Monthly variation and spatial distribution of quadrant tropical cyclone size in the Western North Pacific

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Abstract

With the tropical cyclone (TC) size parameter defined as the radius of 17-m·s\(^{-1}\) oceanic surface wind, 225 TC cases were recorded in the western North Pacific during 2000–2009 based on the QuikSCAT near-surface wind vector database and the best-track dataset. In accordance with the symmetry index (the ratio of minimum and maximum quadrant sizes), the TCs were classified into symmetric and asymmetric structures. The asymmetric TCs were divided into four types: the northeast, southeast, southwest, and northwest. The spatio-temporal characteristics of these TC types were further investigated. The monthly variation and the spatial distribution of maximum quadrant TC size exhibited significant differences among the four types. By contrast, the quadrant size of the symmetric TCs from June to November showed few changes (2.6°–2.7° latitude). It was found that the TC lifetime is an important factor affecting the quadrant TC size because of its close relationship with the activities of the western Pacific subtropical high. In addition, the climatological mean circulation also has a notable influence on the quadrant TC size through superposition of prominent background wind. Symmetric TCs are more likely to occur in the oceanic region where the background low-level wind is the weakest.

KEYWORDS
circulation, lifetime, quadrant, size, symmetry, tropical cyclone

1 | INTRODUCTION

Tropical cyclone (TC) size is an important parameter which has attracted increasing attention. Large storms are likely to cause both greater wind damage and larger storm surge, posing a significant threat to lives and property. Therefore, a more comprehensive understanding of TC size is of great importance.

There is so far no universal definition for TC size. When few surface wind datasets are available, TC size is...
often defined as the radius of outer closed isobar (ROCI) observed on surface weather maps (Brand, 1972; Merrill, 1984). The shortcoming of the ROCI method is obvious owing to the subjectivity and method dependence (Knaff et al., 2014). With the development of remote-sensing technology and the related algorithms in the past two decades, more and more datasets of oceanic near-surface wind have been obtained from the early European Remote Sensing (ERS-1 and ERS-2) scatterometer (Quilfen et al., 1998) and the QuikSCAT satellite (Hoffman et al., 2003), which have been widely used in TC-related studies (Liu and Chan, 1999; Chavas and Emanuel, 2010; Knaff et al., 2014; Chavas et al., 2016) because of the simpler calculation of wind speed radius. At present, the general consensus on the definition of TC size is the radius of the area with a wind speed of 15 m·s⁻¹ (R15: Shoemaker, 1989; Cocks and Gray, 2002; Lee et al., 2010) or of 17 m·s⁻¹ (R17: Lu et al., 2011; Chan and Chan, 2012, 2015; Guo and Tan, 2017). On the one hand, Frank and Gray (1980) found that the occurrence frequency of 15-m·s⁻¹ wind around TCs increases with TC size. This is known as the mean ROCI. On the other hand, deviation exists between the QuikSCAT wind and the actual value. For example, wind with a speed of less than 15 m·s⁻¹ is often overestimated by QuikSCAT because of surface roughening and signal scattering, whereas wind with a speed of more than 20 m·s⁻¹ is usually underestimated, because the rain attenuates scattering signals (Atlas et al., 2001; Stiles and Yueh, 2002; Brennan et al., 2009). Previous studies have focused on the relationship between TC intensity and size, showing that, typically, inner-core intensity change precedes change in the storm outer-core wind (Merrill, 1984; Maclay et al., 2008; Chan and Chan, 2012). Maclay et al. (2008) demonstrated through a study of the trends in the kinetic energy with respect to intensity and structure that TCs generally either intensify and do not grow or weaken/maintain intensity and grow. Hence, a very strong typhoon may not be very large, and vice versa.

