Determining Probability-Circle Radii of Tropical Cyclone Track Forecasts with Multiple Ensembles

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1. Introduction

The Regional Specialized Meteorological Center (RSMC) Tokyo – Typhoon Center (referred to here simply as “the Center”) of the Japan Meteorological Agency (JMA) revised its 70% probability-circle radii for tropical cyclone (TC) track forecasts in June 2016 and 2017 (Fukuda 2018). Table 1 shows the radii used as of April 2019, with those for 3- to 72-hour forecasts being determined in line with TC direction and speed and pre-determined based on verification results for operational TC track forecasts for the period from 2011 to 2015. The radii for 96- to 120-hour forecasts are determined in line with forecast confidence levels and TC direction/speed. Confidence levels are derived from cumulative ensemble spread[1] calculated using outputs from the Global Ensemble Prediction System (GEPS; Tokuhiro 2018), and the radii for different confidence levels are pre-determined based on verification results for the period from 2015 to 2016. As the methods used to determine probability-circle radii differ between 3- to 72-hour and 96- to 120-hour forecasts, there are discontinuities in the rate of radius increase. Although this discontinuity was alleviated to some extent with the above-mentioned radii upgrades in 2016 and 2017, the issue still remains (Figure 1).

The World Meteorological Organization (WMO) Tropical Cyclone Programme (TCP) and World Weather Research Programme (WWRP) launched the North Western Pacific Tropical Cyclone Ensemble Forecast Project (NWP-TCEFP) in 2009 to explore the utility of ensemble forecasts, including multiple ensembles, and to promote such products for operational TC forecasting (Yamaguchi et al. 2014). Yamaguchi et al. (2012) evaluated the relative benefits of multiple ensembles with respect to a single ensemble under the project and demonstrated that multiple ensembles bring better correlations between ensemble mean TC track prediction errors and ensemble spreads than a single ensemble. Based on the outcomes of the project, the Center started providing Typhoon Committee Members with real-time ensemble TC track predictions from JMA, the European Centre for Medium-Range Weather Forecasts (ECMWF), the National Centers for Environmental Prediction (NCEP) and the Met Office in the United Kingdom (UKMO) in 2015 under the *Enhanced use of Ensemble Forecasts* project of the Working Group on Meteorology run by the Typhoon Committee. Radii based on multiple ensembles have yet to be introduced on an operational basis at the Center, although forecasters reference ensemble TC track predictions from the four centers.

Against such a background, the Center has examined a new method of determining radii in the same way throughout forecast lead times of up to five days using multiple ensembles. The appropriacy of

[1] The ensemble spread is calculated every six hours and accumulated from the initial time to the forecast time to give a snapshot of uncertainty at each forecast time and a history from the initial time. The confidence level for each forecast time is defined as high (A), medium (B) or low (C) in line with the cumulative ensemble spread to make the ratios of their populations 40, 40 and 20 percent, respectively.

this approach was evaluated via comparison to the conventional statistical and single ensemble-based methods. Considering the operational use of ensembles from producers in other countries (e.g., ECMWF, NCEP, UKMO), the time periods of availability (a factor not incorporated by Yamaguchi et al. (2012)) were taken into account in this study.

Here, the data used and the methodology adopted are described in Section 2, the results are outlined in Section 3, the proposed probability circle radii based on the results of this study are detailed in Section 4, and a summary of the work is given in Section 5.

Table 1 Probability-circle radii after the 2016 and 2017 revisions

Forecast time [h]	Direction of movement[2]	Probability-circle radii [nm] (confidence level[3])		
		Speed of movement (V) ≤ 10 kt	10 kt < V ≤ 30 kt	V > 30 kt
3	All	15	20	25
6	All	20	25	30
9	All	25	30	35
12	All	30	40	
15	NW	35	45	
	Other	40	50	
18	NW	40	50	
	Other	45	60	
21	NW	45	55	
	Other	50	70	
24	NW	50	60	
	Other	60	80	
48	NW	95	110	
	Other	110	150	
72	NW	130	140	
	Other	170	220	
96	NW	160(AB)/200(B')/240(C)	160(AB)/200(B')/240(C)	
	Other	210(AB)/300(B')/350(C)	260(AB)/300(B')/350(C)	
120	NW	200(AB)/290(B')/375(C)	200(AB)/290(B')/375(C)	
	Other	290(AB)/425(B')/500(C)	350(AB)/425(B')/500(C)	

2 The directions All, NW and Other refer to 0 – 359°, 260 – 359° and 0 – 259° clockwise from north (0 degrees), respectively.

3 The confidence levels A and B were unified to reduce the number of choices in radius determination, and B' was introduced to suppress rapid changes in radius for AB and C.

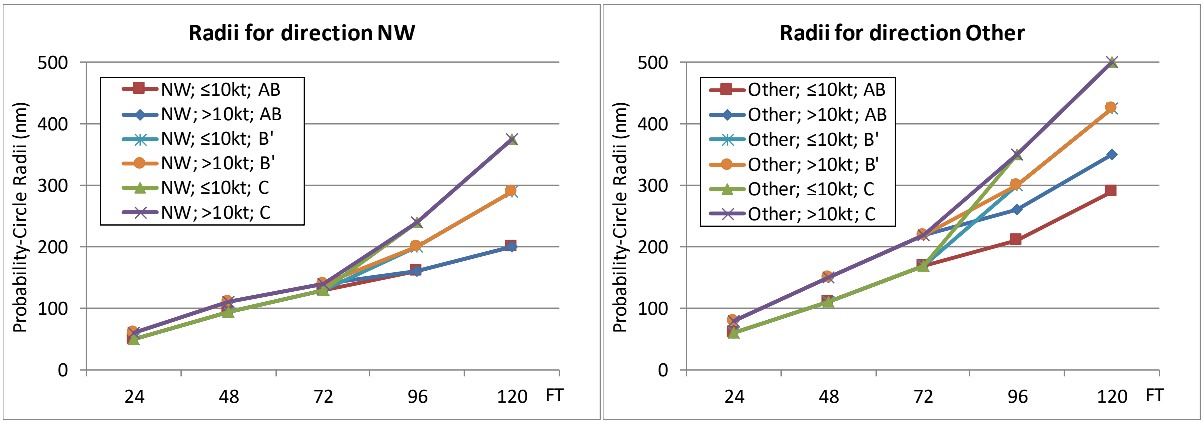

Figure 1 Changes in radius for forecast times with directions NW (left) and Other (right)

2. Methodology and data used

In this study, the effectiveness of using multiple ensembles to determine the 70% probability-circle radii of the Center's operational TC track forecasts was investigated via comparison of this approach to statistical and single ensemble-based methods. Specifically, four single ensembles from JMA, ECMWF, NCEP and UKMO as well as eleven multiple ensembles involving combinations of these four were examined. This paper reports on a combination of all four single ensembles (referred to as JENU) and three combinations thereof (JMA, ECMWF and NCEP (JEN), JMA, ECMWF and UKMO (JEU), and ECMWF, NCEP and UKMO (ENU)). The configurations of the four single ensembles are shown in Table 2.

The data period for the single and multiple ensembles is from 2016 to 2018, covering TC verification from T1601 to T1829. The initial times of the ensemble predictions are 00, 06, 12 and 18 UTC. As the ECMWF ensemble is initiated at 00 and 12 UTC only, the ensemble predictions of 06 and 18 UTC initials use six-hour-old predictions. The availability time of the ensemble data is taken into consideration. By way of example, for the verification of an official TC track forecast issued by the Center at 18 UTC on a certain day, an ensemble prediction initiated at 12 UTC on that day is used for JMA data and those initiated at 06 UTC are used for ECMWF, NCEP and UKMO data. The ensemble prediction initiated at 00 UTC is actually used for ECMWF data due to the above-mentioned reason. The forecast time is verified every 6 or 24 hours from 0 to 120 hours, and results for 48-hour forecasts (T+48) and 96-hour forecasts (T+96) are reported as typical values in this paper. Best-track data from the Center are used for TC location and intensity verification, which is performed only when the data show tropical storm intensity or higher in both initial and verification times and all four single ensembles have at least two members tracking the TC up to the verification time.

Table 2 Configurations of the four single ensembles

Ensemble	Number of ensemble members	Initial times [UTC]	Forecast range [hours] (initial times)	Forecast time periodicity [hours]	Availability time after initial time [hours]
JMA	27	00, 06, 12, 18	264 (00, 12 UTC) 132 (06, 18 UTC)	3	6
ECMWF	52	00, 12	240	6	12
NCEP	21	00, 06, 12, 18	384	6	12
UKMO	24 (– T1703) 36 (T1704 –)	00, 06, 12, 18	168	6	12

3. Results

3.1 Ensemble spread-error relationship

The ensemble spread-error relationship is first assessed for single and multiple ensembles. Figure 2 shows these relationships between ensemble mean TC track prediction errors and ensemble spreads. The spreads for JMA ensembles tend to be smaller than the errors, especially with longer forecast times. Such gaps between spreads and errors are more notably seen in NCEP ensembles, while spreads show close correspondence with errors in ECMWF ensembles for all forecast times up to five days. In the multiple ensembles, the spread matches the error quite well with any multiple ensembles (i.e., JENU, JEN, JEU and ENU).

