Characteristics of Typhoon Eyewalls According to World Wide Lightning Location Network Data

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ABSTRACT

Methods for the estimation of typhoon eyewall characteristics (the center location, the radius and the width, and radii of inner and outer boundaries) based on World Wide Lightning Location Network (WWLLN) data are presented and discussed in this work. The center locations, the eyewall radii, and inner boundary radii estimated from WWLLN data for the typhoons of the northwestern Pacific from 2011 to 2015 were compared with the typhoon centers, radii of maximum winds, and the radii of the eyes obtained from Advanced Scatterometer (ASCAT) wind data, the Japan Meteorological Agency (JMA) archives, and the Joint Typhoon Warning Center (JTWC) archives. It is shown that the eyewall characteristics estimates based on the lightning discharge data are most closely related to characteristics of the ASCAT wind speed fields, and the radii of the eyewalls and their inner boundaries are linearly related to the radii of maximum winds and the radii of the eyes, with correlation coefficients reaching approximately 0.9 and 0.8, respectively. It was shown that the distances between locations of the eyewalls and typhoon centers estimated according to the WWLLN and those of the ASCAT, JMA, and JTWC data on average were 19, 16, and 17 km, respectively. The eyewall widths varied from 15 to 69 km, with an average of ~ 30 km.

1. Introduction

A typical feature in the structure of the central region of mature tropical cyclones (TCs) is the ring of powerful cumulus clouds, the so-called cloud wall, which surrounds an almost cloud-free inner area—the eye of a typhoon (a hurricane). The cloud wall (or eyewall) and the typhoon's eye form an internal active zone of the TC, where the strongest winds, maximum horizontal gradients of pressure and temperature, and storm rainfalls from powerful thunderstorm clouds are observed (La Seur and Hawkins 1963; Shea and Gray 1973). The characteristics of this zone, including the TC center coordinates, the maximum wind and its radius, the radius of the eye, and many other

parameters, are important for storm reports and numerical prediction schemes, including regional mesoscale models with a high resolution such as the Weather Research and Forecasting (WRF) Model (Powers et al. 2017). Therefore, a large number of techniques for estimating the above parameters has been developed, using mostly remote sensing data and satellite images of TCs at various wavelength ranges [e.g., the visible (VIS), infrared (IR), and microwave (MW)] (Kossin et al. 2007; Olander and Velden 2007; Wimmers and Velden 2010).

In recent decades, remote passive methods for lightning location by regional and world networks, with ground stations for receiving radio pulses emitted by an electrical discharges from lightning, were used for the study of fields of deep convective cloudiness in TCs (Abarca et al. 2011; Bovalo et al. 2014; DeMaria et al. 2012; Dowden et al. 2002; Molinari et al. 1994, 1999). Regional lightning location networks, such as the National Lightning Detection Network (NLDN; Cummins and Murphy 2009), the

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Long-Range Lightning Detection Network (LLDN; Pessi et al. 2009), the Pacific Lightning Detection Network (PacNet; Pessi et al. 2009), the European Cooperation for Lightning Detection (EUCLID; Poelman et al. 2016), the Guangdong Lightning Location System (GDLLS; Chen et al. 2004) and others, are currently operating in many parts of the world. However, coverage areas of the regional network data are usually limited to continents, and observations over oceans, where TCs form and develop, are limited to distances of ~ 400 km from the coast (Abarca et al. 2011). Established in 2003, the World Wide Lightning Location Network (WWLLN) registers the radio signals from lightning discharges in the range of very low frequencies (3–30 kHz) around the entire Earth, including areas of the open ocean (Rodger et al. 2006). The WWLLN records electric discharges of cloud-to-ground (CG) lightning (and some in-cloud discharges) and continuously detects the occurrence times and geographic coordinates of lightning with peak currents typically above 15 kA (Hutchins et al. 2012). Currently, the WWLLN includes approximately 80 receiving stations.

