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A 28-Year Climatological Analysis of Size Parameters for Northwestern Pacific Tropical Cyclones

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ABSTRACT

A 28-year best track dataset containing size parameters that include the radii of the 15.4 m s^{-1} winds (R15) and the 25.7 m s^{-1} winds (R26) of tropical cyclones (TCs) in the Northwestern Pacific, the NCEP/NCAR reanalysis dataset and the Extended Reconstructed Sea Surface Temperature (ERSST) dataset are employed in this study. The climatology of size parameters for the tropical cyclones in the Northwestern Pacific from 1977 to 2004 is investigated in terms of the spatial and temporal distributions. The results show that the major activity of TCs in the Northwestern Pacific is from July to October. A majority of TCs lie over the ocean west of 150°E, and a few TCs can intensify to the Saffir-Simpson (S–S) categories 4, 5. Both R15 and R26 tend to increase as the tropical cyclones intensify. The values of R15 and R26 are larger for intense TCs in the Northwestern Pacific than in the North Atlantic generally. Both R15 and R26 peak in October, and before and after October, R15 and R26 decrease, which is different from the case in the North Atlantic. The smaller R15s and R26s occur in a large range over the Northwestern Pacific, while the larger R15s and R26s mainly lie in the eastern ocean from Taiwan Island to the Philippine Islands where many tropical cyclones develop in intense systems. The tropical cyclones with size parameters of R15 or R26 on average take a longer time to intensify than to weaken, and the weak tropical cyclones have faster weakening rates than intensification rates. From 1977 to 2004, the annual mean values of R15 increase basically with year; during the 28-year period, the value of R15 increases by 52.7 km, but R26 does not change with year obviously.

Key words: climatology, size parameters of tropical cyclones, Northwestern Pacific, a 28-year best track dataset

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1. Introduction

Tropical cyclones (TCs) are intense atmospheric vortices that develop over the warm tropical oceans. Severe TCs produce destructive winds, high surges, torrential rains and severe floods, usually causing significant loss of property and life. About 26 TCs formation in the Northwestern Pacific each year (Gray, 1985). The TC intensity is often used to estimate the damage potential of a TC (Landsea, 1993). However, the horizontal extent of damaging winds (measured by the radius of gale-force winds), rainfall distribution and amount, and the height of the storm surge are additional important damage potential parameters. The intensity characteristic of TCs is often described by three parameters, which are intensity, strength and size (Holland and Merrill, 1984). The intensity of TCs is associated with not only a uniform flow and β-effect (Duan et al., 2004) but also vertical shear (DeMaria, 1996; Frank and Ritchie, 2001). Merrill (1984) compared the large and small tropical cyclones in the Northwestern Pacific, and found that the size of TCs changes with season and region, and pointed out that the size of TCs is correlated with the intensity. It was found there is a minor relationship between the radius of the outermost closed isobar (ROCI) and maximum

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wind speeds for both Atlantic TCs and Pacific TCs. Wang and Wu (2004) pointed out that the change in TC strength is closely related to the change in TC size. Chen and Shikuo (1997) found that the change in TC size is mainly determined by the inertial and static stabilities.

Several previous studies have concerned the size evolution of TC circulations. Using the ROCI bounding each storm as an index of comparative size, Brand (1972) found that comparatively small TCs tended to occur during February whereas the largest TCs occurred during October in the western North Pacific. Cocks and Gray (2002) classified TCs according to the size of their outer circulations into groups termed small, medium, and large. And they revealed that larger (smaller) TCs in their early life cycle develop into mature larger (smaller) TCs, and found that the larger TCs tend to attain maximum values of radii of the 15 m s^{-1} winds in locations to the west of 135°E, whereas the smaller TCs tend to maximize further to the east.

An in-depth analysis of TC outer wind structure by Weatherford and Gray (1988a,b) was based entirely on aircraft reconnaissance data. In those studies, an "outer core strength" (OCS) parameter was derived for the average wind speed in the region extending from 1.08° to 2.58° latitude from the TC centers. This OCS parameter was found to be highly correlated with R15 as measured by aircraft. However, changes of OCS during intensification were observed to be small compared to changes in minimum central pressure (MCP), thereby indicating a poor relationship between time variations of OCS and MCP. Weatherford and Gray (1988a) defined the "inner core" of a TC to extend from the center out to a 111-km (1.08° latitude) radius. The radial distance from 111 to 278 km (2.58° latitude) represents the "outer core". The inner core consists of the strongest winds and heaviest rainfall rates, while outer-core winds are important to outer-radius wind damages and possible storm surges. Inner-core changes often occur independently from outer-core changes.

The size of a TC is an important parameter, and it may influence the TC track. To predict the size of destructive TC wind is a very important issue for weather forecasters. So the characteristics and evolution of TC size need to be better understood for forecasters. Kimball and Mulekar (2004) studied the climatology of size parameters for North Atlantic TCs. However, such studies about the western North Pacific have not been reported in the literature. This study will briefly discuss temporal and spatial distributions of TCs and will then explore statistical properties of the two size parameters—the radii of the 15.4 m s^{-1} winds (R15) and the 25.7 m s^{-1} winds (R26) of tropical cyclones—using TC data covering a 28-yr period (1977–2004) of Northwestern Pacific TC size measurements. The climatology of TCs size parameters in the Northwestern Pacific will provide weather forecasters with important statistical information about TC winds in that area.

2. Data and methods

The atmospheric climatological data are cited from the NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) global atmospheric reanalysis dataset, which are gridded onto a 2.5° × 2.5° latitude-longitude grid. The climatological sea surface temperature (SST) data are cited from the ERSST (Extended Reconstructed Sea Surface Temperature, from the National Climatic Data Center, North Carolina), which are gridded onto a 2.0° × 2.0° latitude-longitude grid. The monthly means of these datasets data are used in this study.