Figures 3 and 4 show relationships linking ensemble mean TC track prediction errors and cumulative ensemble spreads at T+48 and 96 for single and multiple ensembles, respectively. A positive correlation between errors and cumulative ensemble spreads is seen for all single and multiple ensembles, suggesting that the spreads can be used as an indicator of prediction errors. The correlation coefficients are larger than those for JMA ensembles for all multiple ensembles at both T+48 and 96, and are larger than all single ensembles at T+48.

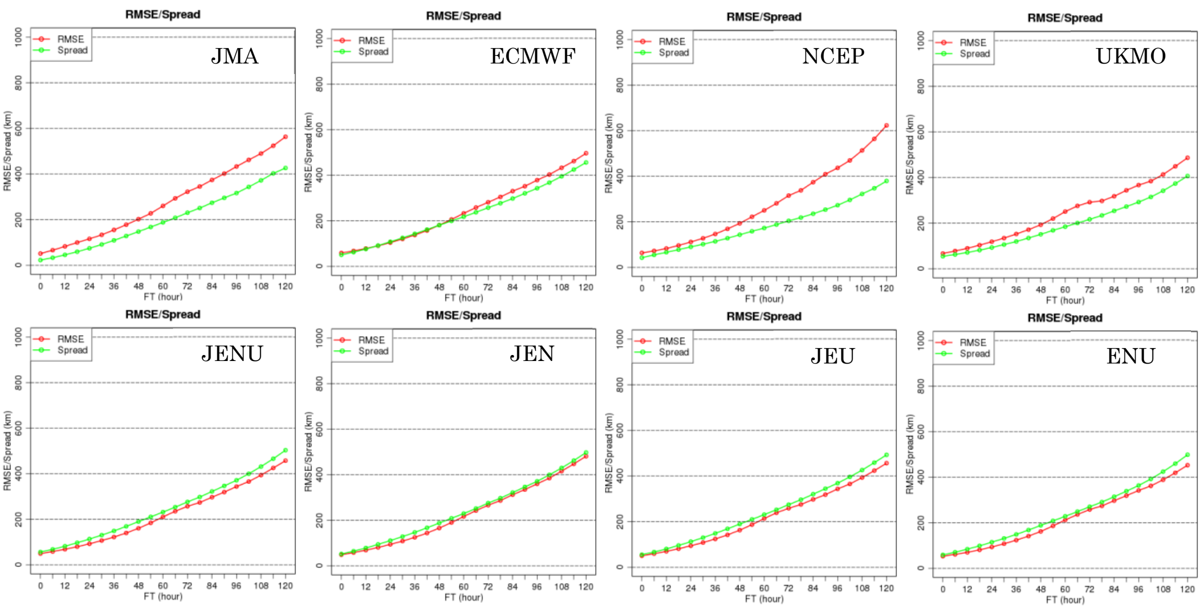

Figure 2 Relationships linking ensemble mean TC track prediction root mean square errors (RMSEs) (red lines: km) and ensemble spreads (green lines: km) in forecast times for single (top) and multiple (bottom) ensembles

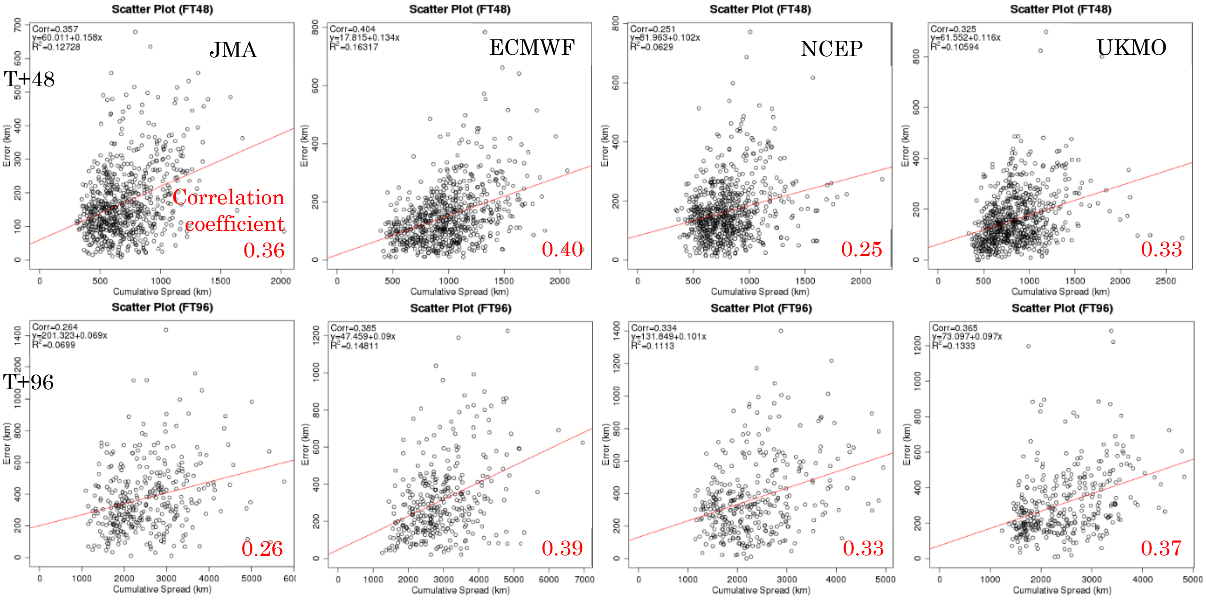

Figure 3 Relationships linking ensemble mean TC track prediction errors (km) and cumulative ensemble spreads (km) at T+48 (top) and 96 (bottom) for single ensembles. Regression lines are shown in red.

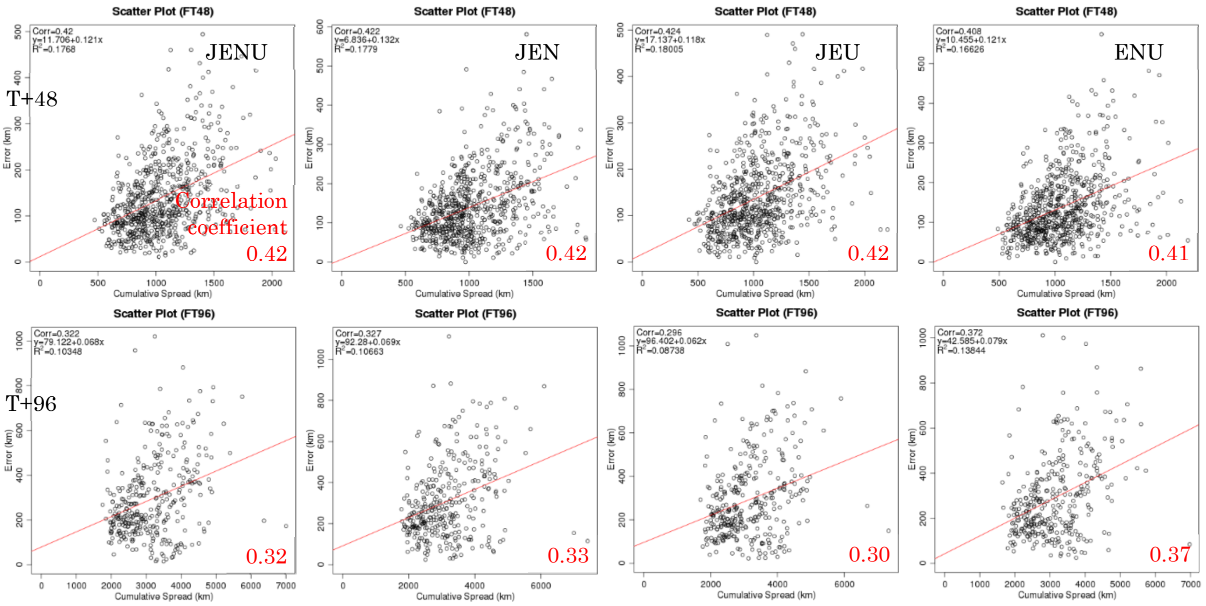

Figure 4 Relationships linking ensemble mean TC track prediction errors (km) and cumulative ensemble spreads (km) at T+48 (top) and 96 (bottom) for multiple ensembles. Regression lines are shown in red.

3.2 Comparison of probability circles for single and multiple ensembles

Probability circles for single and multiple ensembles were compared. Figures 5 and 6 show relationships linking errors of operational TC track forecasts issued by the Center and cumulative ensemble spreads for both ensemble types, respectively. As seen in Figures 3 and 4, the correlation coefficients are larger for all multiple ensembles than for JMA ensemble alone. The JENU and ENU multiple ensembles have larger correlation coefficients at T+48 and T+96, respectively, than the best single ensembles (i.e., ECMWF and UKMO at T+48 and ECMWF at T+96, respectively).

