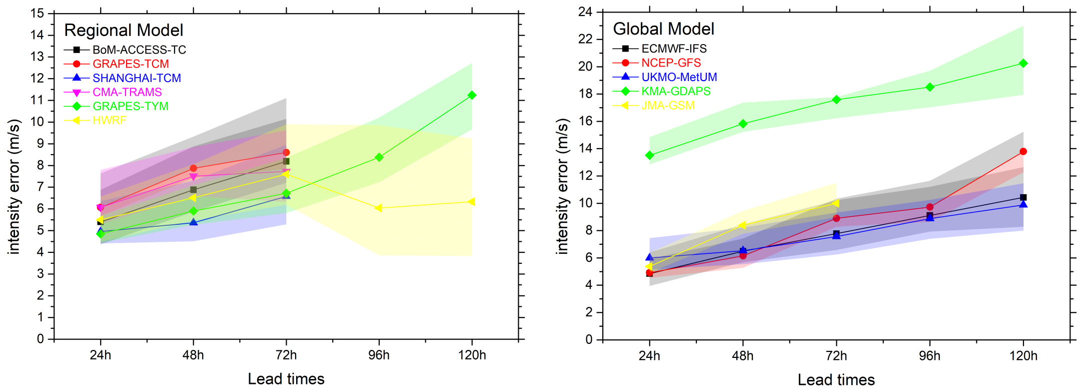


Fig.17 Same as fig.15, but for regional and global models.

Fig.18 shows the intensity forecast skill score for regional and global models at 24 h and 48 h. In 2017, ECMWF-IFS and NCEP-GFS have made positive skills at 24 h, and NCEP-GFS and UKMO-MetUM have also made positive skill at 48 h. In general, intensity forecast skill is increasing year by year from 2010.

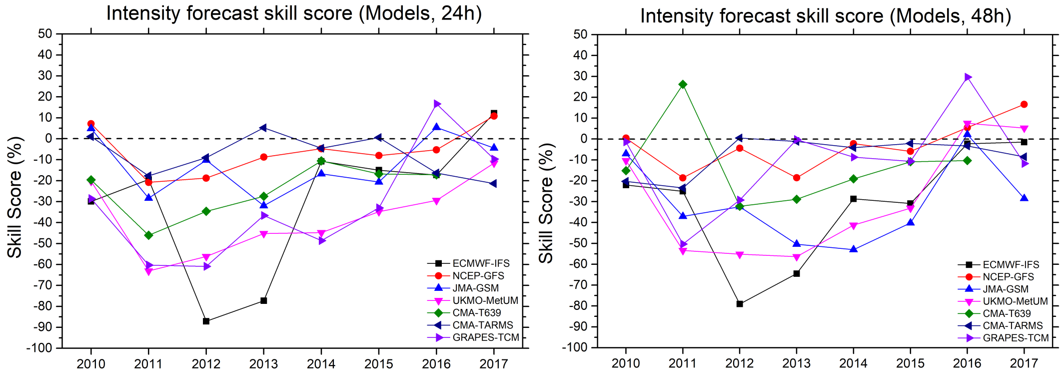


Fig.18 Same as fig.16, but for regional and global models.

Fig.19 presents two taylor diagrams to assess the performances of the maximum wind speed forecasts from both regional and global models. Taylor diagrams are used in the verification of TC intensity forecasts to analyze the internal relationships between the standardized deviation, the correlation coefficient, and the central different root-mean-square. The best prediction always has the highest correlation coefficient when with the “OBS”, and a standardized deviation and central different root-mean-square close to “1”. As seen in Fig.9, the center difference RMS errors of maximum wind speed were smallest at 0 h for JMA-GSM and GRAPES-TYM, respectively. For most global models, the correlation coefficients of the observed and forecast maximum wind speed were in the range of 0.6 to 0.9, and the standardized deviations were in the range of 0.75 to 1.2 in 2017. For the regional models, the correlation coefficients of the observed and forecast maximum wind speed were in the range of 0.7 to 0.9, and the standardized deviations were in the range of 0.75 to 1.1 in 2017.