The best track (BT) data of tropical cyclones in the western North Pacific and the South China Sea are provided by the RSMC (Regional Specialized Meteorological Center) Tokyo-Typhoon Center, which is operated by the JMA (Japan Meteorological Agency), under the framework of the World Weather Watch (WWW) Programme of the World Meteorological Organization (WMO). The data contain track, intensity and four size-parameter information every 6 h for tropical cyclones from 1977 to 2004. The information of the BT data obtained by operational data sources is a clearly defined source of reliable information. The raw BT data files contain 738 tropical cyclones (TCs),

Table 1. List of original parameters contained in the JMA TC best track dataset and used in this study. Original units have been converted to SI units.

Variable	Description	Units
No	Tropical cyclone ID number	-
Name	Tropical cyclone name	-
Year	Tropical cyclone year	-
Month	Month of tropical cyclone	-
Day	Day of tropical cyclone	-
Time	Hour of observation, every 6 h	-
Grade	Grade of tropical cyclone	-
Lat.	Latitude	°N
Lon.	Longitude	°E
Psmin	Center pressure of tropical cyclone	hPa
$V_{\max}$	Maximum winds	m s^{-1}
R26L	The longest radius of 25.7 m s^{-1}	km
R26S	The shortest radius of 25.7 m s^{-1}	km
R15L	The longest radius of 15.4 m s^{-1}	km
R15S	The shortest radius of 15.4 m s^{-1}	km

17174 records of R15 size parameters and 9863 records of R26 size parameters observed at 6-h intervals. A summary of all the variables contained in the BT dataset is presented in Table 1. The variables R15 and R26 have records for the longest and the shortest radius at each observation time. In this study, only the single symmetric values of R15 and R26 are analyzed by averaging their respective the longest radius and shortest radius.

Only the R15 and R26 are contained in this dataset, so only the tropical systems with maximum wind speeds greater than 15.4 m s^{-1} are included in this analysis. The size parameter dataset does not contain the tropical depressions (TDs) that did not develop into TCs. In this analysis, the TCs contain tropical storm (TS) and Saffir-Simpson Hurricane scale 1–5 (S–S H1–H5).

The statistical methods of analysis in this study are basically consistent with the methods of Kimball and Mulekar (2004), who studied size parameters of Atlantic TCs from 1988 to 2002. The statistical software package Minitab was used in the analysis, and the distributions of the data were examined using histograms and boxplots. If the distribution is skewed or there are outliers, the median was used rather than the means. A Student's t-test was used to compare the means of two groups, and the analysis of variance (ANOVA) technique was used to compare the means of more than two groups. On the other hand, Mood's median test (Conover, 1999) was used to compare the medians of two or more groups having skewed distributions with outliers. To study the relationship between two numerical variables, Pearson's correlation coefficient was used. Furthermore, some comparisons of size parameters were made between the Northwestern Pacific TCs and the North Atlantic TCs.

3. Climatological analysis of TC size parameters

At first, we want to simply introduce the distributions the TCs that possess of R15 and R26 values. Figure 1 shows the temporal distributions of 6-hourly TC observations from June to November over the Northwestern Pacific. Actually, the TCs may occur in every month of a year, however the distributions in those main months are given here. It is clear that most of the activity of TCs is from July to October; earlier and later than this period, the activity of TCs tapers off. Figures 2a–f show the spatial distributions of 6-hourly BT observations by the maximum category (TS, H1–H5) of a TC obtained. Here, the different TC categories use different symbols. Many TCs form in the intertropical convergence zone (ITCZ) and in the tropical easterly winds of the low latitudes in the Northwestern Pacific, then move to the west or northwest by the beta effect and steering winds in the south or southwest part of the subtropical high. Some of the TCs travel to midlatitudes, meet westerlies, then recurve and move toward the northeast. Many TCs move toward the west or northwest, and make landfall and then disappear. A majority of TCs lie on the ocean west of 150°E, and a few TCs can intensify to the H4 and H5 S–S categories.

Table 2 lists the statistical properties of the R15 and R26 size parameters of all TCs in the Northwestern Pacific basin from 1977 to 2004, which include the 10%, 25%, 50% (or median), 75%, and 90% quantiles; the minimum and maximum observations in the sample; and the mean and standard deviations. These properties give an idea of the outline of the frequency distribution of the R15/R26 size parameter. The distribution of R26 is right-skewed with 12 outliers on the higher end (Fig. 3); the R26 distribution ranges from 18.5 km to 463.0 km; the mean R26 is 150.6 km with a standard deviation of 68.2 km. The median of R26 is 138.9 km, which is smaller than the mean value owing to the result of outliers, where about 50% of R26 values range from 92.6 km to 185.2 km. At least 90% of R26 observations are at or below 240.8 km, and only 10% of R26 values lie between 240.8 km and 463.0 km. The distribution of R15 is slightly right-skewed with 4 outliers on the higher end (Fig. 3); the R15 distribution ranges from 37.0 km to 926.0 km; the mean R15 is 350.0 km with a standard deviation of 162.6 km. The median of R15 is 324.1 km, which is smaller than the mean value owing to the result of outliers, too. About 50% of R15 values range from 222.2 km to 463.0 km, and only 10% of R15 values lie between 555.6 km and 926.0 km, which is located on the higher end of the spectrum. These indicate that TCs come in a wide range of sizes. The statistical results show that the

Table 2. Statistical properties of the distributions of the two TC size parameters discussed in this paper, for NW Pacific TCs, between 1977 and 2004.