The possibility of using data from the WWLLN and other networks is shown in investigations of the structure of TC lightning fields and its relation to the cyclone intensity, the cloudiness structure, the vertical wind shear, and the TC movement (Abarca et al. 2011; Bovalo et al. 2014; DeMaria et al. 2012; Lay et al. 2005; Pan et al. 2010, 2014; Permyakov et al. 2015; Price et al. 2009; Solorzano et al. 2008; Stevenson et al. 2014; Thomas et al. 2010; Zhang et al. 2016; Molinari et al. 1994, 1999). These studies indicated common features of radial distributions of lightning discharges in mature TCs: a local maximum in the eyewall region, a clear minimum in the region 50–100 km outside the eyewall, and a maximum in the outer rainbands (150–300 km). This allows the lightning activity fields to determine the central area of the TC as the area with a radius of 100 km (Houze 2010).

In the central area of some TCs, the set of lightning points takes the form of clearly discernible rings or ring parts, reflecting the distribution of powerful cumulus clouds forming the cloudy wall of the typhoon eye (Permyakov et al. 2015, 2016, 2017; Vagasky 2017). According to Vaisala's Global Lightning Dataset (GLD360), some typhoons and hurricanes have a unique lightning signature within the eyewall named the enveloped eyewall lightning (EEL) signature (Vagasky 2017).

From the viewpoint of operational monitoring of typhoons, it is important that the existence of such structures allows an almost real-time evaluation of the

coordinates of the TC center and its movement speed according to spatial distributions of discharges, as well as the radius of the eyewall, which corresponds to the radius of the annulus of maximum density of discharges. In mature typhoons and hurricanes, positions of the eyewall and the areas of maximum winds are very close to each other (Shea and Gray 1973; Houze 2010). Therefore, radii of the eyewall or eye can be related to the radii of maximum winds (Kossin et al. 2007). The distribution of cloudiness and its features in the central area of TCs seen in satellite images of various ranges are used in operational centers to determine the eye and maximum wind radii (Velden et al. 2006).

This paper presents methods for the estimation of geometric characteristics of the TC eyewall (coordinates of the center, the radius and the width, and radii of inner and outer boundaries) according to the WWLLN data. The received estimates are compared with the TC parameters obtained according to the data from Advanced Scatterometer (ASCAT) measurements and best tracks of the U.S. Joint Typhoon Warning Center (JTWC) and the Japan Meteorological Agency (JMA).

The organization of the remainder of the paper is as follows: the data and methods are described in section 2, the demonstration of methods is presented in section 3a, results of the comparison of the obtained characteristics are presented in sections 3b–3d, and conclusions are provided in section 4.

2. Data and methods

a. JTWC and JMA

The best track (BT) data containing the information about TCs with 6-h (mostly) intervals were received from archives of the JTWC (<http://www.metoc.navy.mil/jtwc/jtwc.html>) and the Regional Specialized Meteorological Center (RSMC) Tokyo-Typhoon Center operated by the JMA (available in text format online at <http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/trackarchives.html>). Coordinates of the TC centers (latitude and longitude) from the JTWC (C_{JTWC}) and JMA (C_{JMA}) archives, the radii of maximum winds (RMW_{JTWC}) and the typhoon eye radii ($REYE_{JTWC}$, according to the eye diameter) from the JTWC archives were used in this work. Operational centers estimate these TC parameters using the Dvorak method (Velden et al. 2006), which is based on empirically established relationships between the intensity of TCs and structures of cloud fields on satellite images in the visible and infrared

TABLE 1. Statistics of the number of typhoon best track positions and the number of their coverage with WWLLN and ASCAT data.

The number of:	Stages of the TC's intensity					TCs ^a
	TD	TS	TY	ST	Total	
1) 6-h best track positions	312	589	951	142	1994	54
2.1) Days with the LA ≥ 1 discharges according to the WWLLN	115	149	206	49	368 ^b	54
2.2) 6-h best track positions in days with the LA ≥ 1 discharges	222	415	642	123	1402	54
3.1) Days with diurnal WWLLN annular structures	4	16	67	41	82 ^b	39
3.2) 6-h best track positions with WWLLN in days with annular lightning structures	3	20	142	102	267	39
4) WWLLN annular structures within ± 1 h of JTWC/JMA 6-h best track position	Not considered		41	45	86 ^c	24
5) WWLLN annular structures within ± 1 h of ASCAT	Not considered		17	16	33 ^c	19

^a The total number of cyclones for which information is given in the five columns on the left.

