2016 and 2017 Reviews of Probability-circle Radii in Tropical Cyclone Track Forecasts

Junya Fukuda
Tokyo Typhoon Center, Forecast Division, Forecast Department,
Japan Meteorological Agency

1. Introduction

In April 2009, the RSMC Tokyo – Typhoon Center (referred to here simply as "the Center") of the Japan Meteorological Agency (JMA) began to provide five-day track forecasts of tropical cyclones (TCs) moving over the western North Pacific and the South China Sea (Kishimoto 2010). Track forecast uncertainty is expressed using probability circles to indicate expected TC locations at each forecast time with a probability of 70% (Mannoji 2005). The radii of these circles for 3- to 72-hour forecasts have conventionally been statistically determined according to the direction and speed of TC movement based on the results of recent TC track forecast verification. Meanwhile, those for 96- to 120-hour forecasts have been statistically determined according to confidence levels based on cumulative ensemble spread[1] as calculated using the Typhoon Ensemble Prediction System (TEPS; Kyouda and Higaki 2015) (Narita 2015) as described in Section 2.

Probability-circle radii for all forecast times were reviewed in June 2016 as described in Section 3 based on TC track forecast improvements made in recent years. In June 2017, radii for 96- to 120-hour forecasts were also updated based on recent forecast results obtained using JMA's new Global Ensemble Prediction System (GEPS; Tokuhiro 2018), which was introduced in January 2017 to replace TEPS and One-week EPS (WEPS) as outlined in Section 4. Section 5 details future work plans, and Section 6 summarizes the report.

2. Previous probability-circle radii

In July 1997 when the Center began to provide three-day TC track forecasts, probability-circle radii for forecasts with a lead time of up to 72 hours were statistically determined according to the direction and speed of TC movement based on the results of recent TC track forecast verification. Radii were reviewed to reflect recent forecast results in 2000, 2004 and 2008. After the review conducted in May 2008, radii were determined based

[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.

on forecast results obtained from 2004 to 2007. In April 2009 when the Center began to provide five-day TC track forecasts, radii for 96- to 120-hour forecasts were statistically determined according to the confidence levels based on the cumulative ensemble spread as calculated using TEPS. Radii were again reviewed in May 2014 using pre-operational TEPS results obtained from 2011 to 2013 to reflect major TEPS modifications implemented at that time, including an increase in the number of ensemble members from 11 to 25 and a decrease in horizontal grid spacing from around 55 to 40 km. Radii as of January 2016 following these reviews are shown in Table 1.

Table 1. Probability-circle radii as of January 2016

Probability-circle radii [nm] for 3- to 72-hour forecasts are categorized by forecast time and direction/speed (V) of TC movement, while those for 96- to 120-hour forecasts are categorized by forecast time and confidence level based on cumulative ensemble spread.

Forecast time [h]	Direction of movement[2]	Probability-circle radii [nm]		
		V ≤ 10 kt	10 kt < V ≤ 30 kt	V > 30 kt
3	All	20	20	35
6	All	30	30	50
9	All	40	40	70
12	All	50	50	85
15	NW	55	55	95
	Other	60	60	
18	NW	60	65	110
	Other	70	70	
21	NW	65	70	120
	Other	75	75	
24	NW	70	75	130
	Other	85	85	
48	NW	110	140	210
	Other	160	180	
72	NW	160	210	325
	Other	220	250	

Forecast time [h]	Confidence level based on cumulative ensemble spread[3]				
	A	A’	B	B’	C
96	200	240	280	350	425
120	250	300	375	450	500

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

[3] The confidence levels A’ and B’ were introduced to suppress rapid changes in radius for only A, B and C.

3. June 2016 review of probability-circle radii

Since the reviews described in Section 2, the accuracy of TC track forecasts has improved thanks to enhanced numerical prediction models and other forecast techniques as shown in Figure 1. The hit ratios of 70% probability circles are today in fact well over 70%, as shown in Figure 2. Discontinuities were also occasionally observed in the rate of radius increase between 3- to 72-hour forecasts and 96- to 120-hour forecasts (as seen in Figure 4, left) due to differences in radius determination methods, meaning that operational forecasters often needed to adjust radii subjectively in line with expected forecast uncertainties. To address such problems, radii were revised using recent forecast results in 2016.