		R26 (km)	R15 (km)
Quantiles	Maximum	463.0	926.0
	90%	240.8	555.6
	75%	185.2	463.0
	Median	138.9	324.1
	25%	92.6	222.2
	10%	74.1	157.4
	Minimum	18.5	37.0
Moments	Mean	150.6	350.0
	Std dev	68.2	162.6
	No. of records	9863	17174

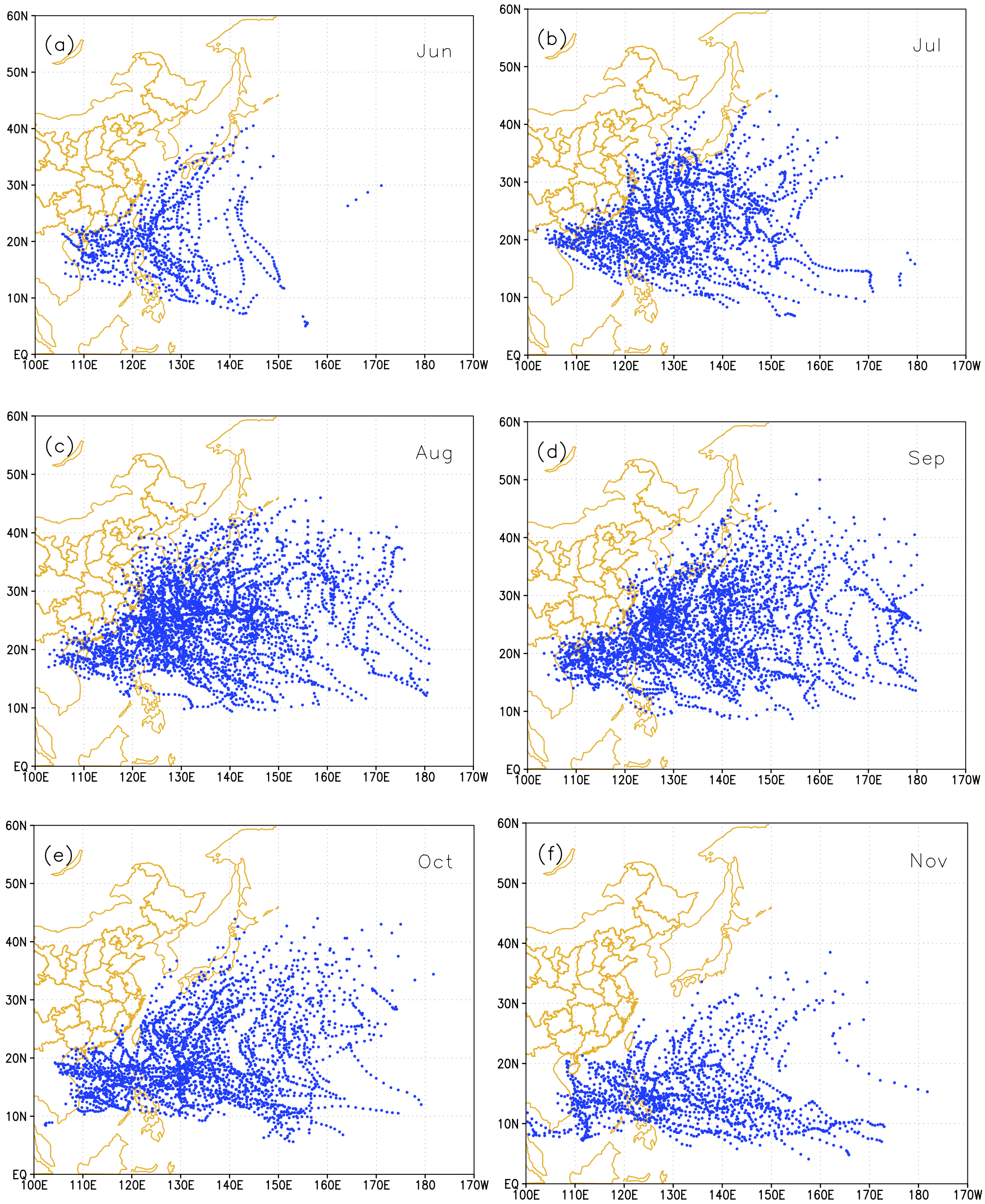

Fig. 1. Location of all TCs observation in the BT dataset by month: (a) June, (b) July, (c) August, (d) September, (e) October, (f) November.

mean R26 (150.6 km) in the Northwestern Pacific is little larger than the mean R26 (141.4 km) in the North Atlantic, and the mean R15 (350.0 km) in the Northwestern Pacific is close to the ROCI (351.9 km) in the North Atlantic.

Figure 4 shows the medians of the two size parameters R15 and R26 stratified by TS and S-S categories. The medians indicate that as the TCs increase in intensity, the R15 moves far off the outer core and the R26 moves far off the inner core, and the values of R15 and R26 both increase as the TCs intensify. That is to say, the more intense the TC is, the larger R15 and R26 are in the Northwestern Pacific. But in the North Atlantic the situation is different. It can be found that the values of R15 and R26 are larger for intense TCs in the Northwestern Pacific than in the North Atlantic generally.