^b The total number of days is not equal to their sum in the columns “TD,” “TS,” “TY,” and “ST,” since within one day the TC can go through several stages of intensity.

^c The sizes of WWLLN, JTWC/JMA, and ASCAT data samples.

ranges. A numerical intensity index corresponding to an estimate of the maximum surface wind (MSW) is determined according to the cloud patterns in the images. The radius of maximum winds is defined as the distance between the warmer TC center and the colder eyewall rings according to the IR imagery cloud top temperature fields. The eye diameter is defined as a diameter of the area practically free from clouds on VIS images or as an area of relatively high temperatures in IR images. However, the Dvorak method has certain limitations and disadvantages due to the subjectivity of the analysis and classification of cloud patterns, the dependence on the satellite scan angle, and the closing of the TC central area by cirrus clouds (Velden et al. 2006). Therefore, after the storm passes, its characteristics are corrected with reanalysis using all available data, allowing significant reductions in errors of the estimates of the TC characteristics (Martin and Gray 1993; Velden et al. 2006; Kishimoto 2008).

We selected TCs for the period of 2011–15 in the northwestern (NW) part of the Pacific Ocean, which, in their evolution, reached the intensity of typhoons ($\text{MSW} \geq 33 \text{ m s}^{-1}$) or super typhoons ($\text{MSW} \geq 67 \text{ m s}^{-1}$) and were mostly away from the mainland coast (at a distance of more than 100 km) and large islands (characteristic sizes more than 100 km). According to the JMA data, a total of 127 TCs of varying intensity were recorded for the period 2011–15 in the NW Pacific. Out of 127 TCs, we selected 54 TCs for analysis that met our criteria, of which 28 were super typhoons and 26 were typhoons. The total number of

available 6-h BT positions for these 54 TCs was 1994, of which 312 were during the stage of a tropical depression (TD, $\text{MSW} \leq 17 \text{ m s}^{-1}$), 589 were during the stage of a tropical storm (TS, $17 < \text{MSW} < 33 \text{ m s}^{-1}$), 951 were during the typhoon stages (TY), and 142 were during the super typhoon stage (ST) (Table 1, item 1). BT positions and days at the stages of extratropical systems (cyclone) were not taken into account. The MSW values are from the JTWC BT data. Table 1 also lists the number of 6-h BT points of TCs at different intensity stages with available WWLLN and ASCAT data, the descriptions and the selection criteria of which are given in sections 2b and 2c, respectively.

b. WWLLN

1) DATA OF WWLLN

The WWLLN data were used to estimate characteristics of the typhoon eyewall. Errors in the lightning location coordinates in the early years of the network were 5–10 km (Rodger et al. 2006). A comparison of the WWLLN data (60 stations) with the Earth Networks Total Lightning Network data (ENTLN) (500 stations) showed that the average (median) value of the error in lightning discharge coordinates is 4.3 km (3 km) and that the error range at a level of 0.5 from the maximum distribution is from 1 to 6 km (Hutchins et al. 2012). The efficiency of lightning detection (DE, the ratio of lightning recorded by the global network WWLLN to the number of lightning events observed by the regional networks) in this network was 5%–11% until 2010

FIG. 1. Diurnal compositions of lightning discharges in the Super Typhoon Vongfong core between 3 and 9 Oct 2014.

(Abarca et al. 2011; Dowden et al. 2002; Lay et al. 2005; Rodger et al. 2006). Current estimates of the detection efficiency are 15% for all CG discharges and more than 50% for discharges above 40 kA (Hutchins et al. 2012). It should be noted that the DE of the WWLLN is determined by the state of the ionosphere, local geographic factors (topography, conductivity of Earth's surface, the configuration of the network stations, etc.) and it has a noticeable diurnal variation—at nighttime the DE is two to three times higher than at daytime (Pessi et al. 2009).