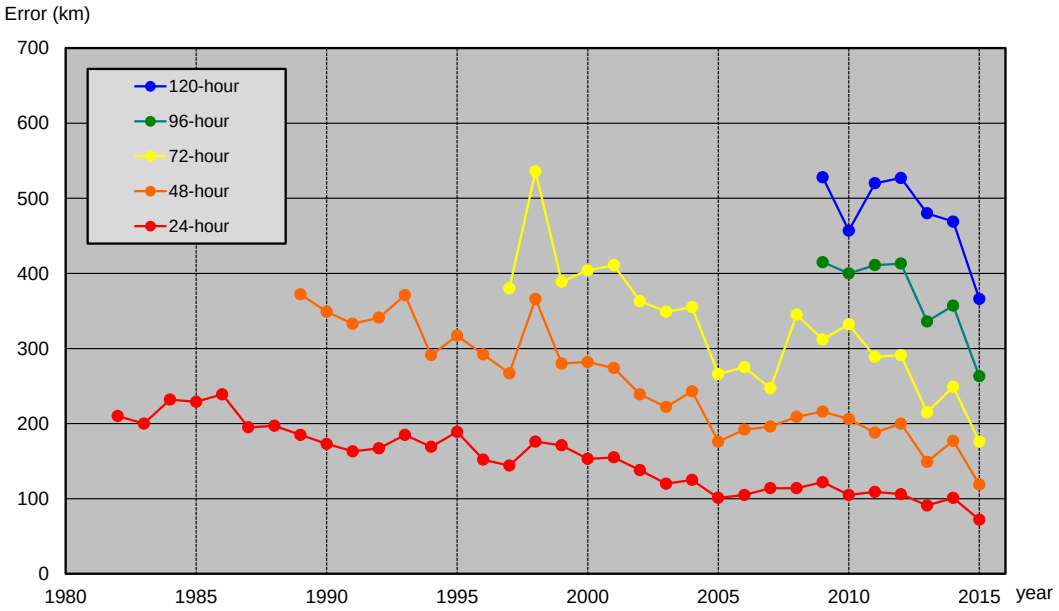

Figure 1. Time-series representations of TC track forecast errors

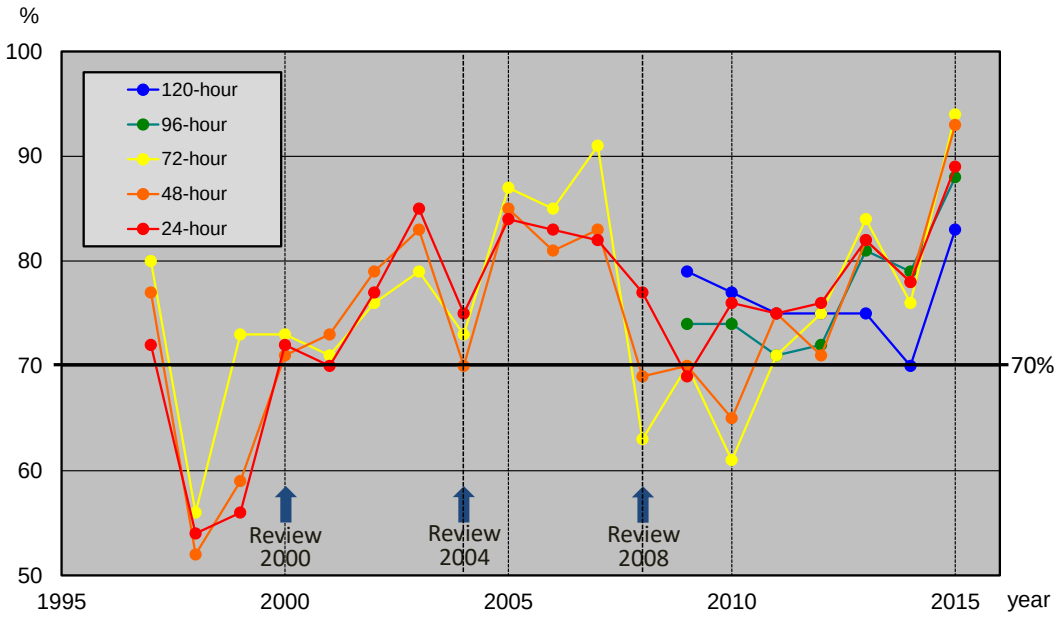

Figure 2. Time-series representations of hit ratios for 70% probability circles until 2015

In this work, the Center first conducted TC track forecast verification for the period from 2011 to 2015. Table 2 shows probability-circle radii calculated from 70-percentile values of forecast errors for individual cases categorized by the direction and speed of TC movement at the previous thresholds (Table 1). Figure 2 shows the dependencies of forecast errors for direction and speed, respectively. These data indicate that the radius gradually increases with speed and rapidly increases when the direction is Other (0 – 259°), and that the number of cases is low when the forecast time exceeds 15 hours and speed exceeds 30 kt.

Next, the relationship between TEPS cumulative ensemble spread and TC track forecast errors observed from 2014 to 2015 after the TEPS modification was examined. Figure 3 shows a scatter diagram for forecast errors and cumulative ensemble spread, and the relationship between probability-circle radii and confidence levels. A close correlation is observed between the TEPS cumulative ensemble spread and TC track forecast errors/confidence levels.

Table 2. Probability-circle radii based on forecast verification for the period from 2011 to 2015

Forecast time [h]	Direction of movement	Probability-circle radii [nm] (number of cases)		
		V ≤ 10 kt	10 kt < V ≤ 30 kt	V > 30 kt
3	All	13 (251)	19 (295)	37 (30)
6	All	21 (229)	24 (285)	31 (28)
9	All	26 (227)	31 (262)	36 (26)
12	All	36 (842)	42 (1070)	42 (26)
15	NW	29 (106)	37 (87)	52 (23)
	Other	41 (95)	53 (145)	
18	NW	32 (109)	46 (68)	51 (20)
	Other	37 (81)	61 (150)	
21	NW	36 (91)	47 (73)	51 (18)
	Other	41 (83)	71 (139)	
24	NW	55 (1059)	60 (673)	49 (21)
	Other	59 (401)	79 (324)	
48	NW	96 (888)	106 (447)	67 (2)
	Other	113 (326)	146 (189)	
72	NW	130 (644)	139 (316)	299 (1)
	Other	166 (317)	222 (149)	
96	NW	191 (488)	212 (195)	- (0)
	Other	234 (264)	305 (126)	
120	NW	228 (341)	250 (134)	- (0)
	Other	331 (198)	361 (112)	