The climatology of TC size over the western North Pacific (WNP), Eastern Pacific, North Atlantic (NA), and other oceanic areas has been intensively investigated (Brand, 1972; Merrill, 1984; Kimball and Mulekar, 2004; Chan and Chan, 2015). Chan and Chan (2012) found that, in midsummer (July) and late season (October), TCs are significantly larger in the WNP, while they are the largest in September in the NA. It was further revealed (Chan and Chan, 2015) that TCs over the WNP show the largest size and variance, while they are characterized by the smallest ones over the eastern North Pacific. Knaff et al. (2014) verified that small TCs are always generated at lower latitudes and westward steering, while large TCs are generally located at higher latitudes and poleward steering. Over the NA, it has been suggested (Kimball and Mulekar, 2004) that R17 usually increases when storms move poleward or westward. Moreover, the TC size also exhibits interannual variation. Chan and Yip (2003) found that TCs over the WNP tend to be larger during El Niño years than during La Niña years. Yuan et al. (2007) showed that the annual mean values of R15 increased during the period of 1977–2004.

Thus, TC size depends on many factors, such as season, region, intensity, lifetime, track, and subtropical ridge activity. It has been found that, although the size of the convective inner core is closely related to TC intensity, the size of the broad outer nonconvective area does not vary with the same (Chavas et al., 2016). TC lifetime and seasonal subtropical ridge activities have been considered as potential factors affecting TC size and intensity (Chan and Chan, 2012). Atmospheric circulation patterns have also been reported to have a notable influence on TC size (Liu and Chan, 2002). Lee et al. (2010) believed that mid-to-large TCs are likely to develop under monsoon-related formation patterns, and small TCs tend to form under synoptic wave patterns. As for large TCs, the existence of strong low-level southwesterly winds in the outer core area has important effects on TC size throughout the intensification period. Carr and Elsberry (1997) proposed that the northwestward motion of TC is consistent with a larger northwestward beta-effect propagation, which favors a larger outer core wind speed. Moreover, Lin et al. (2015) investigated the TC size by using rainfall area, which is controlled primarily by the relative sea surface temperature (SST), defined as the SST difference between the TC environment and the tropics (30°S–30°N). Additionally, the sensitivity of TC size to SST (Wang and Toumi, 2018) has also been studied, as along with microphysics schemes (Chan and Chan, 2016).

There have been a large number of studies with respect to mean TC sizes (Knaff et al., 2014; Chan and Chan, 2015), and TC asymmetry has also been investigated with satellite data in some studies (Alvey et al., 2015; Klotz and Jiang, 2016, 2017). However, relatively few studies have focused on the quadrant size of asymmetric TCs. Therefore, the climatology of quadrant TC size and the impact of climatological mean circulation on quadrant TC size are discussed in this work. The remainder is organized as follows: in Section 2, datasets and methods are briefly illustrated; in Section 3, the monthly variation and spatial distribution of quadrant TC size for asymmetric and symmetric TCs are described, as well as the possible impacts of the climatological atmospheric circulation. The summary and discussion are provided in Section 4.
2 DATA AND METHOD

2.1 Data

Aiming at retrieving the oceanic surface wind data with a swath width of approximately 1,800 km, QuikSCAT is a polar-orbiting satellite that served from 1999 to 2009. In this study, the gridded QuikSCAT data during 2000–2009 from the Remote Sensing Systems database were adopted with a spatial resolution of 0.25° × 0.25° and a time interval of 12 hr. The best-track dataset with a 6-hr interval was obtained from the International Best Track and Archive for Climate Stewardship (Knapp et al., 2010), providing specific information about the location and intensity, as well as the TC size parameters estimated by the Joint Typhoon Warning Center (JTWC) from 2001. The 34-kt wind radii of four quadrants recorded by JTWC were also used in the study. The atmospheric circulations were examined using the ERA-Interim dataset during 2000–2009.

2.2 Method

Following Chan and Chan (2012, 2015), the R17 is used to represent the TC size in this study, with procedures similar to those presented by Lee et al. (2010). The best-track data from JTWC are recorded at 0000, 0600, 1200, and 1800 UTC. However, the observation time of QuikSCAT is not entirely consistent with that of the best-track data, which is mainly because the QuikSCAT observation time is greatly affected by the location of the satellite swath and is thus variable. Therefore, the TC position at the QuikSCAT observation time is obtained from temporal interpolation based on the TC center positions recorded by the JTWC.