The medians of size parameters changing with TC

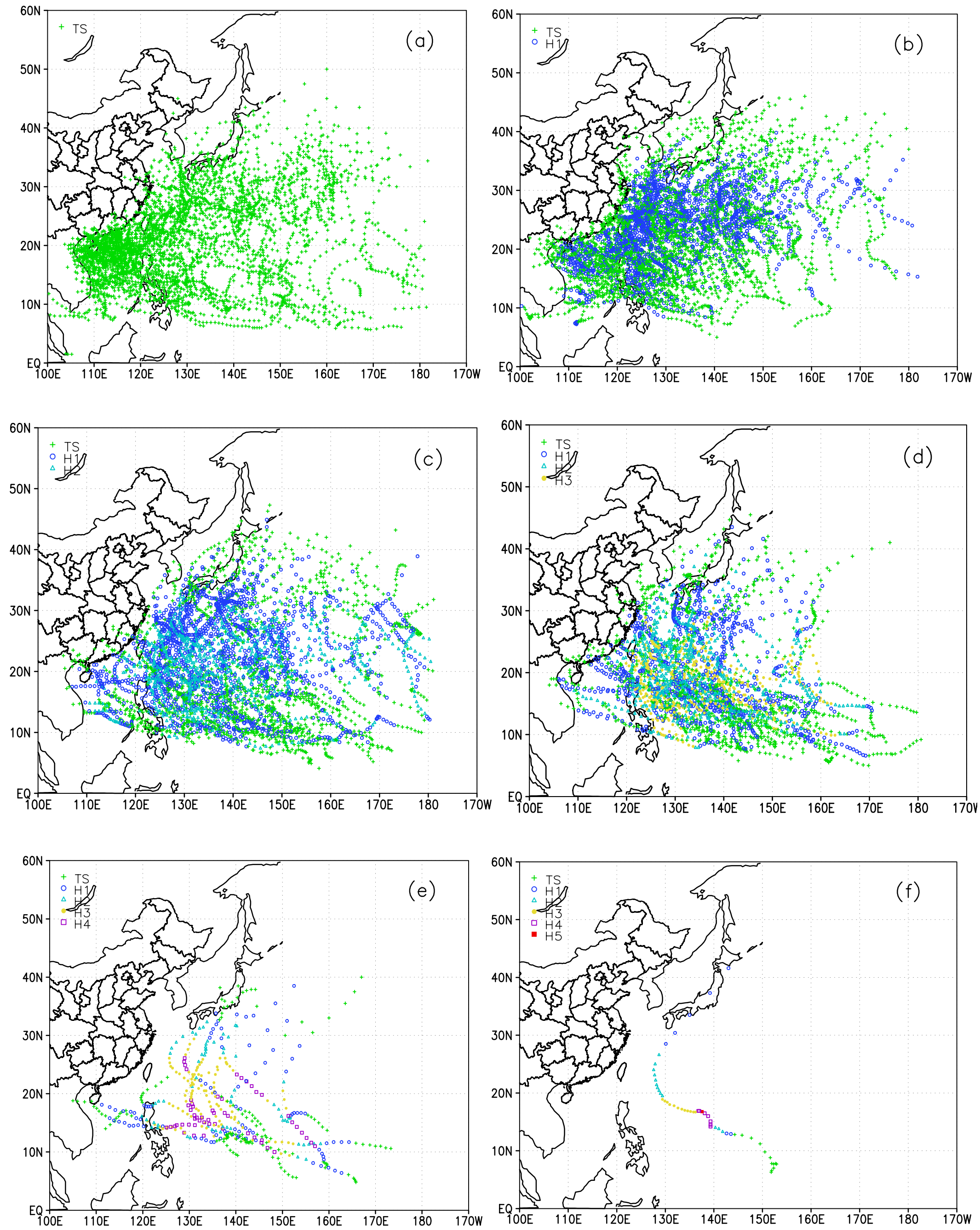

Fig. 2. Location of TCs by maximum obtained category: (a) TS, (b) H1, (c) H2, (d) H3, (e) H4, and (f) H5. Each symbol denotes a different category, as indicated in the legend.

intensification tendency are shown in Fig. 5. Mood's median test indicates that the difference between the medians of R15 and the medians of R26 is statistically significant ($p<0.001$). The intensifying TCs have minimum values of R15 and R26. The weakening TCs have maximum values of R15, and the TCs in a steady state have maximum values of R26. The TSs and H1s are predominant for weakening, steady state, and intensifying TCs, because the TSs and H1s include many pre-mature and post-mature phases of intense TCs (Fig. 6). The percentage of intensifying TCs is larger than the percentage of weakening and steady state TCs for the weaker systems that include TSs, H1s, and H2s. For the intense systems that include H3, H4, and H5, the percentage of the weakening TCs is larger than the percentage of the intensifying TCs,

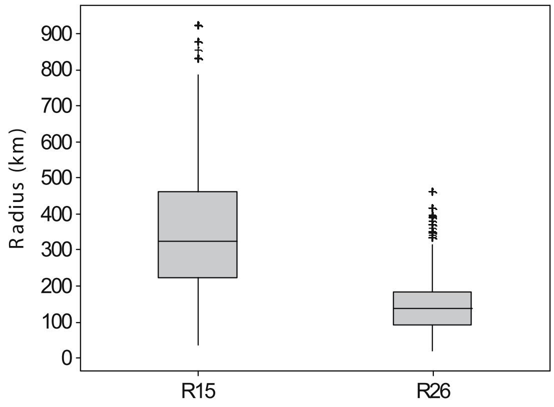

Fig. 3. Boxplots of radius stratified by R15 and R26.

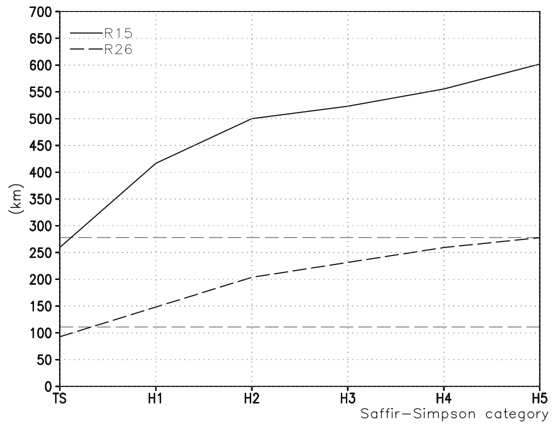

Fig. 4. Medians of the two size parameters stratified by TS and the S–S categories. Thin dashed lines mark the boundaries of the inner and outer cores.

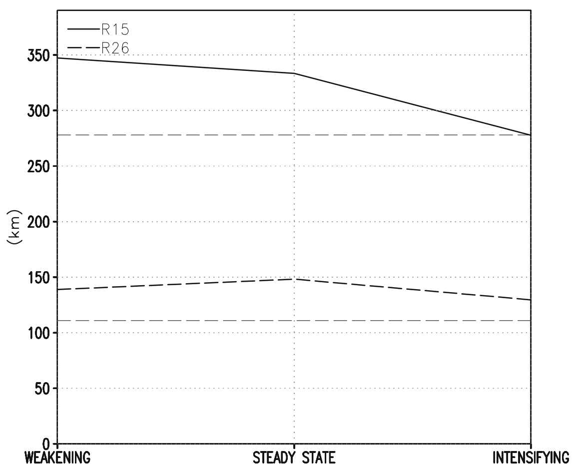

Fig. 5. Medians of R15 and R26 parameters stratified by the intensification tendency. Thin dashed lines mark the boundaries of the inner and outer cores.