2) WWLLN DATA IN THE CENTRAL AREA OF TCs AT DIFFERENT STAGES OF THEIR EVOLUTION

To analyze lightning fields in the central region of the chosen 54 TCs at different stages of their evolution, the WWLLN data were selected for the entire life period of the each TC along its trajectory in the area within a radius of 100 km from the center. Then, diurnal distributions (compositions) of lightning discharges relative to the TC center were made for each TC. For this purpose, the location of each discharge in the diurnal sample (for 24 h) was converted into a rectangular coordinate system with the origin at the TC center whose coordinates at the time of discharge were determined from the JMA data by a spline interpolation. As an example, Fig. 1 shows diurnal compositions of lightning discharges for

seven days during the evolution of Super Typhoon Vongfong from 3 to 9 October 2014 (hereinafter ND is the number of lightning discharges in the sample).

The analysis of the lightning activity (LA), determined by the number of lightning discharges per day in the central area of the selected TCs, showed significant variability from cyclone to cyclone and from stage to stage of intensity, as seen, for example, in Fig. 2 and Table 2. The beginning of the LA (registration of first lightning discharge) was observed in 47 TCs at the TD stage, in 6 TCs at the TS stage, and in 1 TCs at the TY stage. The number of discharges in the days of the LA beginning ranged from 1 to 2757 (Table 2). The end of the LA (registration of last lightning discharge) was observed in 2 TCs at the TD stage, in 13 TCs at the TS stage, in 38 TCs at the TY stage and in 1 TCs at the ST stage. The number of discharges in the days of the LA end varied from 1 to 1210 (Table 2). The number of days with $LA \geq 1$ lightning discharge in the central area of the TCs ranged from 20% to 90% of the TC days. The total number of days with $LA \geq 1$ discharge for all TCs was 368 days (Table 1, item 2.1). The number of 6-h BT positions in these days was 1402 (Table 1, item 2.2). The diurnal number of lightning discharges in the typhoon core during the entire life period varied over a wide range from zero to several thousand. For example, for days of maximum intensity of the Super Typhoon

FIG. 2. Diurnal compositions of lightning discharges in central areas of Typhoons Nesat (26 Sep 2011), Haiyan (7 Nov 2013), Vongfong (8 Oct 2014), and Neoguri (4 Jul 2014).

TABLE 2. The lightning activity in the investigated TCs in the NW Pacific during 2011–15 according to the WWLLN data.

	Stages of the TC's intensity			
	TD	TS	TY	ST
The beginning of the LA in TCs	47	6	1	—
Min–max number of lightning discharges	1–2357	1–2757	8	—
The end of the LA in TCs	2	13	38	1
Min–max number of lightning discharges	952–1210	1–912	1–930	1

Vongfong, 7 and 8 October 2014, 1373 and 629 discharges were registered, respectively, and on the next day, only 2 were detected (Fig. 1).

3) WWLLN DATA SAMPLES FOR THE ESTIMATION OF THE TC EYEWALL CHARACTERISTICS

As seen in Figs. 1 and 2, in some diurnal (for 24 h) compositions of discharges, it was possible to visually distinguish annular lightning structures—the annulus (ring) or their parts. The WWLLN data were selected for separate TCs in the presence of these annular structures, while the minimum number of discharges was set to 20. The clear annular structures in diurnal lightning fields were found in only 39 TCs (i.e., in 72% of the selected TCs) at different stages of intensity. The total number of days with annular lightning structures was 82 days (Table 1, item 3.1). This is approximately 15% of the total number of the days of all selected TCs in the archives of best tracks (excluding days of the extratropical system stage). It is worth noting that all typhoons in the period 2012–15, in which Vagasky (2017) distinguished the EEL signatures within 6 h, were included in our sample.

To compare the geometric characteristics of annular lightning structures and the characteristics of TCs from the JTWC and JMA archives, lightning compositions were made in 6-h BT positions of these 82 days according to 2-h samples [e.g., at (0000, 0600, 1200, 1800) UTC $\pm$ 1 h] (see example in Fig. 3). We selected 86 BT positions (for 24 TCs) when the TCs intensity reached the typhoon or/and super typhoon categories (over the ocean), the number of the WWLLN data exceeded 20 discharges which formed visually clear annular lightning structures (Table 1, item 4). Note that the total number of the BT positions with the available WWLLN data (≥ 1 discharge) in days with annular lightning structures was 267 (Table 1, item 3.2). Thus, only one-third (32%; ratio of totals from Table 1, item 4 to Table 1, item 3.2) of the BT positions had pronounced annular lightning structures (or their parts) in the eyewalls.