For example, the observation time of TC Ewiniar in Figure 1b was at 0848 UTC on August 11, 2000; thus, the TC center at the time should be interpolated from related JTWC center positions at 0600 UTC and 1200 UTC. After ascertaining the TC center, the determination of R17 was performed using a method similar to that of Lee et al. (2010). The gridded QuikSCAT wind was converted to the components of tangential and radial wind in a storm-relative cylindrical coordinate system. The radial increment was 0.1° latitude, and the azimuthal resolution was 1.0° (360 data points on a circle), obtained by inverse distance interpolation. Subsequently, the azimuthally averaged tangential wind profile of the entire TC at the QuikSCAT swath time was obtained. Hereafter, R17 represents the radius at which the azimuthally averaged tangential wind speed equals 17 m·s⁻¹ outward from the maximum wind near the TC center. Because the satellite swath may not cover the entire TC, QuikSCAT wind data should cover at least 50% of the TC (Lee et al., 2010; Chan and Chan, 2012). Each size parameter represents a TC case at the corresponding QuikSCAT swath time. In other words, a single TC could undergo multiple size changes during its lifetime. Therefore, 1,229 cases were derived from 225 TCs over the WNP during 2000–2009 based on the QuikSCAT near-surface oceanic wind data. Afterward, the TCs were divided into four quadrants—northeast (NE, 0°–90°), southeast (SE, 90°–180°E), southwest (SW, 180°–270°E), and northwest (NW, 270°–360°E)—based on the Earth relative frame used by many warning centers, such as JTWC. The size of each TC quadrant can be obtained with the above-mentioned method. Eliminating missing values, the numbers of size parameters in the NE, SE, SW, and NW quadrants were 1,195, 1,220, 1,132, and 1,125, respectively. Because “TC size” and “quadrant TC size” have different meanings, the mention of “TC size” without the word “quadrant” refers to the average size of the entire TC derived from calculations at all grid points on the storm circle.

3 RESULTS

3.1 Symmetry index

The TCs can be categorized as symmetric and asymmetric. In this study, we define “symmetry index” as the ratio of minimum to maximum quadrant size. If the symmetry index equals 1, the four quadrants are equal in size. Under such an assumption, the TC is fully symmetric and round—a circumstance that, however, rarely exists. Hence, it was stipulated that a TC with a symmetry index larger than 0.7 would be considered symmetric. In fact, Alvey et al. (2015) and Klotz and Jiang (2017) presented a new method for calculating full storm symmetry. After comparing both indexes in detail (not shown), the index used here seemed reasonable. The symmetry index was used to analyze TC cases at a given time, which is generally consistent with the satellite swath time. As aforementioned, a single TC is likely to experience several symmetric and asymmetric structures during its lifetime. To ensure that four quadrant size parameters of TCs exist simultaneously, 851 cases were collected in total. As shown in Table 1, there were 198 symmetric TCs, which constituted 23.3% of the total. Correspondingly, it was observed that the majority of TC cases were asymmetric. Based on maximum quadrant size, these asymmetric TCs were classified into four types based on the Earth relative frame. The number of the NE-type TCs was 246, which constituted 37.7% of the
total asymmetric cases. For the SW type, both the case number and the maximum quadrant size were smaller than those of other types. The maximum quadrant size was introduced, because its location implied the type of a certain TC. For example, the TC with the maximum quadrant size appearing in the SW direction was defined as an SW type TC. For the NW type, the mean and median of the NW quadrant size were 2.5° latitude (278 km) and 2.86° latitude (317 km), respectively, which were both larger than those of other asymmetric types. Figure 1 shows examples of the satellite wind fields for four asymmetric TC cases. As displayed in Figure 1c, the TC Dianmu (2004) was characterized by the maximum SW quadrant size. The TC Podul (2001), which occurred in October, showed a very large NW quadrant size (Figure 1d). These examples are in good agreement with the four types of asymmetric TC, demonstrating the justifiability of the classification method.