Figures 7 and 8 are as per Figures 5 and 6 with confidence levels classified as A, B and C (high, medium and low, respectively) based on cumulative ensemble spreads. The frequency of each category is set to 40, 40 and 20 percent for each forecast time, respectively (Yamaguchi et al. 2009). The red, green and blue lines show probability-circle radii corresponding to 70th-percentile values of operational TC track forecast errors for each confidence level. As will be shown in Figure 11, the degree of separation of probability-circle radii between the confidence levels of the multiple ensembles tends to be larger than that of single ensembles.

Figures 9 and 10 show cumulative relative frequency distributions of operational TC track forecast errors at T+48 and 96 for single and multiple ensembles, respectively. In comparison of distributions at T+48 for confidence level A between JMA and JENU, the JENU ensemble has a more upright profile above a high frequency levels (e.g., 80%). This indicates that the number of cases in which TC track forecast errors are large despite high confidence (i.e., A) is lower for multiple ensembles. Similarly, the number of cases in which TC track forecast errors are small despite low confidence (i.e., C) is also lower for multiple ensembles. Essentially, outlier ratios for multiple ensembles are smaller than for single ensembles, representing a relative benefit of the former.

Figure 11 shows 70th-percentile values in operational TC track forecast errors for each confidence level with single and multiple ensembles at T+24, 48, 72, 96 and 120. The values are expected to increase in the order of confidence levels A, B and C, but exhibit no distinguishable difference between A and B at T+24 and 48 in the JMA ensemble. Meanwhile, values show a clear distinction among A, B and C for all forecast times in multiple ensembles.

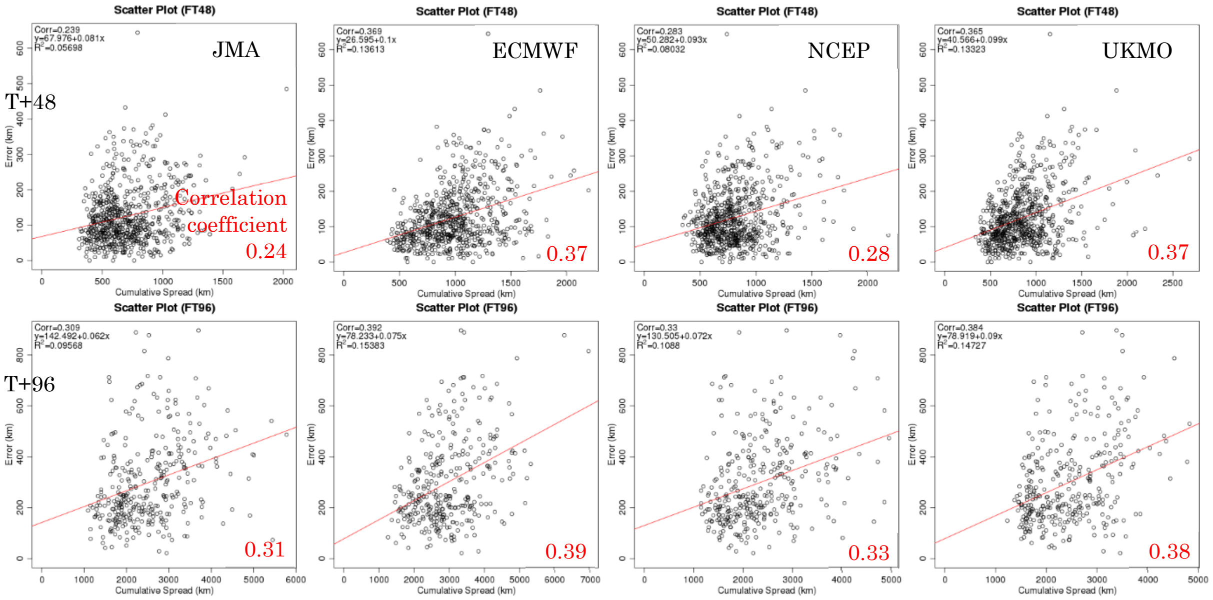

Figure 5 Relationships linking operational TC track forecast errors (km) and cumulative ensemble spreads (km) at T+48 (top) and 96 (bottom) for single ensembles. Regression lines are shown in red.

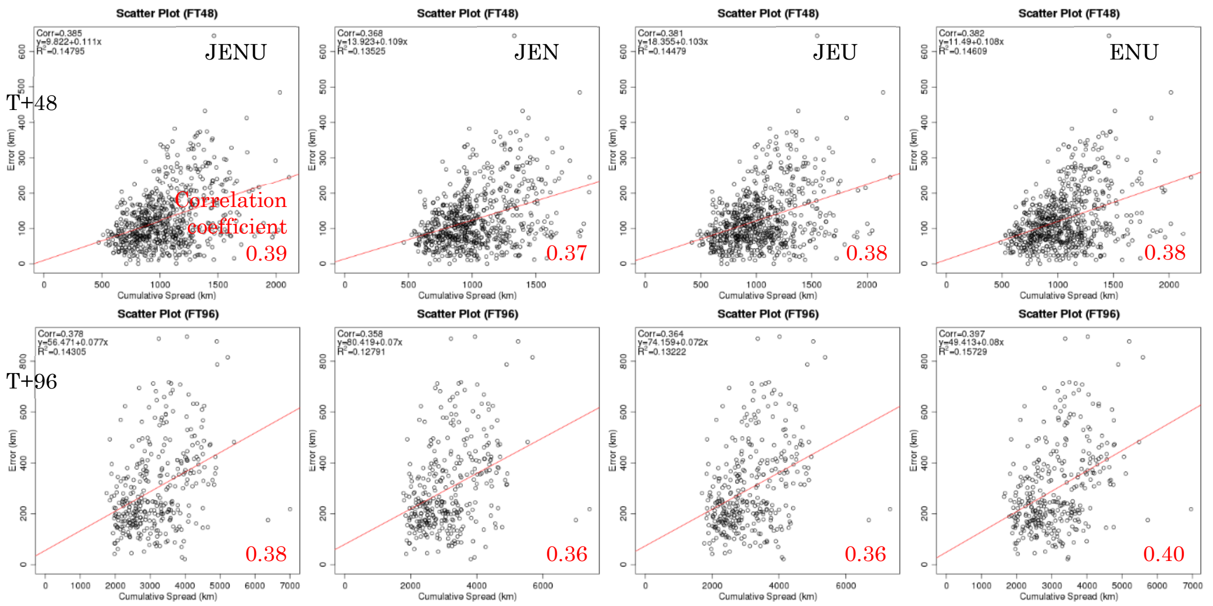

Figure 6 Relationships linking operational TC track forecast errors (km) and cumulative ensemble spreads (km) at T+48 (top) and 96 (bottom) for multiple ensembles. Regression lines are shown in red.

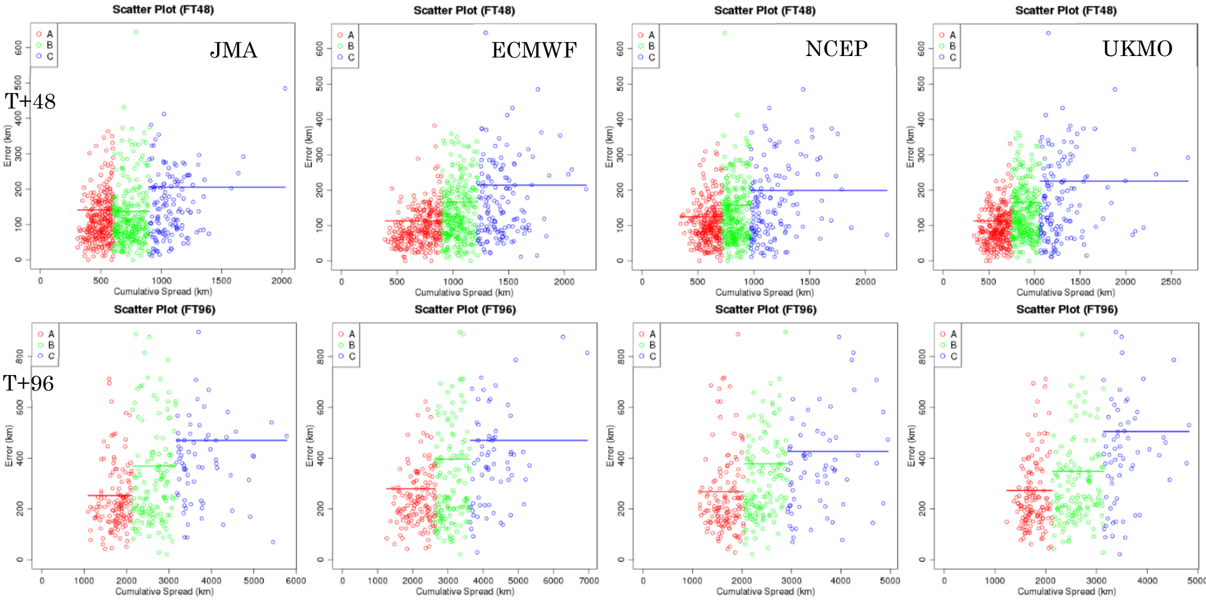

Figure 7 Relationships linking operational TC track forecast errors (km) and cumulative ensemble spreads (km) with coloring based on confidence levels A (red), B (green) and C (blue) at T+48 (top) and 96 (bottom) for single ensembles. Red, green and blue lines show probability-circle radii corresponding to 70th-percentile values of operational TC track forecast errors at each confidence level.