To compare the geometric characteristics of annular lightning structures according to the WWLLN data and characteristics of the ASCAT wind fields, the lightning discharge samples were formed in such a way that their average times were within 1 h of the ASCAT data

times. In total, we managed to obtain 33 samples of the WWLLN data that were quasi-synchronous with the ASCAT data for 19 TCs (Table 1, item 5).

4) ESTIMATIONS OF THE TC EYEWALL CHARACTERISTICS ACCORDING TO THE WWLLN DATA

Lightning clusters in the WWLLN data reflect the distribution of deep cumulus convection areas in an eyewall (Houze 2010; Leary and Ritchie 2009). Therefore, it is natural to assume that the maximum density of discharge points in the WWLLN data in the central area of typhoons determines the position of the eyewall. The position of the density maxima of the discharge points in annular lightning structures, shown for example in Fig. 2, can be approximated by closed lines such as ellipses or circles having obtained the numerical values of their parameters. When approximating by an ellipse, it is necessary to evaluate its five parameters: the two coordinates of the center, major and minor axes, and the orientation. However, preliminary numerical calculations showed that the ellipticity of point signatures is not clearly expressed and that they can be approximated with sufficient accuracy by a circle having determined only three parameters: the two coordinates of the center, $C = (x_c, y_c)$, and the radius, RCW. For this, a numerical procedure of minimization of a summarized distance of lightning points to the approximating circle was used. The summarized distance is a function of three parameters, x_c , y_c , and RCW, and to find its minimum, the simplest method of a regular search of the extremum of a function of several variables without calculating the derivatives was used (Brent 1973). This method is stable in a choice of initial values (x_c , y_c , RCW) [(0, 0, 50 km) in the present work] and to the asymmetry of the lightning field; it converges rather quickly (10–20 steps in a minimum search algorithm) for a given estimate accuracy of 0.1 km. The values obtained for $C = (x_c, y_c)$ and RCW will be assumed as the center coordinates and the radius of the eyewall, respectively (Fig. 3, upper panel). For comparison with the data of the JMA and JTWC archives, the center coordinates $C = (x_c, y_c)$ were converted to geographic coordinates, $C = (\lambda_c, \varphi_c)$.

FIG. 3. (top) The 2-h compositions of lightning discharges, (middle) radial normalized discharge distributions, and (bottom) the MSAT IR imagery from the UW-CIMSS archive with the obtained eyewall characteristics for the Super Typhoon Haiyan at 0000, 0600, 1200, 1800 UTC 7 Nov and at 0000 UTC 8 Nov 2013. The orange lines in the imagery at 0000 UTC 8 Nov are the coastlines of the Philippine Islands.

The coordinates of the center, $C = (x_c, y_c)$, make it possible to construct a radial distribution of the lightning points, from which it is possible to estimate the width of the eyewall and its outer and inner boundaries radii. To construct a smoothed radial distribution of points, the kernel method was used, which was adopted in statistics for approximating the distribution density using kernel density functions (Parzen 1962). As a kernel density function of each lightning discharge, a Gaussian was used with the width equal to the estimate of the error of its coordinates (WWLLN data files contain estimates of the error of lightning time of 10^{-6} s and multiplying by the speed of light gives an estimate of the error of coordinates). When the number of discharge points is approximately 20, fairly smooth distributions are obtained (Fig. 3, middle panel), which are used to estimate the radii of outer and inner boundaries of the eyewall, as well as the width. These characteristics are determined by the scale of the radial scattering of the discharge points from the radius of the eyewall (maximum in distribution). As such a scale,

one can use the mean square distance of discharges from the approximating circle σ_p . Supposing that the radial distribution of discharges is close to normal and assuming that $\sim 95\%$ of the lightning points of the annular structure lie in an eyewall of width $D = 4\sigma_p$, we obtain estimates of inner $RIN_1 = RCW - 2\sigma_p$ and outer $ROUT_1 = RCW + 2\sigma_p$ radii of the eyewall. In the calculations, there were separate cases when $2\sigma_p$ exceeded RCW and when the value of RIN_1 became negative. Such cases were excluded. For example, out of 86 estimates of RIN_1 at 6-h BT positions, there were 3 such cases.