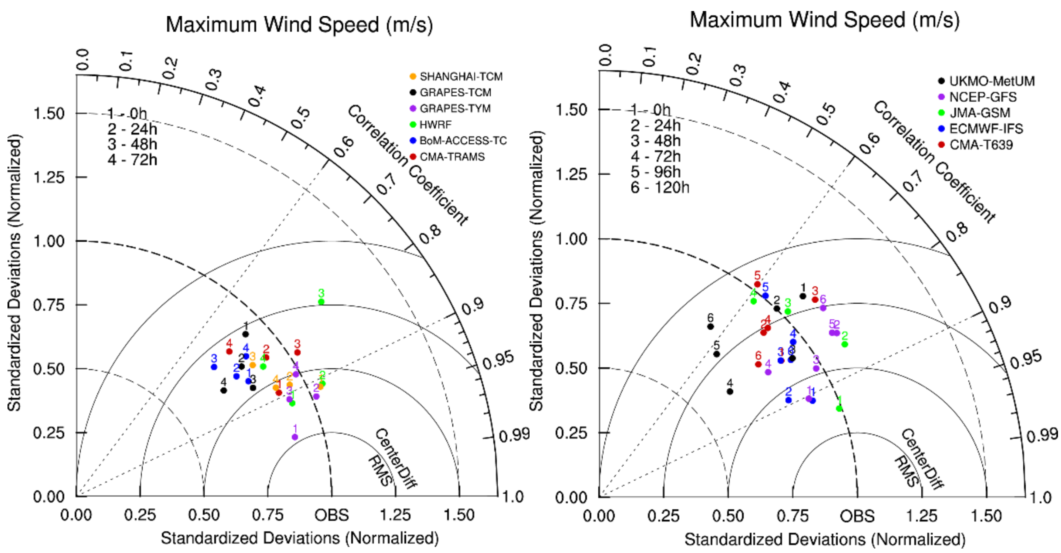


Fig.19 Taylor diagrams for the evaluation of TC maximum wind speed forecasts from models. Left: regional models, right: global models.

6. Future plans

Verification of TC forecasts is important for improving the NWP and official guides that underpin the forecasts; making the best use of this guidance in a forecasting context; and assisting the public, emergency managers, and other users of TC forecasts in developing appropriate levels of confidence in the forecasts.

This report briefly discussed the verification results and characteristic of tropical cyclone operational forecast in 2017. The verification results included TC track and intensity for both deterministic and ensemble forecast guides. In the future, at STI, we will not only focus on the evaluation of the basic TC attributes, such as track, intensity, and genesis but will also focus on verifying TC impact variables, such as precipitation, wind, and storm surge. We will continue to develop and improve methodologies for verifying forecast aspects of TC formation, structure, evolution, and motion, particularly for high-resolution and ensemble NWP models, which are currently the foundation for most operational TC forecasts.

Appendix: acronyms used in this report

BoM	Bureau of Meteorology (Australia)
CMA	China Meteorological Administration
CMC	Canadian Meteorological Center
ECMWF	European Centre for Medium Range Weather Forecasting
EMC	Environmental Modeling Center
EPS	Ensemble Prediction System
GEFS	Global Ensemble Forecast System
GFS	Global Forecast System
HKO	Hong Kong Observatory
ITMM	Institute of Tropical and Marine Meteorology
JMA	Japan Meteorological Agency
JTWC	Joint Typhoon Warning Center
KMA	Korea Meteorological Administration
MAE	Mean Absolute Error
ME	Mean Error
MSE	Mean Squared Error
NCEP	National Centers for Environmental Prediction
NWP	Numerical weather prediction
RMSE	Root Mean Squared Error
STI	Shanghai Typhoon Institute
TC	Tropical Cyclone
TIGGE	THORPEX Interactive Grand Global Ensemble
WMO	World Meteorological Organization