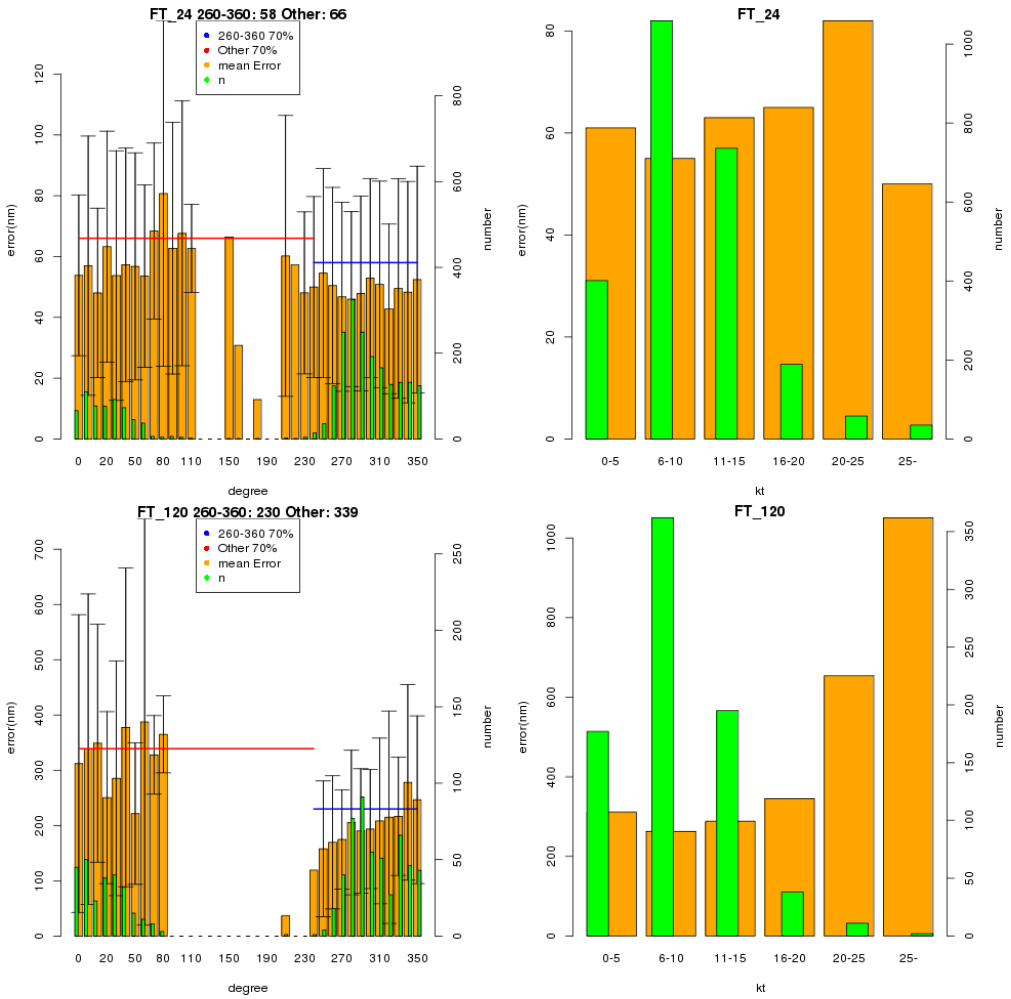

Figure 2. Dependencies of forecast errors for direction and speed

Top: 24-hour forecasts; bottom: 120-hour forecasts; left: direction; right: speed of TC movement. Orange and green bars represent mean forecast errors and numbers of cases, respectively. Red and blue lines show the radii of 70% probability circles for Other and NW, respectively.

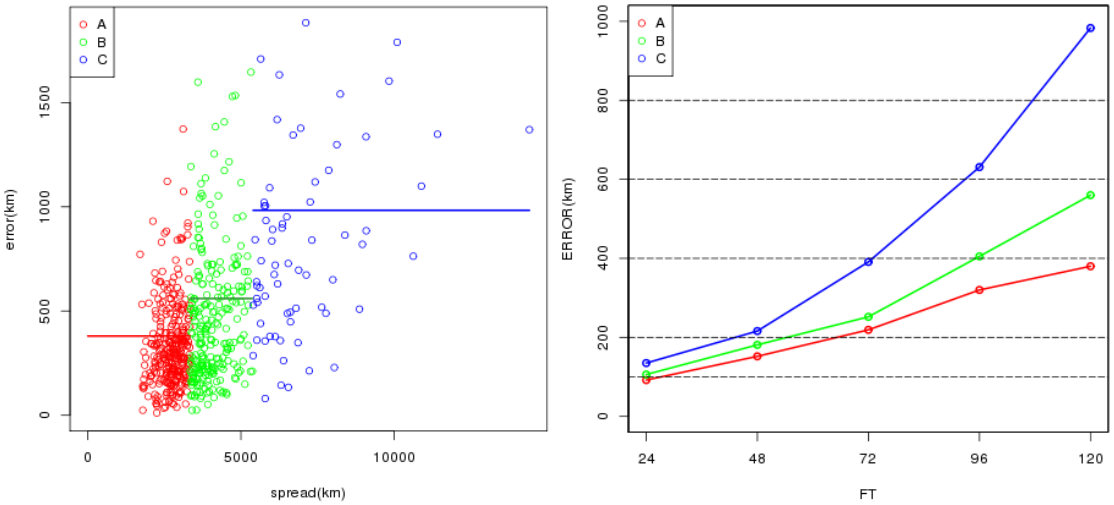

Figure 3. Relationship between forecast errors and TEPS cumulative ensemble spread

Left: scatter diagram for forecast errors and cumulative ensemble spread for 120-hour forecasts. Lines show the radii of 70% probability circles for each confidence level. Right: relationship between probability-circle radii and confidence levels; red, green and blue circles or lines: confidence levels A, B and C, respectively.