With the asymmetry of real radial distributions of lightning points and under conditions of significant discharge localization errors, the effective width D_e of the lightning distribution, which is usually determined in statistics as the ratio of the area under the probability density curve to its maximum, can be a more reliable estimate of the eyewall width. In our case, this approach to calculating the effective width of the distribution requires taking into account its cylindrical

geometry (i.e., instead of the area, the volume under the surface, formed by rotating around the axis of the obtained radial distribution, was calculated). To take into account the asymmetry of the discharge distribution relative to RCW, we can determine the effective width of the inner (d_1) and outer part of the eyewall (d_2), which gives $D_e = d_1 + d_2$. As a result, to estimate the effective inner radius of the TC eyewall we obtain $RIN_2 = RCW - d_1$, and for the effective outer radius $ROUT_2 = RCW + d_2$. In contrast to RIN_1 , the RIN_2 values are always positive.

Figure 3 demonstrates the results of evaluating eyewall characteristics by the described methods using the example of Super Typhoon Haiyan. Estimates of eyewall characteristics were obtained according to 2-h WWLLN data samples at 6-h BT positions [i.e., at (0000, 0600, 1200, 1800) UTC ± 1 h] on 7–8 November 2013. Note that by fixing the sample interval (2 h) and changing its beginning, we get the average time of the discharges sample which is equal to the BT position time. Their numerical values with errors are summarized in Table 3. Errors of estimations were calculated using a bootstrap resampling technique (Efron 1979) according to these samples. For this, from each 2-h sample, 33 random samples with volumes of 50% of the original (ND from 142 to 511) were formed, and according to these samples, all eyewall parameters were evaluated. The main statistical characteristics of these parameters [minimum (min), maximum (max), mean, median and standard deviation (std dev)] are given in Table S1 in the online supplemental material. The standard deviations of the center coordinates are within 0.4–1.4 km, and the standard deviations of the effective radii of RIN_2 , RCW, $ROUT_2$ are within 0.3–1 km. The standard deviations of RIN_1 and $ROUT_1$ are approximately two times larger and varied in the range of 0.6–2.2 km, which is due to the sensitivity of these estimates to the presence of individual discharge points at the edges of radial distributions. This may be due to both the stochastic nature of cumulus clouds and lightning, as well as errors in the lightning coordinates in the WWLLN data. It should be noted that the accuracy of calculations of center coordinates is at the level of the accuracy of radar estimates of the eye center positions, with a mean distance bias and a standard deviation of approximately 3.5 and 1.5 km, respectively (Chang et al. 2009).

In connection with the observed significant diurnal variation of the DE (Pessi et al. 2009), we note that in our case it will only determine the number of discharge points used for approximating of annular lightning structures. This number determines the quality of the approximation (errors) and the ability to calculate such

TABLE 3. Characteristics of Super Typhoon Haiyan according to the WWLLN data on 7 and 8 Nov 2013.