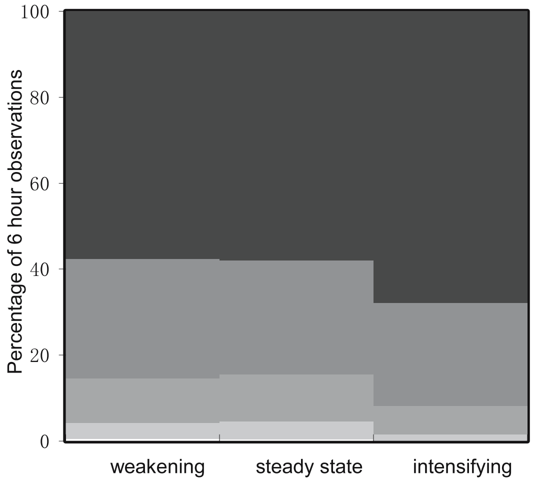

Fig. 6. Percentage of 6-hourly TS (black) through H5 (white) observations by intensification tendency.

because many very intense TCs cannot intensify further but only weaken. By calculating, we find that each TC with size parameter of R15 on average spends about 37 hours intensifying and 32 hours weakening. And each TC with size parameter of R26 on average spends about 29 hours intensifying and 28 hours weakening.

3.1 *Temporal changes of size parameters*

Figure 7 shows the annual means of R15 and R26 from 1977 to 2004. The annual variations of R15 and R26 are visible; and the maximum values for R15 and R16 occur in 1997; but the minimum values of R15 and R26 occur in 1979 and 1977, respectively. A good correlation for annual mean R15 and annual mean R26 can be seen, the correlation coefficient between R15 and R26 is 0.586, and the result is significant at the 5% level ($p=0.001$). Basically, the mean R15 increases with year, and the value of R15 increases 52.7 km during the 28-year period. But the mean R26 does not change with year obviously. On the effect factors' side, the annual mean of SST increases and vertical shear decreases with year in the main region of the Northwestern Pacific (Fig. 8). Two favorable factors for TC development may cause R15 to increase, but R26 changes unclearly.

The median of R15 changing with month is shown in Fig. 9a. From April to October, the median increases or remains unchanged with month, only the median in May is equal to that in June, and the median reaches a maximum value in October. From November to December, the median decreases with month. Figure 9b shows the median of R26 changing with the month. In October, the median of R26 has a maximum value, and before and after October, the median decreases or

Table 3. Percentage of 6-hourly TS and S–S category observations during April to December.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TS	67.38	67.15	67.51	64.13	63.05	55.43	53.00	55.02	65.88
H1	22.14	19.14	25.44	23.74	27.30	29.98	29.50	23.37	19.88
H2	9.52	10.53	5.40	9.39	6.97	11.38	11.18	12.82	11.48
H3	0.95	2.07	1.65	2.48	2.59	3.05	5.18	8.28	2.77
H4	0.00	1.12	0.00	0.27	0.08	0.17	1.11	0.51	0.00
H5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

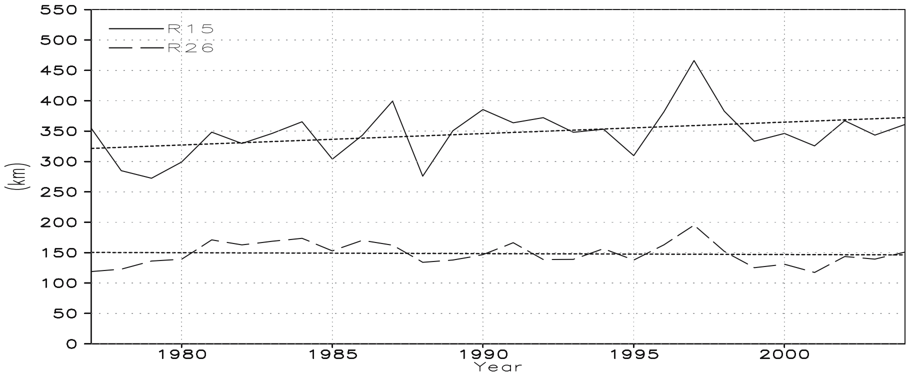

Fig. 7. Time series of the annual means of R15 and R26 from 1977 to 2004. Short dashed lines are trend lines.

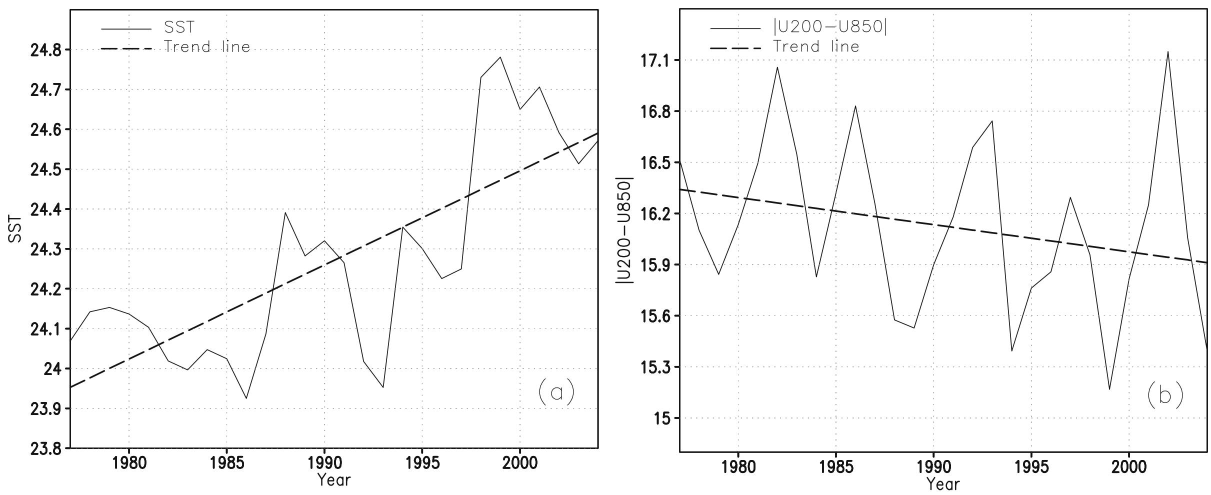

Fig. 8. (a) Annual means of SST (unit: °C) and (b) the absolute value of zonal-wind vertical shear (unit: m s^{-1}) between 200 hPa and 850 hPa during May to December over the region (5°–45°N, 110°–180°E) from 1977 to 2004.