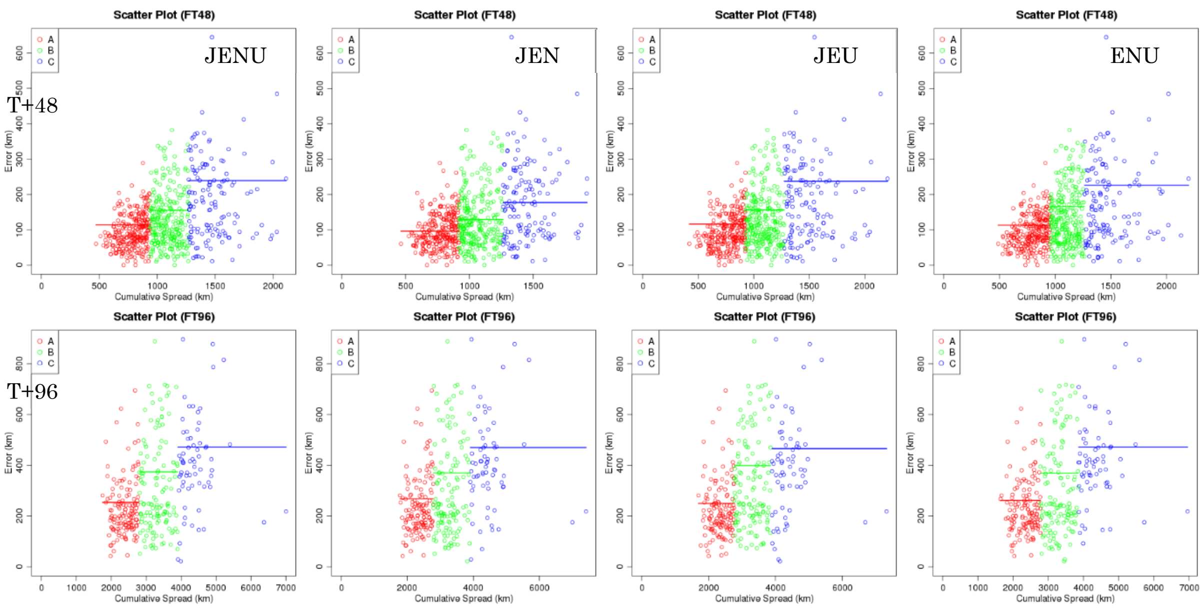

Figure 8 Relationships linking operational TC track forecast errors (km) and cumulative ensemble spreads (km) with coloring based on confidence levels A (red), B (green) and C (blue) at T+48 (top) and 96 (bottom) for multiple ensembles. Red, green and blue lines show probability-circle radii corresponding to 70th-percentile values of operational TC track forecast errors at each confidence level.

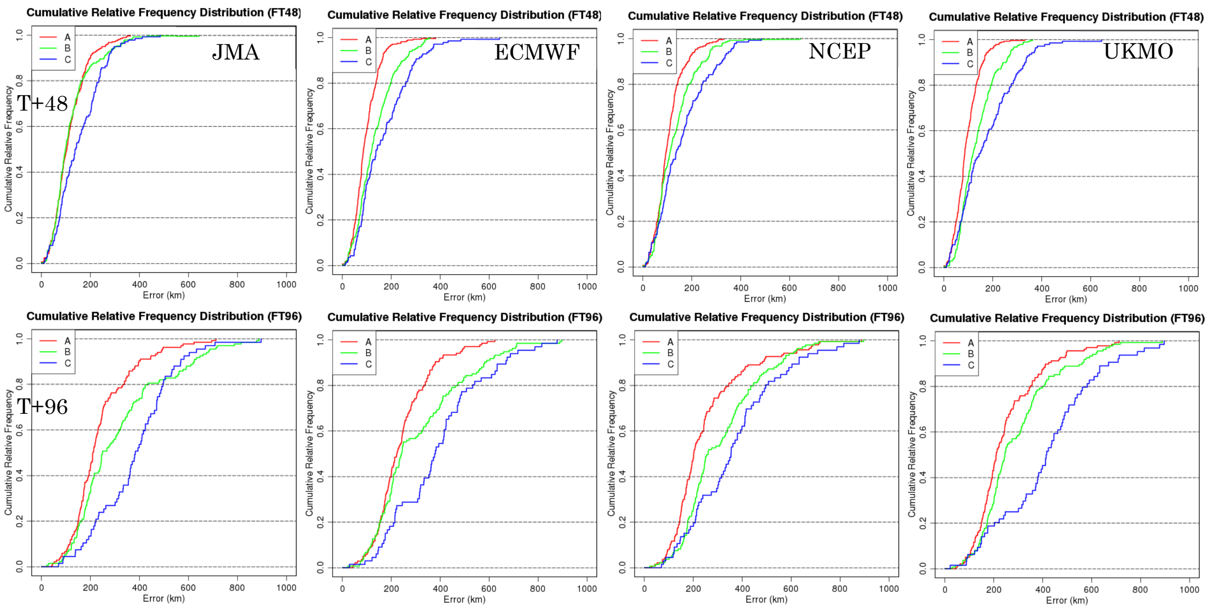

Figure 9 Cumulative relative frequency distributions of operational TC track forecast errors (km) at T+48 (top) and 96 (bottom) for single ensembles

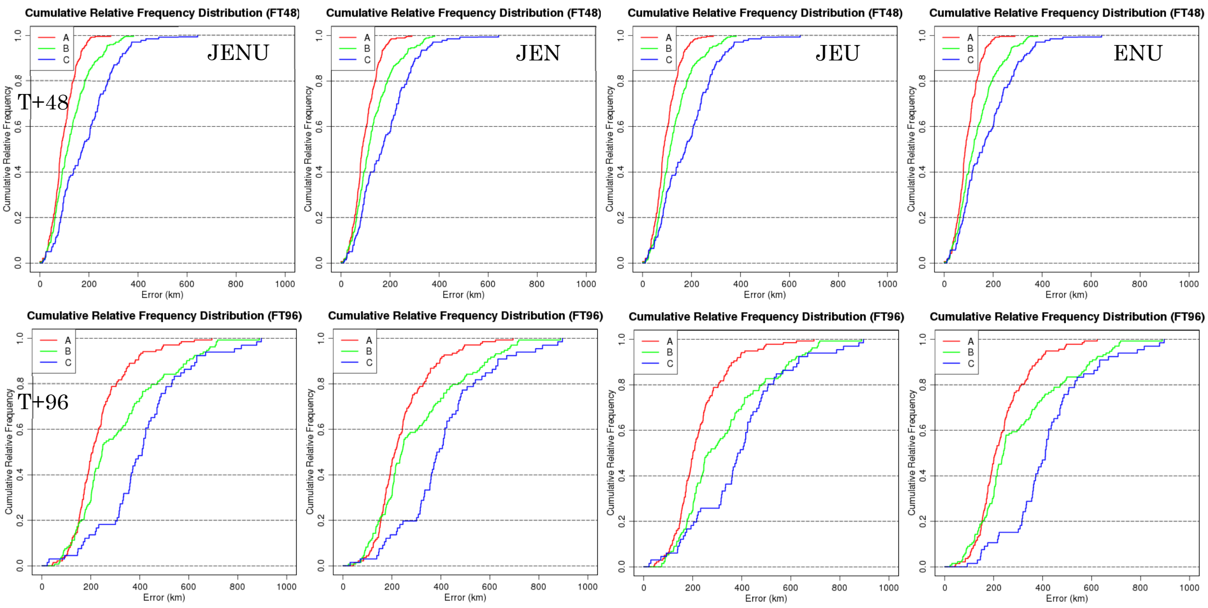

Figure 10 Cumulative relative frequency distributions of operational TC track forecast errors (km) at T+48 (top) and 96 (bottom) for multiple ensembles