Time (UTC)	ND	C										
		x (km)	y (km)	λ (°E)	ϕ (°N)	RIN ₁ (km)	RIN ₂ (km)	RCW (km)	ROUT ₁ (km)	ROUT ₂ (km)	D (km)	D _e (km)
0000 7 Nov	142	-14.7 ± 1.4	-0.8 ± 0.7	132.66	8.69	24.5 ± 1.1	25.8 ± 0.9	34.5 ± 0.7	44.5 ± 0.9	43.4 ± 0.7	20 ± 2	16.3 ± 0.9
0600 7 Nov	403	-6.3 ± 0.5	8.1 ± 0.5	131.04	9.37	18.6 ± 0.6	21.3 ± 0.3	30.5 ± 0.3	42.3 ± 0.7	39.4 ± 0.4	23.7 ± 1.3	17.3 ± 0.4
1200 7 Nov	551	-21.6 ± 0.5	-6.6 ± 0.5	128.9	10.14	9.3 ± 1.3	16.6 ± 0.4	27.5 ± 0.5	45.7 ± 1.4	38.1 ± 0.5	36.4 ± 2.7	20.8 ± 0.5
1800 7 Nov	499	-7.8 ± 0.5	3.1 ± 0.4	126.83	10.63	14.7 ± 0.8	17.6 ± 0.3	26.5 ± 0.3	38.4 ± 0.7	35.1 ± 0.4	23.7 ± 1.5	16.7 ± 0.6
0000 8 Nov	230	-11.7 ± 0.9	-1.1 ± 1.1	124.69	10.99	8.2 ± 2	18.3 ± 0.9	29.5 ± 0.6	50.8 ± 2.2	41.2 ± 1	42.6 ± 3	21.7 ± 1.5

FIG. 4. Fields of (a) the module and (d) the vorticity of the ASCAT (*MetOp-A*) wind speed, (b),(e) their model matrices at the maximum correlation, and (c),(f) their radial distributions in Typhoon Dolphin at 0032 UTC 16 May 2015. Red lines in (c) and (f) are smooth radial distributions. [From [Permyakov et al. \(2018\)](#).]

characteristics as the radius of the inner and outer boundaries. But in our approach, we implement a variant of estimates according to a set of points, the number of which is not less than 20. Therefore, the diurnal variation of the DE can only effect on the number of radii estimates and their errors. Obviously, such estimates at nighttime can be obtained more than in the daytime.

c. ASCAT

To find the relationship between characteristics of the eyewall and ocean surface wind in the cores of the selected typhoons, Level 2 ASCAT (*MetOp-A* and *MetOp-B*) data ([Verhoef et al. 2012](#)) were used. These datasets have a spatial resolution of 12.5 km and were obtained through ftp access from the NASA EOSDIS Physical Oceanography Distributed Active Archive Center ([KNMI 2010, 2013](#)). The ASCAT wind speed is given in the range of $0\text{--}50\text{ m s}^{-1}$; errors of the speed components are approximately 2 m s^{-1} for winds below 25 m s^{-1} and gradually increase with increasing wind velocity ([Verhoef and Stoffelen 2018](#)).

The ASCAT data was sampled in a square of $512.5\text{ km} \times 512.5\text{ km}$ (41×41 points), the center of which was at the minimum distance from the TC center. To evaluate the characteristics of the wind field, we used the same methods that were presented in our previous

work ([Permyakov et al. 2018](#)), and the next three paragraphs have been derived from this with translation and minor modifications. Components of the ASCAT wind were converted into a rectangular coordinate system with the origin at the center of the selected square and the direction of the ordinate axis along the scanning band. As an example of such conversions, [Fig. 4a](#) shows the field of the ASCAT (*MetOp-A*) wind speed module in Typhoon Dolphin (2015) at 0032 UTC 16 May 2015. According to the wind speed field, the coordinates of the typhoon center in the rectangular system $C_{\text{ASCAT}1} = (x_{c1}, y_{c1})$ were estimated [which then were converted into geographical ones $C_{\text{ASCAT}1} = (\lambda_{c1}, \varphi_{c1})$], as well as the radius of maximum winds $\text{RMW}_{\text{ASCAT}1}$ ([Fig. 4b](#)). For this purpose, we used the correlation method ([Pratt 2001](#)), which is often used to analyze shapes and positions of individual structures in digital images. The method consists of searching the values of three parameters ($x_{c1}, y_{c1}, \text{RMW}_{\text{ASCAT}1}$), for which the correlation between the ASCAT wind matrix and the model matrix is maximum ([Fig. 4b](#)). The model matrix is calculated on the same grid by the parameters of the ideal ring wind distribution. In such a ring, the radial distribution of wind is given by the Gaussian of a fixed width (7 km in the present work) with the maximum (equal to one) at the radius $\text{RMW}_{\text{ASCAT}1}$, which is to be