Finally, individual cases categorized by the direction and speed of TC movement were categorized into TEPS confidence levels A to C for combination of the two previous verifications conducted for the period from 2014 to 2015 as shown in Table 3. For simplicity, certain cases were unified to reduce the number of choices in radius determination based on the following relations:

- The forecast error difference with dependence on direction was relatively large for the same speed and confidence level.
- The forecast error difference with dependence on speed was relatively small for the same direction and confidence level (except for levels A and B in Other).
- The forecast error difference between confidence levels A and B was relatively small for the same direction and speed.

As a result, confidence levels A and B as well as speed categories other than confidence level AB in Other were unified.

Table 4 shows the outcomes of the radius review. Due to operational system constraints, confidence level based on TEPS ensemble cumulative spread was introduced only to radii for 96- to 120-hour forecasts, meaning that categories based on the direction and speed of TC movement were implemented for these predictions. This partially resolved the discontinuities in the rate of radius increase between 3- to 72-hour forecasts and 96- to 120-hour forecasts as shown in Figure 4. Table 5 shows rate of radius change, illustrating reductions of around 20 to 40 percent for most cases. This helped to address the issue of warning-area over-dispersiveness. However, in some 96- to 120-hour forecasts, the radius increased due to the new categorization based on the direction and speed of TC movement. Figure 5 shows examples of radius changes for a TC with two directions.

This review was introduced in June 2016 and applied as of T1601 (Nepartak). Figure 6 shows a time-series representation of hit ratios for 70% probability circles including those of 2016. The 2016 ratios more appropriate, being smaller and approaching 70% due in part to the effects of the review.

Table 3. Probability-circle radii based on forecast verification for the period from 2014 to 2015

Radii [nm] for all forecast times are categorized by forecast time, direction/speed (V) of TC movement and confidence levels A to C based on the cumulative ensemble spread. Figures in parentheses show the number of cases.

Forecast time [h]	Direction of movement	V ≤ 10 kt			V > 10 kt		
		A	B	C	A	B	C
24	NW	42 (224)	59 (199)	67 (61)	55 (146)	54 (171)	75 (47)
	Other	48 (104)	60 (63)	73 (27)	65 (56)	57 (63)	78 (51)
48	NW	78 (251)	95 (162)	119 (46)	73 (113)	92 (137)	110 (28)
	Other	91 (81)	100 (68)	170 (30)	103 (34)	125 (68)	102 (36)
72	NW	112 (204)	123 (116)	167 (30)	109 (102)	124 (118)	147 (10)
	Other	140 (79)	152 (68)	242 (35)	155 (37)	150 (59)	241 (36)
96	NW	157 (175)	192 (98)	235 (24)	169 (84)	197 (71)	265 (1)
	Other	190 (73)	240 (68)	434 (20)	269 (22)	242 (61)	435 (46)
120	NW	185 (142)	271 (77)	367 (14)	197 (83)	252 (47)	78 (1)
	Other	253 (54)	283 (55)	536 (18)	287 (35)	365 (72)	711 (36)

Table 4. Outcomes of the June 2016 probability-circle radius review

Confidence level B’ was introduced to suppress rapid changes in radius for only AB and C.

Forecast time [h]	Direction of movement	Probability-circle radii [nm] (confidence level)		
		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	170(AB)/240(C)	170(AB)/240(C)	
	Other	220(AB)/325(B’)/425(C)	260(AB)/325(B’)/425(C)	
120	NW	200(AB)/350(C)	200(AB)/350(C)	
	Other	270(AB)/450(B’)/600(C)	325(AB)/450(B’)/600(C)	