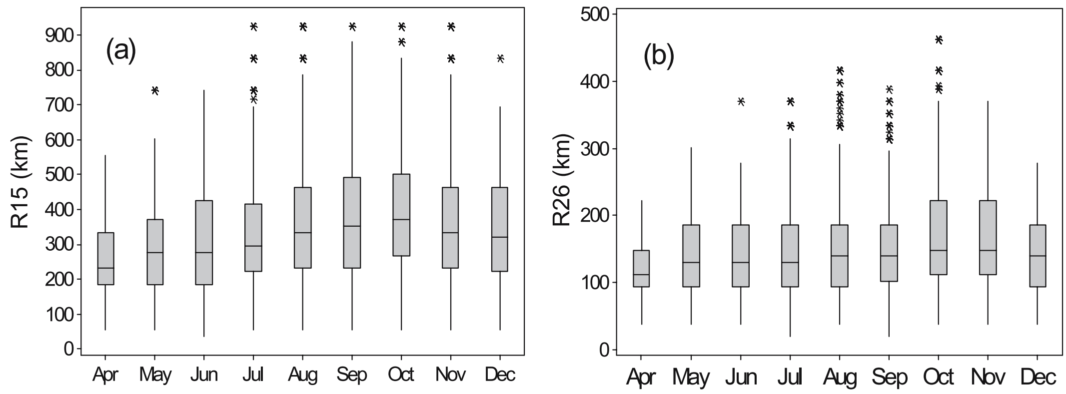

Fig. 9. Boxplots of (a) R15 and (b) R26 stratified by month.

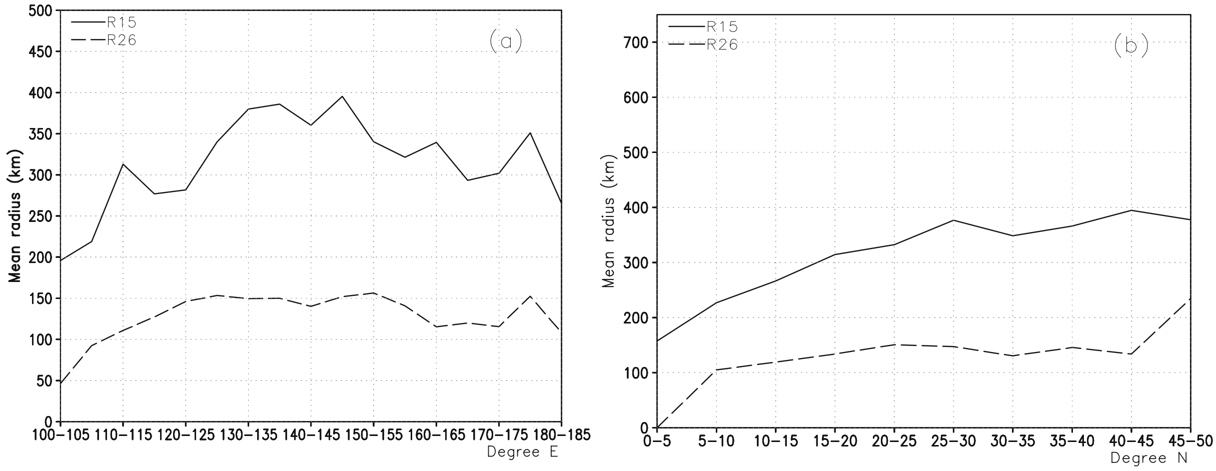

Fig. 10. Mean values of R15 and R26, changed by (a) 5° longitude bins and (b) 5° latitude bins.

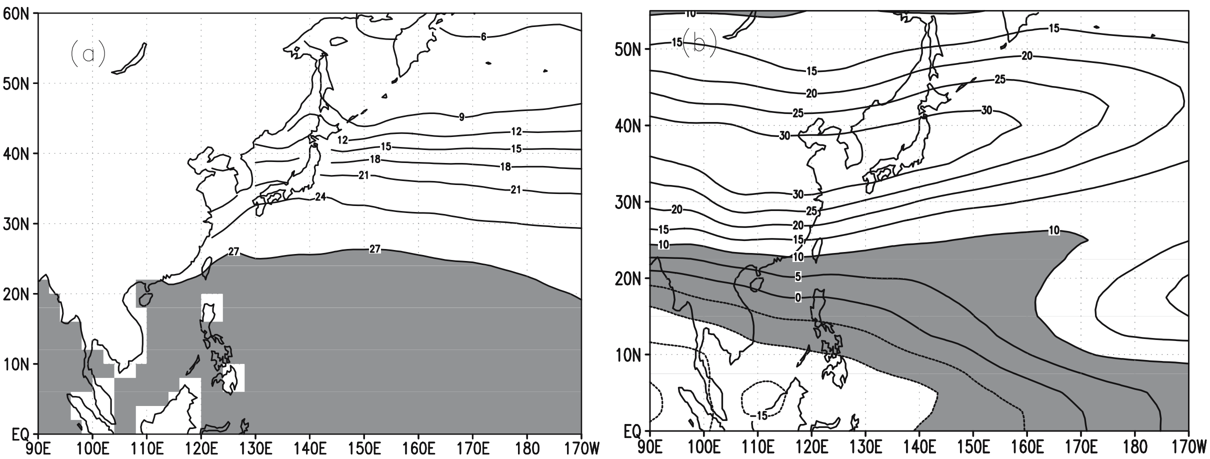

Fig. 11. (a) Climatology of SST (unit: °C) during May to December for the period 1977–2004 with contour interval of 3°C, and the shaded area indicates SST greater than 27°C. (b) Climatology of zonal-wind vertical shear (unit: m s^{-1}) between 200 hPa and 850 hPa during May to December for the period 1977–2004, with contour interval of 5 m s^{-1}, and the shaded area indicates absolute value less than 10 m s^{-1}.