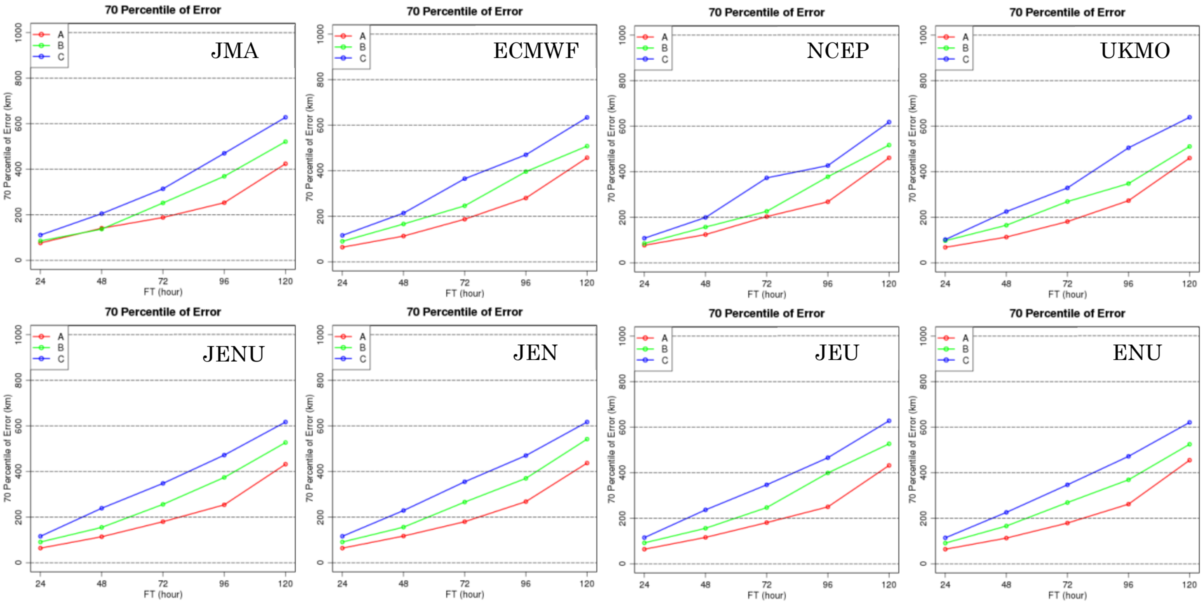

Figure 11 Relationships linking probability-circle radii and confidence levels A, B and C for forecast times with single and multiple ensembles

3.3 Appropriateness of three methods for probability circles

The feasibility of replacing the current approach of determining the 70% probability-circle radii of operational TC track forecasts with a new multiple ensemble-based method was investigated. As described in Section 1, the radii for 3- to 72-hour forecasts is based on historical error statistics relating to operational TC track forecasts issued by the Center, while those for 96- and 120-hour forecasts are based on ensemble spreads from the JMA ensemble, or GEPS. Here, these are referred to as the statistical and single ensemble methods, respectively. For the multiple ensemble method to be compared with the statistical and single ensemble methods here, the JENU ensemble was selected from among the 11 multiple ensembles whose evaluation is described in 3.1 and 3.2 with minimally differing validity. NWP systems including ensembles are often upgraded at individual weather centers during the typhoon season, and related performance changes accordingly. Therefore, the JENU ensemble, which has the largest ensemble size, was chosen for the multiple ensemble method here to minimize the influence of such upgrades on the probability-circle radii adopted at the Center.

The statistical, single and multiple ensemble methods were compared, with metrics including mean probability-circle radii and coefficients of correlation between radii and operational TC track forecast errors. Smaller mean probability-circle radii imply that the area of disaster risk reduction activities (e.g., evacuation) can be reduced, and larger coefficients result in better situation-dependent TC track forecasts. Probability-circle radii are determined in consideration of TC direction (NW: 260 – 359°; Other: 0 – 259°) and speed (≤ 10 kt, > 10 kt) in the statistical method, as in current operations. For single and multiple ensembles, the frequencies of confidence levels A, B and C are set to 40, 40 and 20 percent, respectively, as operationally used for 96- and 120-hour forecasts (Yamaguchi et al. 2009).

Figure 12 (a) shows little difference among the mean radii for the three methods, indicating that the multiple ensemble method produces no significant reduction with respect to the statistical and single ensemble methods. Figure 12 (b) shows mean radii for each confidence level with the single and multiple ensemble methods. The degree of separation between the three levels is more clearly marked with the latter at T+24 and 48, but is similar with longer lead times such as T+96 and 120.

Figure 13 shows relationships linking probability-circle radii and operational TC track forecast errors for the three methods. The related coefficients of correlation increase in the order of the statistical, single and multiple ensemble methods, thus demonstrating the relative benefits of the latter in determining radii.

To determine whether the multiple ensemble method is further improved via consideration of TC direction and speed (as currently considered for radii at T+3 to 72), relationships linking operational TC track forecast errors and TC direction/speed were evaluated. Figures 14 and 15 show the results for 2011 – 2015 and 2016 – 2018, respectively. There is a clear relationship between operational TC track forecast errors and direction/speed in past data; that is, errors are smaller with a NW direction and low speed. However, no such relationship is clearly seen in verification with the latest data from 2016 to 2018. This is attributable to the fact that official TC track forecasts issued by the Center were generally based on JMA Global Spectral Model (GSM) outputs in 2014 and before, while this approach was replaced with a consensus method in 2015 incorporating deterministic TC track predictions from JMA, ECMWF, NCEP and UKMO (Nishimura and Fukuda 2019). With the introduction of the consensus method, biases in operational TC track forecasts based on the JMA GSM may be reduced, and consideration of TC direction and speed may no longer be necessary.

Figures 16 and 17 show the effects of increasing the number of confidence levels for the single and multiple ensemble methods, respectively. In addition to the three confidence levels, a fourth and a fifth are introduced. The category frequency is set to the same among the confidence levels, namely, 25 and 20 percent, respectively. It can be seen that an increased number of confidence levels does not necessarily improve the correlation between probability-circle radii and operational TC track forecast errors. Indeed, some reverse correlations are observed, probably due to the reduced number of samples for each confidence level.

The effect of changing the frequency of each category of the three confidence levels in the multiple ensemble method was also assessed. Relationships linking probability-circle radii and operational TC track forecast errors at T+48 and 96 are shown in Figures 18 and 19, respectively. Relationships linking probability-circle radii and confidence levels for forecast times are shown in Figure 20. It can be seen that the change in the frequency of each category does not necessarily improve the correlation coefficients and the degree of separation among confidence levels, but frequencies of 40, 40 and 20 percent is found to be the most appropriate.

These results indicate that the multiple ensemble method provides the most appropriate probability circles among the three approaches, demonstrating the strongest correlation with operational TC track forecast errors and the clearest degree of separation among confidence levels. Classification based on the direction and speed of TC movement was also found to be unnecessary, and the confidence levels A, B and C with frequencies of 40, 40 and 20 percent, respectively, were found to be appropriate.

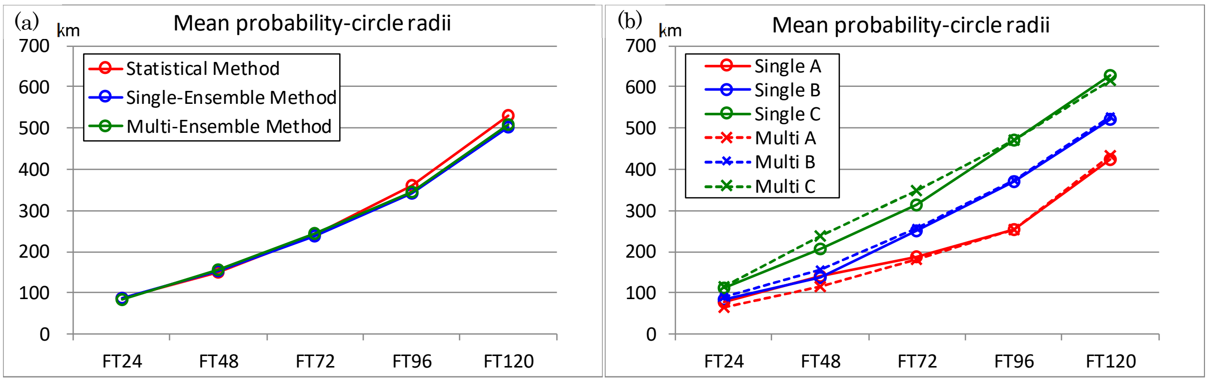

Figure 12 (a) Mean probability-circle radii for the statistical and single/multiple-ensemble methods. (b) Mean radii for each confidence level for the single/multiple ensemble methods.