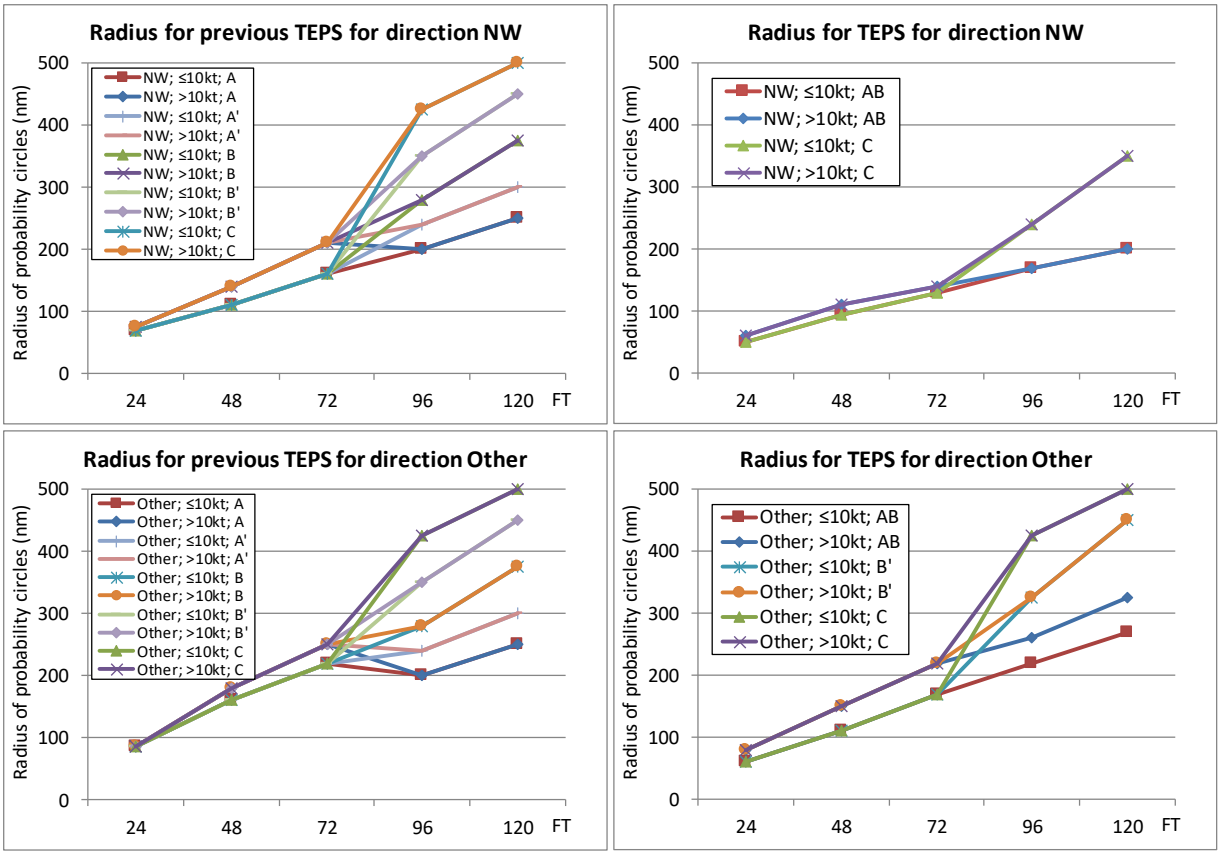

Figure 4. Radius changes for forecast times with the previous and new TEPS
Left; previous TEPS; right: new TEPS; top: NW; bottom: Other

Table 5. Rates of radius change based on the June 2016 review

Forecast time [h]	Direction of movement	Rates of radius change [%]		
		V ≤ 10 kt	10 kt < V ≤ 30 kt	V > 30 kt
3	All	-25.0 %	0.0 %	-28.6%
6	All	-33.3 %	-16.7 %	-40.0%
9	All	-37.5 %	-25.0 %	-50.0%
12	All	-40.0 %	-20.0 %	
15	NW	-36.4 %	-18.2 %	
	Other	-33.3 %	-16.7 %	
18	NW	-33.3 %	-23.1 %	
	Other	-35.7 %	-14.3 %	
21	NW	-30.8 %	-21.4 %	
	Other	-33.3 %	-6.7 %	
24	NW	-28.6 %	-20.0%	
	Other	-29.4 %	-5.9 %	
48	NW	-13.6 %	-21.4 %	
	Other	-31.3 %	-16.7 %	
72	NW	-18.8 %	-33.3%	
	Other	-22.7 %	-12.0%	

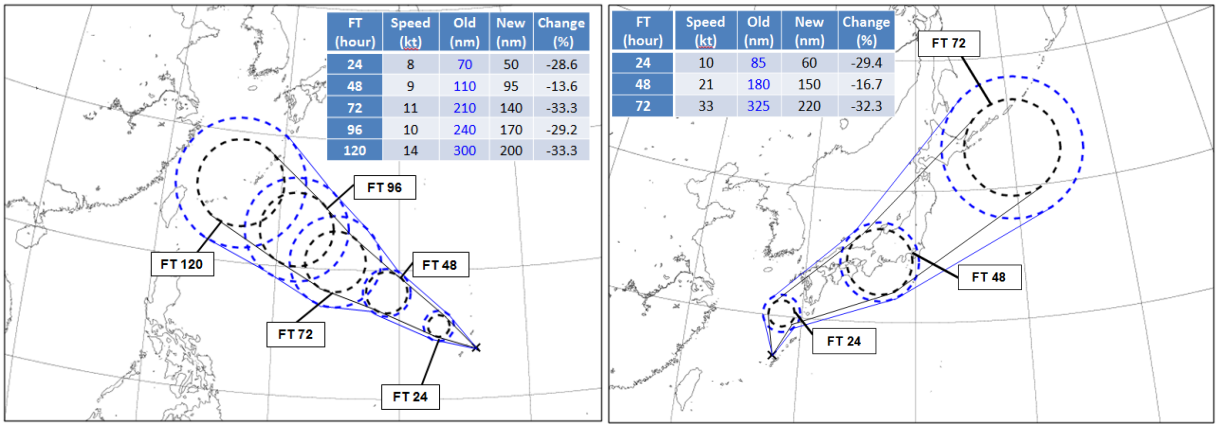

Figure 5. Changes in probability-circle radii for a TC with two directions

The old and new circles are shown in blue and black, respectively. Left: forecasts for T1509 (Chan-hom) moving northwestward with an initial time of 18 UTC on 4 July 2015; right: forecasts for T1419 (Vongfong) moving northeastward with an initial time of 18 UTC on 11 October 2014.