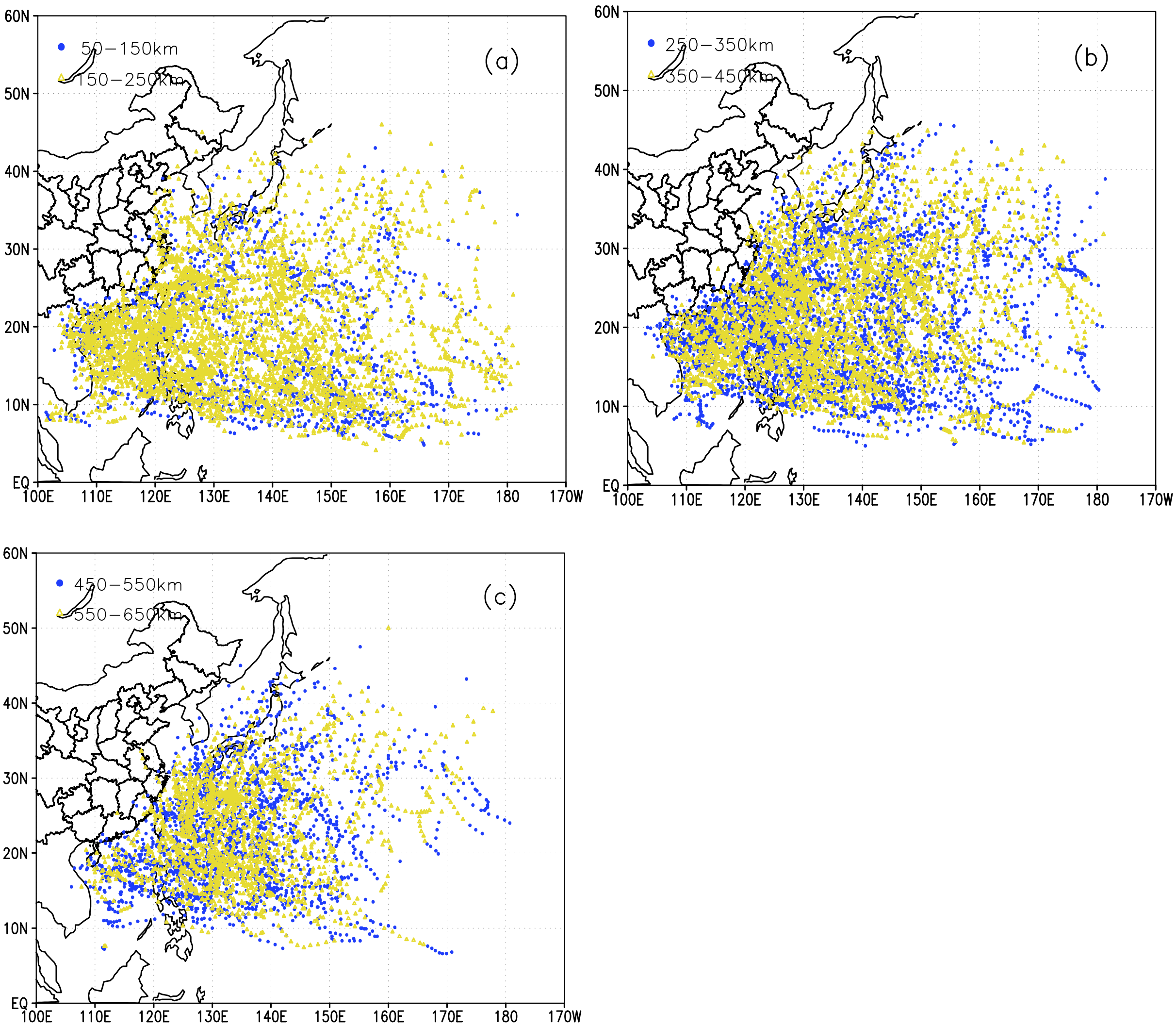

Fig. 12. Spatial distribution of R15 observations stratified by 100-km bins: (a) 50–250, (b) 250–450, (c) 450–650 km.

remains unchanged far outside October. The percentage of 6-hourly TS and S–S category observations during April to December is presented in Table 3. Due to the intense TCs having large R15 and R26 (Fig. 4), the largest proportion of the intense TCs (H1–H5) occurs in October, so the R15 and R26 have maximum values in that month. But the R26 in the North Atlantic has two peaks in July and October, respectively.

3.2 *Spatial changes of size parameters*

The mean values of R15 and R26 by 5° longitude bins show that R15 has large values between 130°E and 150°E; at the same time, the R15 has two small peaks in the longitude bins of 110°–115°E and 175°–180°E, respectively. Moreover, the R26 has large values between 120° and 155°E, at the same time, the R26 has a small peak in the longitude bin of 175°–180°E (Fig. 10a). The mean values of R15 and R26 indicate that R15 and R26 are mainly increasing with latitude to the south of 50°N on account of more intense TCs with large sizes reaching higher latitudes. The mean value of R15 peaks in the 40°–45°N bin and R26 peaks in the 45°–50°N bin because more intense TCs with large sizes arrive in that region (Fig. 10b). The distributions of mean R15 and R26 with longitude and latitude are correlated with the distributions of SST and zonal-wind vertical shear over the Northwestern Pacific (Fig. 11). The warm SST and weak vertical shear are beneficial to TC development. The R15 and R26 have small values when the TCs are in the weak phase, and the R15 and R26 have large values when the TCs are intense systems. So the large values of R15 and R26 mainly occur on the ocean between 120°E and 155°E.