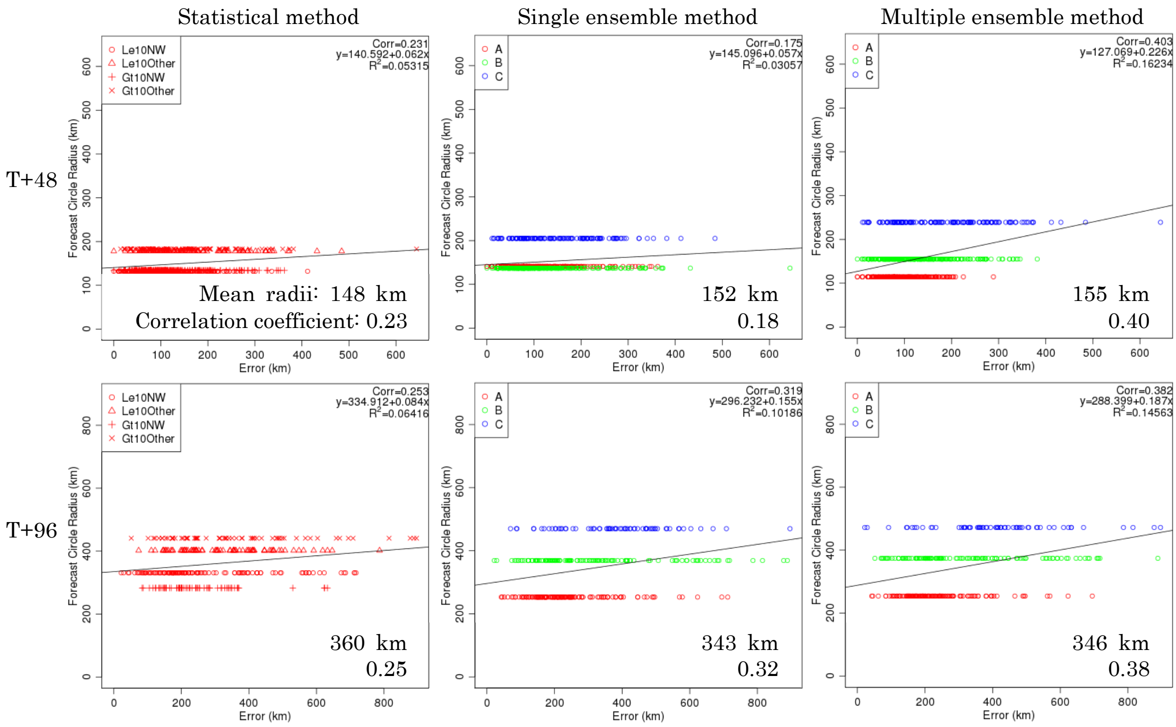

Figure 13 Relationships linking probability-circle radii and operational TC track forecast errors for the statistical (left), single (middle) and multiple (right) ensemble methods at T+48 (top) and 96 (bottom). Regression lines are shown in black.

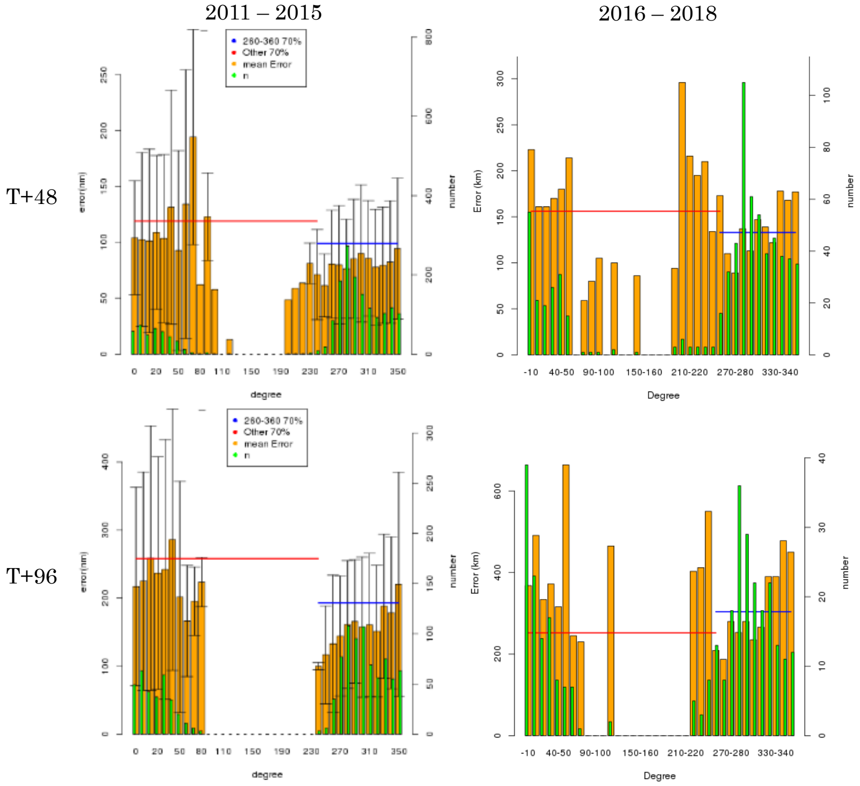

Figure 14 Relationships linking operational TC track forecast errors and TC direction for 2011 – 2015 (left) and 2016 – 2018 (right) at T+48 (top) and 96 (bottom). Orange and green bars represent mean forecast errors and numbers of cases, respectively. Red and blue lines show 70% probability-circle radii for the directions Other and NW, respectively.

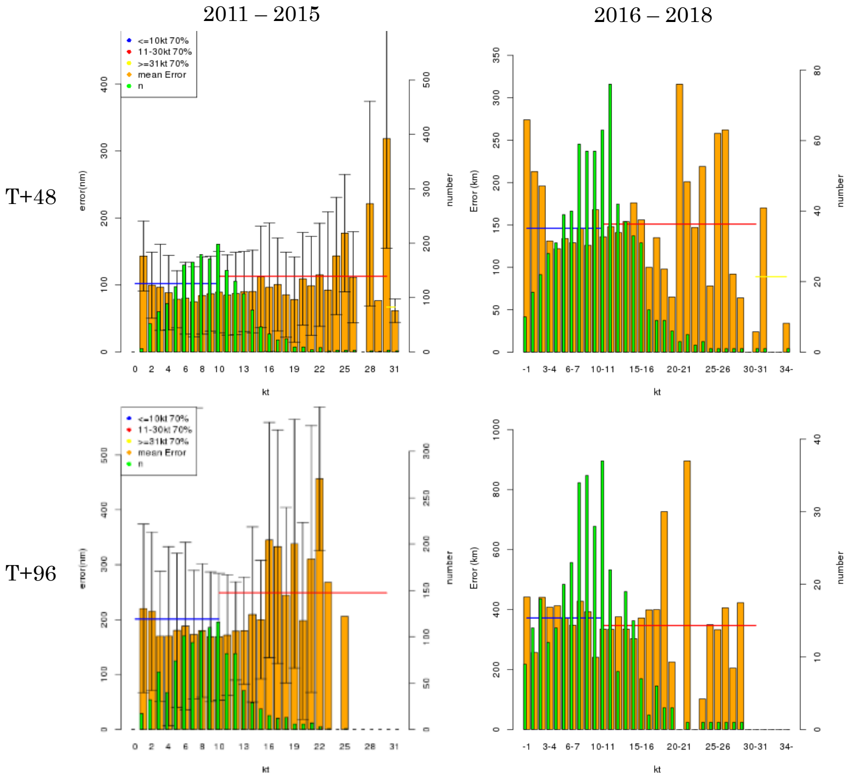

Figure 15 Relationships linking operational TC track forecast errors and TC speed for 2011 – 2015 (left) and 2016 – 2018 (right) at T+48 (top) and 96 (bottom). Orange and green bars represent mean forecast errors and numbers of cases, respectively. Blue, red and yellow lines show 70% probability-circle radii for speed ≤ 10 kt, 10 kt < and ≤ 30 kt, and > 30 kt, respectively.

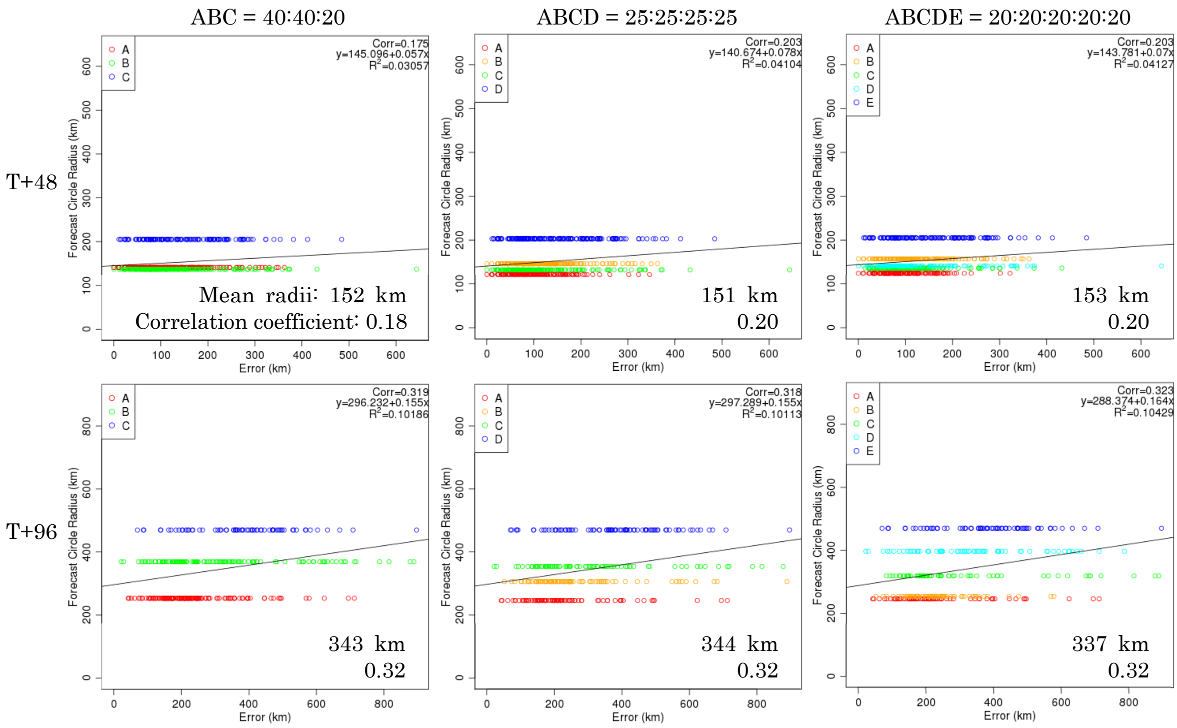

Figure 16 Relationships linking probability-circle radii and operational TC track forecast errors for the single ensemble method using the JMA ensemble for confidence levels 3 (left), 4 (middle) and 5 (right) at T+48 (top) and 96 (bottom). Regression lines are shown in black.