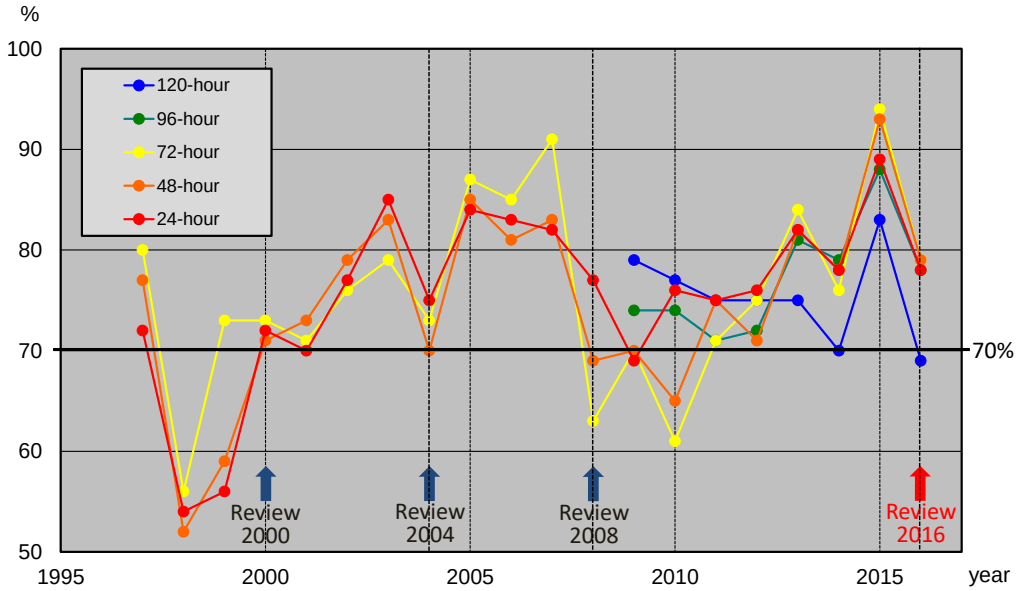

Figure 6. Time-series representation of hit ratios for 70% probability circles up to 2016

4. June 2017 review of probability-circle radii

In January 2017, JMA began to operate the GEPS – a unification of the previous TEPS and WEPS – along with the introduction of an upgraded forecast model, a revision of the initial perturbation production method and other updates. The results of verification for the period from 2015 to 2016 showed a consequent positive impact on TC track forecasts, including a mitigation of spread deficiencies for 96- to 120-hour forecasts and a reduction of track forecast errors.

To incorporate the changes into probability-circle radii for 96- to 120-hour forecasts, the Center researched differences in radius characteristics between the pre-operational GEPS for the period from 2015 to 2016 and the TEPS for the same period. Figure 7 shows such

differences for thresholds of the cumulative ensemble spread between confidence levels A and B, and B and C. The thresholds calculated using the GEPS are lower than those based on the TEPS for the first half of the forecast times and higher for the second half, reflecting a change in model characteristics. Figure 8 shows the relationship between probability-circle radii and confidence levels for the TEPS and GEPS, respectively. There is a close correlation for both, but that of the GEPS is stronger for the first half of the forecast times and weaker for the second. Changes in radius calculated using the GEPS for the forecast times were smoother than those calculated using the TEPS.

Radii calculated using the TEPS and GEPS were then compared for individual cases with categorization by confidence level, direction and speed of TC movement. As the GEPS and TEPS radii were found to have similar characteristics, the unification of confidence levels A and B was maintained and speed categories were also unified except for confidence level AB in Other. Table 6 shows TEPS/GEPS radius differences for 96- to 120-hour forecasts. Some radii calculated using the TEPS grow rapidly in 72- to 96-hour forecasts, but this situation was mitigated for GEPS radii as shown in Figure 9.

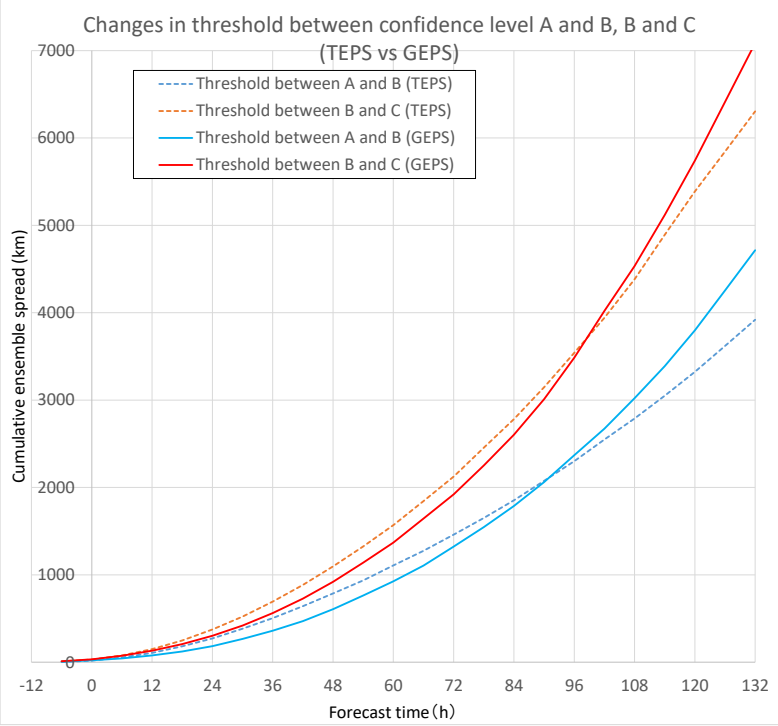

Figure 7. Thresholds of cumulative ensemble spread between confidence levels A and B, and B and C for TEPS and GEPS