The smallest R15s occur in the north of the South China Sea and on the coastal band of South China

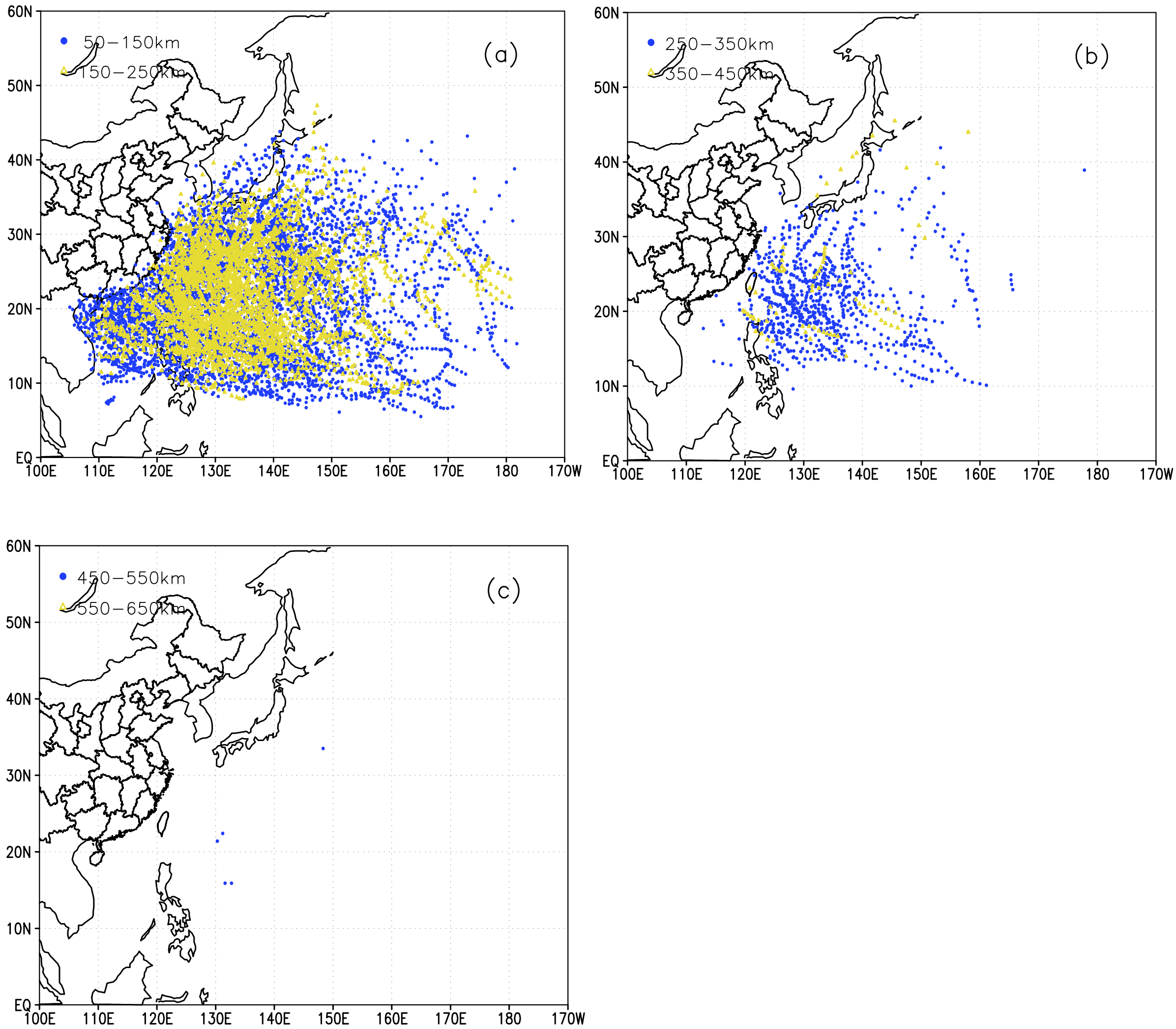

Fig. 13. Spatial distribution of R26 observations stratified by 100-km bins: (a) 50–250, (b) 250–450, (c) 450–650 km.

(Fig. 12a). The larger R15s are located predominantly on the range of the coastal band and ocean from 10°N to 30°N due to the many intense and recurving large-size TCs in this area (Figs. 12b, c).

A large number of the smallest R26s occur in the range to the east of East Asia between l0°N and 35°N (Fig. 13a). A limited number of larger R26s lie in the east of the ocean from Taiwan Island to the Philippine Islands where warm SSTs are favorable for TCs to the intensify and reach a large size (Fig. 11a, Fig. 13b). Very few R26s are larger than 450 km (Fig. 13c) due to the low number of TCs intensifying up to the H5 category in the BT dataset (Fig. 2f).

4. Summary and discussion

Weatherford and Gray (1988a,b) analyzed size parameter characteristics only using 3 years of flight data of 66 Northwestern Pacific tropical cyclones. In this study, the tropical cyclone size parameters of more than 20 years and 738 TCs in the Northwestern Pacific basin are used to investigate the climatology of tropical cyclone size parameters of R15 and R26. The following results are obtained.

(1) The most activity of TCs is from July to October in the Northwestern Pacific, and before and after this period, the activity of TCs tapers off. Many TCs form in the ITCZ and in the tropical easterly winds of the low latitudes in the Northwestern Pacific. And a majority of TCs lie on the ocean to the west of 150°E, however, a few TCs can intensify up to the H4 and H5 S-S categories.

(2) The R15 distribution ranges from 37.0 km to 926.0 km, and the mean R15 is 350.0 km. The R26 distribution ranges from 18.5 km to 463.0 km, and the mean R26 is 150.6 km. Both R15 and R26 tend to

increase as the TCs intensify. The values of R15 and R26 are larger for intense TCs in the Northwestern Pacific than in the North Atlantic generally.

(3) The intensifying TCs have minimum R15 and R26 values, the weakening TCs have maximum R15 values, and the TCs in steady state have maximum R26 values. The tropical cyclones with size parameters of R15 or R26 on average take a longer time to intensify than to weaken. From 1977 to 2004, R15 increases with year, and the values of R15 increase 52.7 km during the 28-year period, but R26 does not change with year obviously.

(4) The largest proportion of intense TCs (H1-H5) occurs in October; both R15 and R26 have maximum values in the Northwestern Pacific; before and after October, R15 and R26 decrease or remain unchanged far outside of October; these phenomena are different from what occurs in the North Atlantic. The smaller R15s and R26s occur in a large range over the Northwestern Pacific, the larger R15s and R26s lie in the east of the ocean from Taiwan Island to the Philippine Islands. Very few R26s can reach larger than 450 km in the Northwestern Pacific.

Additionally, because there are only R15 and R26 size parameters in the BT data, we await studies of other size parameters covering a long time series from other datasets in the future.

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