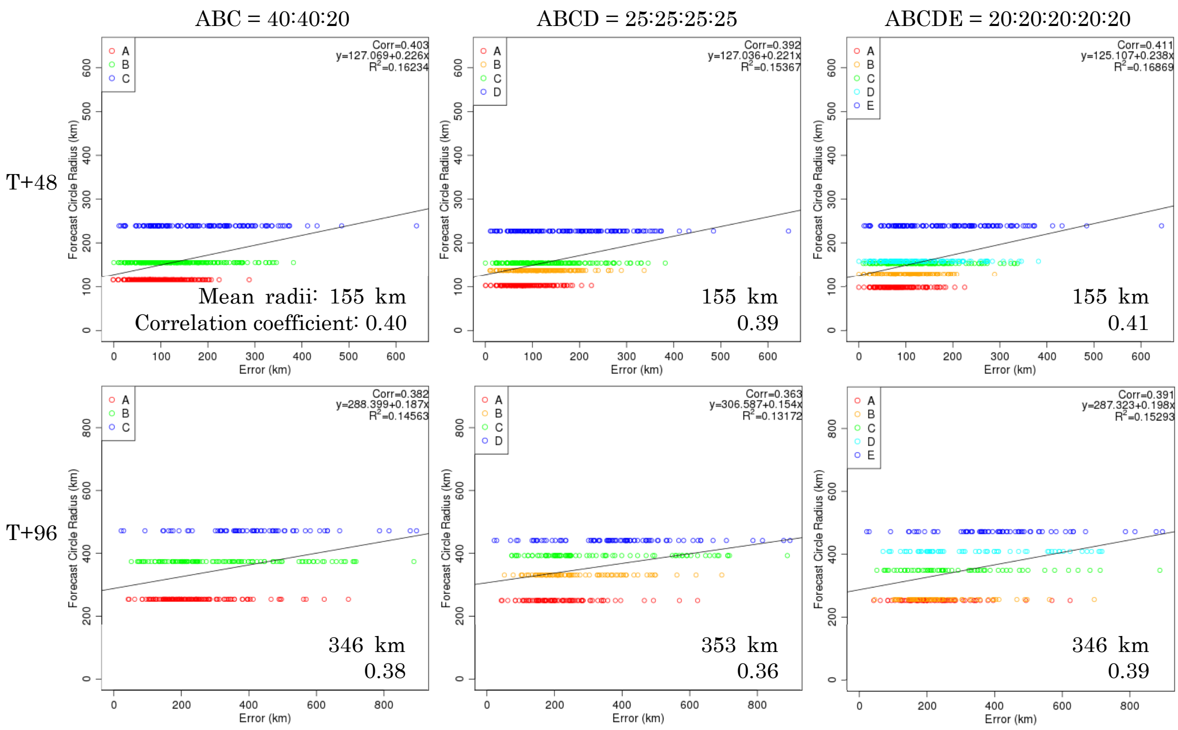

Figure 17 Relationships linking probability-circle radii and operational TC track forecast errors for the multiple ensemble method using the JENU ensemble for confidence levels 3 (left), 4 (middle) and 5 (right) at T+48 (top) and 96 (bottom). Regression lines are shown in black.

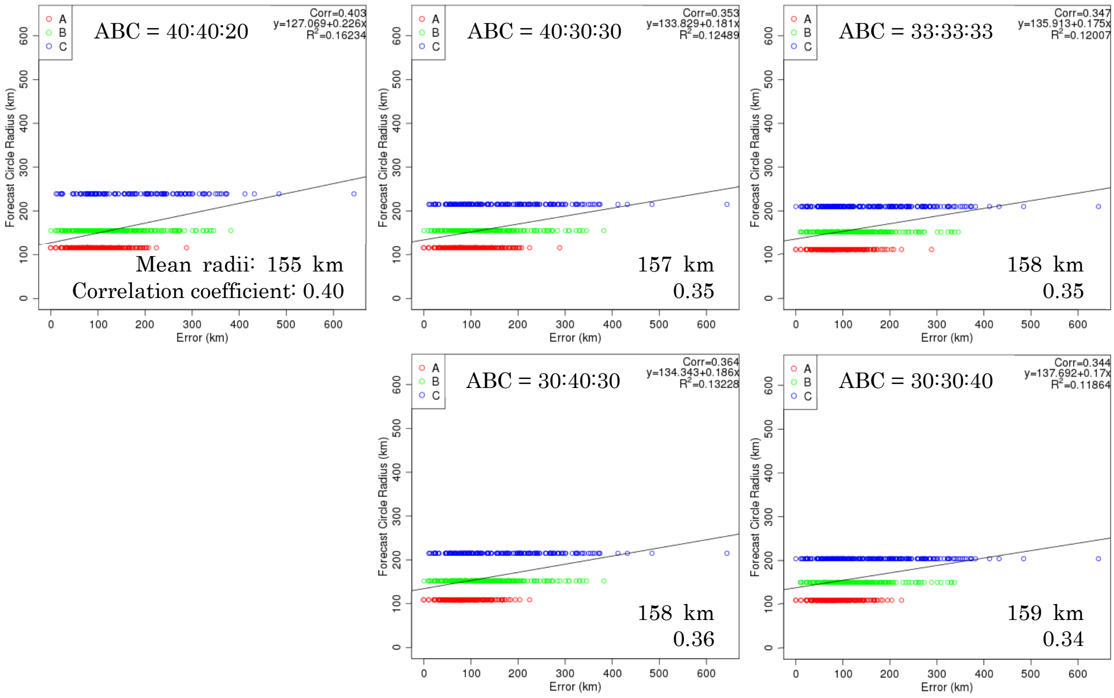

Figure 18 Relationships linking probability-circle radii and operational TC track forecast errors for the multiple ensemble method using the JENU ensemble for various combinations of frequencies for confidence levels A, B and C at T+48. Regression lines are shown in black.

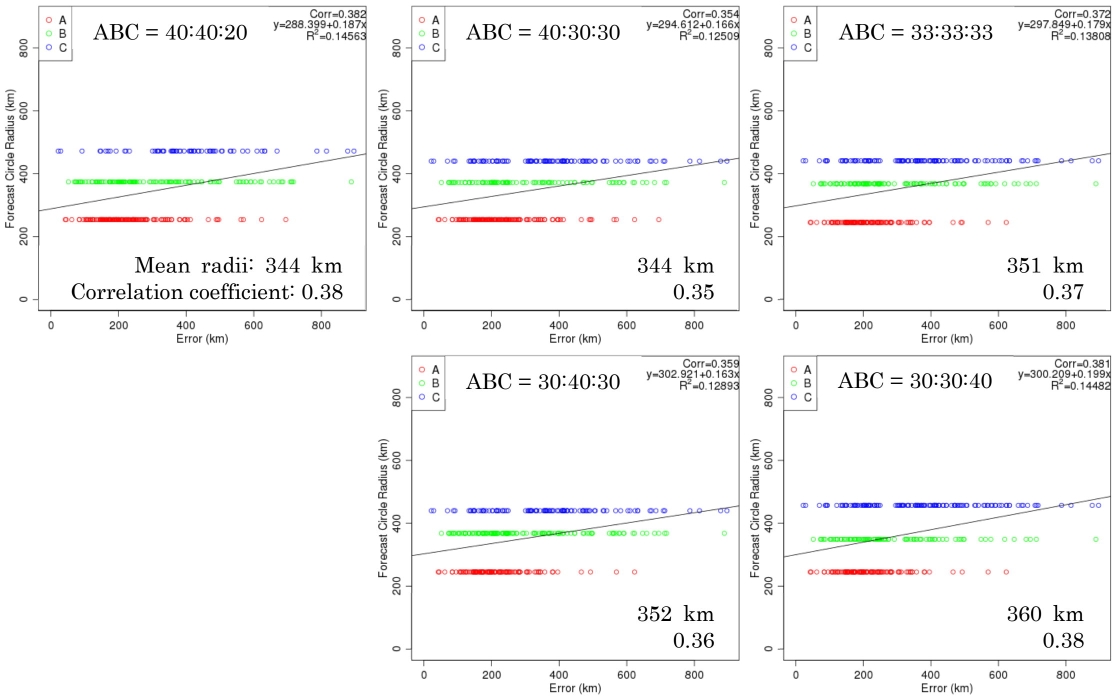

Figure 19 Relationships linking probability-circle radii and operational TC track forecast errors for the multiple ensemble method using the JENU ensemble for various combinations of frequencies for confidence levels A, B and C at T+96. Regression lines are shown in black.