3.2 Monthly variation and spatial distribution of maximum quadrant TC size

Figure 2 shows monthly variation of maximum quadrant size and corresponding lifetime for four types of asymmetric TC. Wang et al. (2008) proposed that TC lifetime is an important factor closely related to TC size. Chan and Chan (2012) suggested that TCs having longer lifetimes may have more time to intensify and grow through angular momentum transports, moisture convergences, upper-level divergences, and so on. Here, the TC lifetime is defined as the period from the moment when the near-center maximum wind speed first reaches 34 kt to the time of the case (the satellite swath time). The black and red lines refer to average maximum quadrant size and corresponding average lifetime, respectively. For the NE type (Figure 2a), the NE quadrant had the maximum size, the largest TC occurring in October (3.04° latitude, 3.30)
337 km), followed by the one in July (2.65° latitude, 294 km). The monthly variation of related average lifetime for the NE type exhibited different features. The occurrence of the longest lifetime (4.5 days) in July was not consistent with the peak of average NE quadrant size, although lifetime is an important factor affecting TC size. As for the SE type (Figure 2b), the peak of average SE quadrant size (3.2° latitude, 355 km) appeared in July and then decreased continuously from July to November. Consistently, the lifetime also exhibited a decreasing trend from July (3.59 days) to November (2.0 days). The average SW quadrant size for the SW type was much larger from June to August than in other months (Figure 2c). The average lifetime for the SW type mainly lasted from 2 to 3 days, which was the shortest among all types. The root-mean-square error (RMSE) for NE, SE, and SW quadrant sizes from July to October varied from 0.18° to 0.27° latitude (20–30 km). In addition, for the NW type, the average NW quadrant size and lifetime matched well, with both their peaks occurring in October. The average NW quadrant size and lifetime in October were about 3.7° latitude (410 km) and 4.5 days, respectively, which were nearly the largest in all these months among the four types (Figure 2d). The RMSE for NW quadrant sizes varied from 0.25° to 0.4° latitude (28–44 km). Although TC size is greatly influenced by lifetime, sometimes the size matches well with it, as observed in the SE and NW types, while sometimes the correlation is not evident, as exhibited by the NE and SW types. In other words, the lifetime is definitely not the only factor affecting TC size; thus, more factors need to be analyzed.

Figure 3 shows the spatial distribution of maximum quadrant size for the four types. The results indicate that most NE-type cases occur in August, September, and October, and they are spread widely in the region of 10°–30°N, 120°–160°E (red rectangle in Figure 3c). The NE quadrant size appeared to be larger to the east of 140°E than to the west, according to Figure 3c,e. For the SE type, the majority of relatively large points were located in the region shown in the blue trapezium in Figure 3b (10°–30°N, to the west of 155°E) from July to September. As for the SW types, they mostly lay in the region to the east of the Philippine Islands (green rectangle in Figure 3a, 10°–23°N, 120°–148°E). The number of points larger than 2° latitudes were obviously fewer than those of the other types, and the SW-type cases with larger sizes were more likely to be located to the west of 140°E,
which is farther westward and southward than the SE type. Most NW-type cases in September and October were located in the region with northeastward recurvature tracks, as shown in the orange quadrilateral in Figure 3d. In November, the NW-type cases were found to lie to the south of 20°N, particularly with northwestward tracks. Table 2
shows the statistical characteristics of storm motion for four types of asymmetric TC. Most NE-type cases (70%) were on the northwestward track. For the SE type, 48% of cases moved northwestward, while 43% of cases moved northeastward. Most SW-type cases moved northeastward, which was similar to the NE type. For the NW type, there were approximately half of the cases with a westward track and approximately 30% of the cases moving northeastward with a recurvature track. The average moving speed of TCs with a westward track was approximately 5 m/s, and the TCs with an eastward track usually had a greater moving speed.