Red line: thresholds of cumulative ensemble spread between A and B; blue line: those between B and C; dashed line: those for TEPS; solid line: those for GEPS

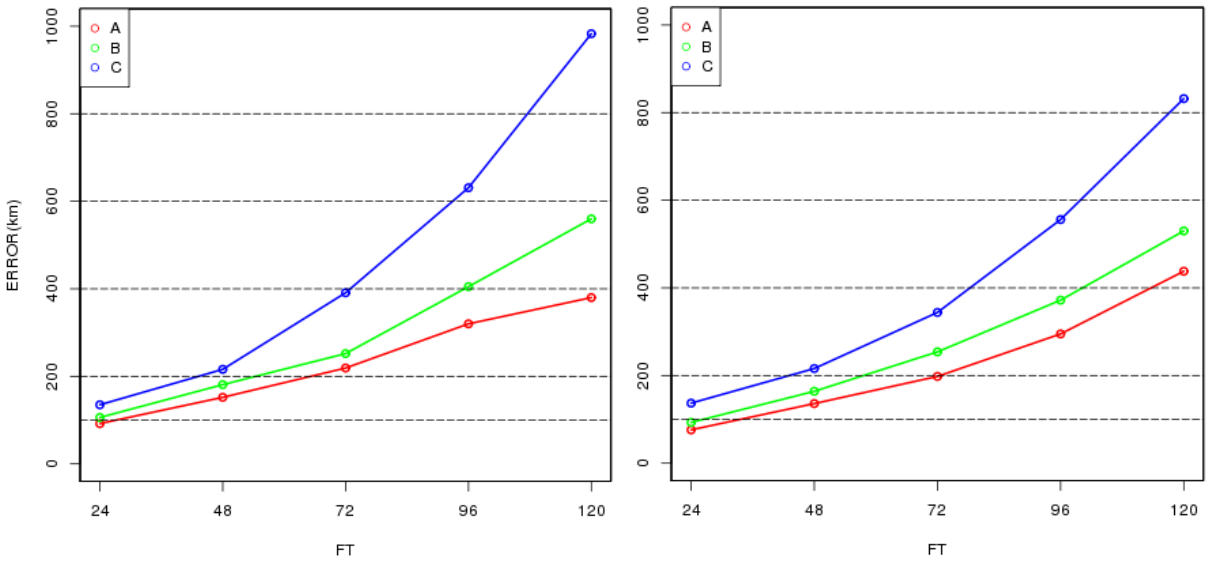

Figure 8. Relationship between probability-circle radii and confidence levels for TEPS and GEPS

Left: TEPS; right GEPS; red, green and blue circles/lines: confidence levels A, B and C, respectively

Table 6. Radius differences for 96- to 120-hour forecasts between TEPS and GEPS

(a) TEPS

Forecast time [h]	Direction of movement	Probability-circle radii [nm] (confidence level)	
		V ≤ 10 kt	V > 10 kt
96	NW	170(AB)/240(C)	170(AB)/240(C)
	Other	220(AB)/325(B')/425(C)	260(AB)/325(B')/425(C)
120	NW	200(AB)/350(C)	200(AB)/350(C)
	Other	270(AB)/450(B')/500(C)	325(AB)/450(B')/500(C)

(b) GEPS

Forecast time [h]	Direction of movement	Probability-circle radii [nm] (confidence level)	
		V ≤ 10 kt	V > 10 kt
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)