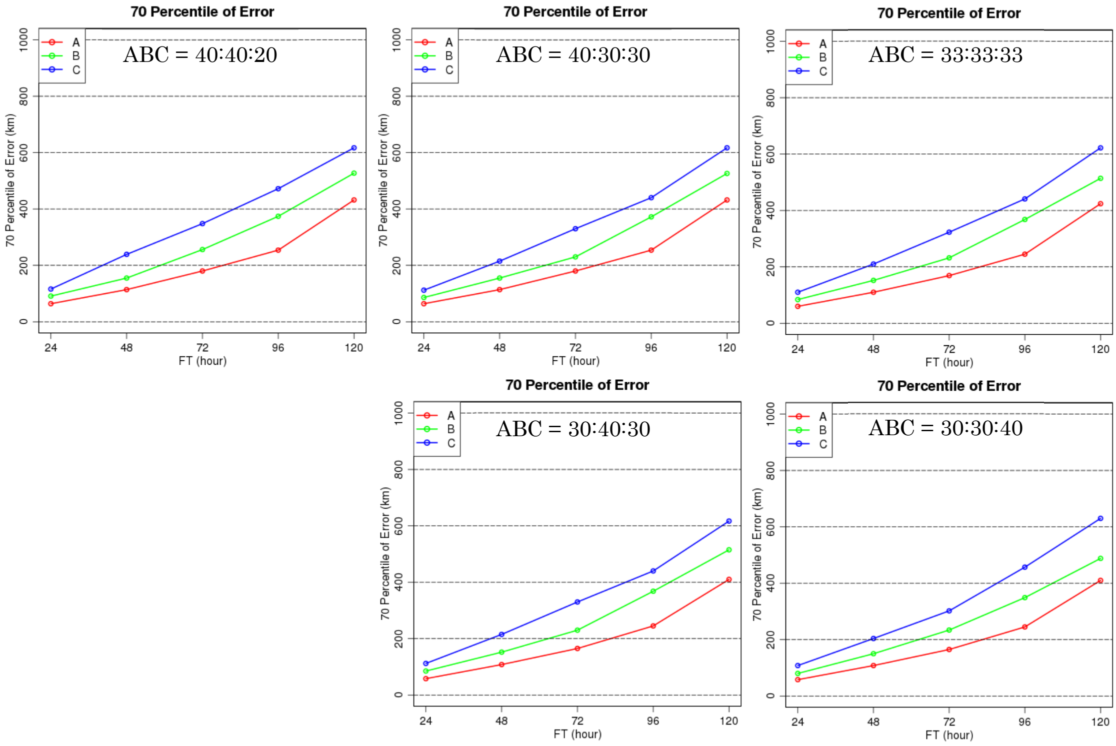

Figure 20 Relationships linking probability-circle radii and confidence levels for forecast times for the multiple ensemble method using the JENU ensemble for various combinations of frequencies for confidence levels A, B and C.

4. Probability-circle radii based on multiple ensemble consideration

Based on the results reported in Section 3, the Center plans to adopt the multiple ensemble method to determine 70% probability-circle radii of operational TC track forecasts for all forecast times up to five days by the 2019 typhoon season. The radii will be based solely on confidence levels derived from cumulative ensemble spreads of multiple ensembles from JMA, ECMWF, NCEP and UKMO. Confidence levels will be categorized as A, B and C with provisional frequencies of 40, 40 and 20 percent, respectively and confidence levels A' and B' will be introduced to suppress rapid changes in radius for A, B and C after 24-hour forecasts.

The planned probability-circle radii are shown in Table 3 and compared with the current radii in Figure 21. The planned radii are smaller, reflecting the latest verification. The new method also resolves the discontinuity issue in the rate of radius increase described in Section 1 via uniform application for all forecast times up to five days.

Table 3 Planned probability-circle radii [nm]

Forecast time [h]	Confidence level				
	A	A'	B	B'	C
3	10		15		20
6	15		20		25
9	15		25		35
12	20		30		40
15	20		35		50
18	25		40		55
21	25		45		65
24	30	40	50	60	70
48	60	75	90	100	120
72	100	120	140	160	180
96	140	170	200	230	260
120	200	240	280	325	350

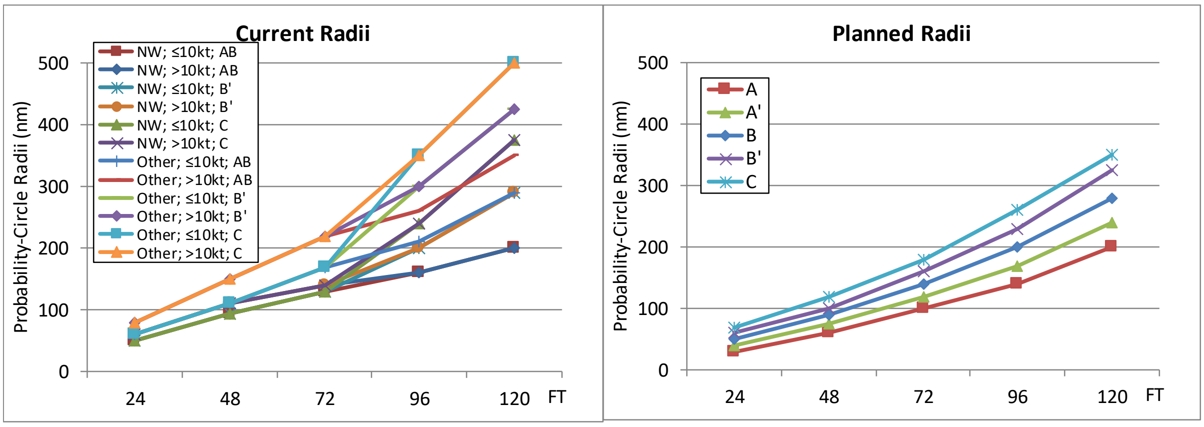

Figure 21 Differences in current (left) and planned (right) radii for various forecast times

5. Summary

JMA's RSMC Tokyo – Typhoon Center revised its 70% probability-circle radii for TC track forecasts in 2016 and 2017. Values are now statistically based on TC direction and speed for 3- to 72-hour forecasts and on confidence levels (based on cumulative spread as calculated using JMA's ensemble) in addition to TC direction and speed for 96- to 120-hour forecasts. These upgrades partially alleviated discontinuity in the rate of radius increase caused by differences in determination methods, but the issue still remains.

The WMO TCP and WWRP launched the North Western Pacific Tropical Cyclone Ensemble Forecast Project (NWP-TCEFP) in 2009 to explore the utility of ensemble forecasts and promote related products for operational TC forecasting. Under the project, the relative benefits of multiple ensembles with respect to a single ensemble were evaluated. Based on the outcomes, the Center started providing ensemble TC track predictions from JMA, ECMWF, NCEP and UKMO to Typhoon Committee Members in real time in 2015. However, radii based on multiple ensembles have yet to be operationalized at the Center.

Against this background, the Center has explored a new method of determining radii uniformly for forecast lead times up to five days using multiple ensembles. This approach was evaluated in comparison to the conventional statistical and single ensemble-based methods using data for the period from 2016 to 2018. Four single ensembles (from JMA, ECMWF, NCEP and UKMO) and eleven multiple ensembles consisting of combinations thereof were evaluated, and data availability was considered in light of the operational use of ensembles from international sources.

Comparison of the spread-error relationship between the single and multiple ensembles showed superiority in the latter. All ensembles exhibited a positive correlation between ensemble mean TC track errors and cumulative ensemble spreads, indicating the usefulness of such spreads as an indicator of prediction errors. The correlation coefficients in the multiple ensembles tended to be larger.

Comparison of single and multiple ensembles in terms of probability circles indicated that the coefficients of correlation between operational TC track forecast errors and cumulative ensemble spreads were larger in the multiple ensembles, whose outlier ratios were also smaller. The degree of separation in probability-circle radii between multiple-ensemble confidence levels also tended to be larger.

The feasibility of replacing the current method of determining probability-circle radii of operational TC track forecasts with the new multiple ensemble method was considered via comparison of the statistical, single and multiple approaches using metrics including mean probability-circle radii and related coefficients of correlation with operational TC track forecast errors. The multiple ensemble method provided the most appropriate probability circles with the highest correlation to operational TC track forecast errors, and the clearest degree of separation among confidence levels. Classification based on TC direction and speed was also found to be unnecessary, and confidence levels A, B and C with frequencies of 40, 40 and 20 percent were found to be appropriate.

Based on these results, the Center plans to adopt the multiple ensemble method to determine the probability-circle radii of operational TC track forecasts for all lead times up to five days by the 2019 typhoon season. The radii will be based solely on confidence levels derived from cumulative spreads of multiple ensembles consisting of JMA, ECMWF, NCEP and UKMO data. These levels will be categorized as A, B and C with 40, 40 and 20% frequencies, respectively. The planned radii will be smaller than the current versions, reflecting the latest verification. The new method also resolves the reported discontinuity issue in the rate of radius increase via uniform application for all forecast times up to five days.

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