In summary, the largest number of NE-type cases was located in the western North Pacific. The SW-type cases were the fewest and smallest to the east of the Philippine Islands. The SE-type cases were mainly located more eastward and northward than the SW-type ones, and the NW-type cases were mainly concentrated near the coastal region along East Asia. In other words, the spatial distributions of the four asymmetric TC types vary greatly.

Figure 4 shows the monthly and spatial features of the quadrant size for symmetric TCs. The symmetric cases usually tend to have a longer lifetime of more than 4 days compared with asymmetric ones as shown in Figures 2 and 4. The maximum quadrant size from June to November did not change considerably (2.6°–2.7° latitude, 289–300 km), demonstrating that the monthly variation was less prominent compared with that in asymmetric TCs (Figure 4a). Symmetric TCs were probably a result of the process of intensification, so the initial size of the vortex may have played an important role in determining TC size (Lee et al., 2010). Most symmetric points were located over 10°–30°N, 120°–140°E, and the spatial distribution in different months showed no prominent differences. Therefore, asymmetric TC sizes varied considerably with time, but the opposite was the case for symmetric TCs. Additionally, the climatological mean atmospheric circulation exhibited different characteristics in different months, which may explain the monthly variation and the spatial distribution of maximum quadrant TC size to some extent.

### Table 2: Statistical attributes of storm motion for TC cases

| Type  | Variable            | Moving direction |
|-------|---------------------|------------------|
|       |                     | 270–315° | 315–360° | 0–45° | 45–90° |
| NE    | Case percent        | 45%      | 25%      | 14%   | 11%   |
|       | Average moving speed (m/s) | 5.5 | 5.0 | 5.8 | 10.6 |
| SE    | Case percent        | 27%      | 21%      | 26%   | 17%   |
|       | Average moving speed (m/s) | 5.1 | 4.9 | 6.4 | 10.3 |
| SW    | Case percent        | 45%      | 22%      | 11%   | 10%   |
|       | Average moving speed (m/s) | 5.9 | 4.2 | 4.1 | 7.6  |
| NW    | Case percent        | 49%      | 6%       | 16%   | 13%   |
|       | Average moving speed (m/s) | 5.2 | 5.6 | 6.4 | 8.5  |

### 3.3 Influence of atmospheric circulation on quadrant TC size

In general, the western Pacific subtropical high (WPSH) in July extends westward to around 120°E (Su et al., 2014), which is in favor of the TCs’ northwestward movement toward eastern China. In September, the WPSH retreats eastward, generating more recurving storms, which corresponds to their longer lifetime. Consequently, the variation of seasonal WPSH movements could lead to variation of TC lifetime via the track. Moreover, the climatological low-level circulation also exhibits seasonal variations, which could affect the TC size as well.