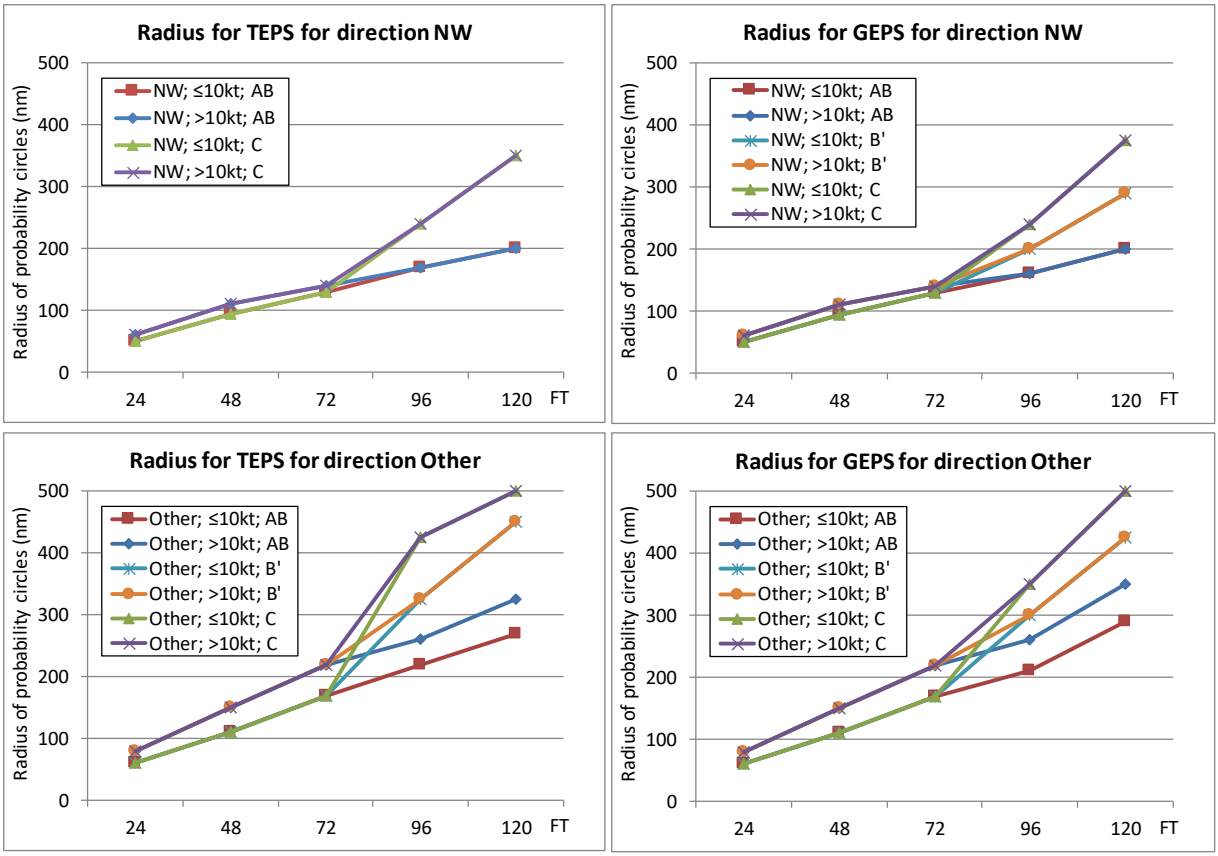

Figure 9. Changes in radius for forecast times for TEPS and GEPS
Left: TEPS; right: GEPS; top: NW; bottom: Other

5. Further work

As described in Sections 2 to 4, discontinuities have been observed in rate of radius increase between 3- to 72-hour forecasts and 96- to 120-hour forecasts due to differences in the method of radius determination. Such discontinuities remain, although partial resolution has been achieved via the June 2016 introduction of categorization based on the direction and speed of TC movement in 96- to 120-hour forecasts in consideration of system constraints and the June 2017 change from the TEPS to the GEPS for calculation of cumulative ensemble spread. A consistent method of determining radii for all forecast times is required in connection with the removal of system constraints. In this context, ensemble spread-based probability circles for all forecast times need to be developed, as TC movement alone does not appear to sufficiently represent forecast uncertainty from a statistical or physical viewpoint. In addition, development of probability circles based on spread information from overseas centers' EPSs in addition to that of JMA's needs to be considered.

6. Summary

In April 2009, JMA's RSMC Tokyo – Typhoon Center began to provide five-day track forecasts of TCs moving over the western North Pacific and the South China Sea. Track forecast uncertainty is expressed using probability circles to indicate expected TC locations at

each forecast time with a probability of 70%. Probability-circle radii for 3- to 72-hour forecasts have conventionally been statistically determined according to the direction and speed of TC movement based on the results of recent TC track forecast verification. Meanwhile, those for 96- to 120-hour forecasts have been statistically determined according to confidence levels based on cumulative ensemble spread as calculated using the TEPS.

Probability-circle radii for all forecast times were reviewed in June 2016 to make the hit ratios of 70% circles more appropriate and resolve discontinuities in the rate of radius increase between 3- to 72-hour forecasts and 96- to 120-hour forecasts due to differences in radius determination methods. The Center used the results of recent TC track forecast verification for the period from 2011 to 2015 and partially resolved the discontinuities via the introduction of categorization based on the direction and speed of TC movement in 96- to 120-hour forecasts. As a result, the radius decreased by approximately 20 to 40% in most cases.

The radius for 96- to 120-hour forecasts was also updated in June 2017 based on recent forecast results obtained using JMA's new GEPS, which was introduced in January 2017 as a replacement for the TEPS and WEPS. Changes in the radius calculated using the GEPS for forecast times were smoother than those of TEPS, reflecting changes in model characteristics. As a result, the situation of rapid radius growth in 72- to 96-hour forecasts was mitigated.

Discontinuities in the rate of radius increase between 3- to 72-hour forecasts and 96- to 120-hour forecasts remain, although partial resolution has been achieved as a result of the reviews described above. For further consistency, ensemble spread-based probability circles for all forecast times need to be introduced. In addition, development of probability circles based on spread information from overseas centers' EPSs in addition to that of JMA's needs to be considered.

References:

Kishimoto, K., 2010: JMA's five-day tropical cyclone track forecast. RSMC Tokyo – Typhoon Center Technical Review, 12, 55 – 63.

Kyouda, M. and M. Higaki, 2015: Upgrade of JMA's Typhoon Ensemble Prediction System. RSMC Tokyo – Typhoon Center Technical Review, 17.

Mannoji, N., 2005: Reduction of the radius of probability circle. RSMC Tokyo – Typhoon Center Technical Review, 8, 1 – 9.

Narita, M., 2015: Probability Circles Representing the Uncertainty of Tropical Cyclone Track Forecasts. RSMC Tokyo – Typhoon Center Technical Review, 17.

Tokuhiro, T., 2018: Introduction to JMA's new Global Ensemble Prediction System. RSMC Tokyo – Typhoon Center Technical Review, 20 (this issue).