Figure 5 shows a composite of wind at 850 hPa based on the cases of four types in their notable months. The red rectangle where the NE-type cases mostly occurred was controlled by the easterly wind, and the superposition of the easterly wind on TC was in favor of larger NE quadrant size and more NE-type cases (Figure 5a). The easterly wind was stronger to the east of 140°E than to the west. This corresponds to larger NE-type cases lying to the east of 140°E, as shown in Figure 3c,e. The convergence of southwesterly wind and southeasterly wind in the blue region favors the SE-type typhoons (Figure 5b). The two inflows may have important effects on the development of the SE quadrant. The green rectangle where the SW-type cases mainly occurred exhibited the characteristic of a monsoon trough, and the strong westerly wind could lead to a larger SW quadrant size (Figure 5c). The SW-type cases were found to be situated further southward and westward than the SE types, because the westerly wind is strong to the west of 140°E from June to August, which is well correlated with the spatial distribution of the SW type. From September to November, the East Asian continent is controlled by the anticyclone, and the cold air is active; hence, the orange region corresponding to the NW type in Figure 5d was occupied by a prominent northeasterly wind. The superposition of northeasterly wind is in favor of a larger NW quadrant.
size; thus, more NW-type cases occur near the coastal regions from northeast to southwest along East Asia. The environmental atmospheric circulation could affect the storm motion, and stronger wind is usually located right of motion, which is in favor of a larger quadrant size (Klotz and Jiang, 2016). According to Table 2, most NE-type cases moved westward or northwestward, and the storm motion favors a larger NE quadrant size. For the SE type, a northeastward track is helpful for a larger SE quadrant size, but two inflows (southeasterly and southwesterly wind) were more important when SE-type cases moved westward. Most SW-type cases moved
northwestward, and this was not favorable for a larger SW quadrant; therefore, it was noted that the southwesternly wind induced by the summer monsoon plays a prominent role in the formation of the SW type. For the NW type, the NW quadrant size was amplified for the cases with a westward track, and the superposition of northeasterly wind related to cold air was found to play a key role when NW-type cases move northeastward.

Compared with other regions north of 10°N in the WNP, the minimum average wind speed value was observed in the region 15°–30°N, 120°–140°E at 850 hPa from July to October during 2000–2009 (not shown), which is in favor of the frequent occurrence of symmetric TCs. The monthly variation of the weak background atmospheric circulation did not change apparently, resulting in little variation in the average size of symmetric TCs from July to October (Figure 4a). Therefore, the background atmospheric circulation definitely had important influences on the asymmetric structure and related quadrant TC size.

4 | SUMMARY AND DISCUSSION

In this study, the monthly variation and spatial distribution of asymmetric and symmetric TCs in the WNP were investigated. In this work, 1,229 TC size parameters were derived from 225 TCs during 2000–2009 based on QuikSCAT near-surface oceanic wind data.

The monthly variation of maximum quadrant sizes and corresponding lifetime for four types of asymmetric TC exhibited different features. The NE-type cases were widely located in the western North Pacific, with two peaks in July and October. For the SE type, the peak of the quadrant size appeared in July and decreased afterward, and the SE-type cases mostly were to the west of 155°E. The SW-type cases were relatively larger from June to August than in other months, and they were mainly located to the east of the Philippine Islands. For the NW type, the average size and lifetime changed consistently, with larger points being usually located near the coastal region along East Asia. Lifetime and atmospheric circulation were both important factors that could affect the quadrant size. A basic overview of the storm motion vectors was also provided to address the background circulation’s relative contribution to the quadrant TC size more clearly.

The influences of TC track, lifetime, and background atmospheric circulation on TC size were also discussed. Four kinds of circulation in the specified regions (Figure 5) were described, which correlate well with the four types. However, four specified regions overlap, so that two or more kinds of circulation may occur simultaneously. Therefore, it may be difficult to estimate which quadrant size is larger in this situation.

Considering the TCs with different tracks, moving to different regions could lead to different quadrant sizes, and staying in the specified region for a long or short time could also cause different results. A NE-type TC at this time may change to a NW type the next time. These factors together can affect the TC size. More factors should be discussed in future studies, such as the relative SST. The relationship between the relative SST and TC size in the WNP is not apparent, but a positive relationship was found in the specific region 15°–30°N, 120°–140°E (figure not shown). The climatological mean circulation in the region was the weakest, which indicates that the influence of the relative SST on TC size could be more prominent after weakening the circulation factor. Klotz and Jiang (2016) showed that the entire TC surface wind asymmetry is down motion left for all basins in a motion relative reference frame after removing the motion vector, which differs from the Earth relative reference frame. It is better to consider the TC structure in a motion relative reference frame. The influence of some other factors, such as wind shear, on the TC asymmetry may be clearer in a motion relative reference frame without transition effects. Therefore, further studies are planned to gain a more comprehensive understanding of the TC size.

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CONFICT OF INTEREST

Authors declare that they have no conflict of interest.

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