determined. When searching for the maximum correlation, we used the same regular search method (Brent 1973) as in section 2b(4), and to increase accuracy, instead of wind speed, its square was used. As initial approximations in various typhoons, we used rough visual estimates of the position of the minimum ASCAT wind speed and 50 km for the radius RMW_{ASCAT1} . It should be noted that the ASCAT wind speed over 25 m s^{-1} is much lower than the real wind (Verhoef et al. 2012). However, in general, the scatterometer wind fields reflect the qualitative features of the wind field in the typhoon core area. In our case, this is the area of maximum winds. Therefore, for estimating geometric characteristics of the ASCAT wind field, it seems more appropriate to use the correlation method.

The position of the maximum at the smoothed radial distribution of the wind speed (relative to the found center, C_{ASCAT1}) gives a second estimate of the maximum wind radius RMW_{ASCAT2} (Fig. 4c). However, in a number of cases, the radial distribution did not have a clear maximum, as in Fig. 4c, which caused unrealistically large/small values of RMW_{ASCAT2} , which were then rejected. It should be noted that in this case, the correlation method gave more realistic values of the maximum wind radius.

It is known that the convective cloudiness in the TC eyewall arises with ascending air movements, whereas downward movements are observed in the cloudless eye (Houze 2010; Shea and Gray 1973). In accordance with the theory of the Ekman boundary layer of the atmosphere, in which the vertical speed is associated with the wind vorticity (Ekman pumping), the direction of vertical movements in the atmospheric thickness is determined by the sign of the wind speed vorticity. Thus, a change in the sign [from plus (+) to minus (−) when moving to the center] of vorticity can be a sign of crossing the boundary of the TC eye. This corresponds to the “dynamic” definition of the eye region as a negative vorticity region (Permyakov et al. 2018). Of course, parameters for this area, including the radius, will differ from the traditional definition of the eye as seen on satellite images. The wind speed vorticity field (Fig. 4d) was calculated by the method of central differences at a five-point stencil. The coordinates of the typhoon center, C_{ASCAT2} , (Fig. 4e), obtained with the help from the above described correlation method according to the field of the wind vorticity, made it possible to construct a profile of its radial distribution. We used the radius of the sign change from negative to positive on a profile of a vorticity radial distribution as an estimate of the “dynamic” radius of the typhoon eye, $REYE_{ASCAT}$, (Fig. 4f). In this case, values of $REYE_{ASCAT}$ may be less than the spatial resolution of the ASCAT data.

However, it should be noted that because of errors in the ASCAT wind and the low spatial resolution, the vorticity fields can contain significant errors exceeding 100% of the field values.

As was noted in section 2b(3), annular structures in diurnal lightning fields were found in only 39 TCs at different intensity stages for 82 days (Table 1, item 3.1). In some TCs, they were not seen (the discharge distributions were in the form of spots) but appeared in samples of a shorter duration. The inclusion of such cases increased the number of TCs to 43 (107 days), for which we collected the ASCAT data. In total, 117 estimates of C_{ASCAT1} , C_{ASCAT2} , RMW_{ASCAT1} , RMW_{ASCAT2} , and $REYE_{ASCAT}$ were obtained in 69 days with the LA for 34 TCs. Of these, only 33 estimates for 19 TCs were overlapped by the WWLLN data (Table 1, item 5). Of 33 estimates of RMW_{ASCAT2} , four values were rejected. We managed to obtain only 14 values for $REYE_{ASCAT}$.

In a comparative analysis of different methods and data sources as a measure of the discrepancy between the radius estimates, we used the root-mean-square difference, which was calculated for two arrays, f and r , by the formula

$$\text{rmsd} = \sqrt{\frac{1}{N} \sum_{n=1}^N [(f_n - \bar{f}) - (r_n - \bar{r})]^2}.$$

3. Results and discussion

a. The demonstration of methods for estimating the characteristics of the TC eyewall

We now demonstrate methods for estimating characteristics of the eyewall of tropical cyclones according to the WWLLN data using the example of Super Typhoon Haiyan (2013). According to the JTWC data, the cyclone crossed the western part of the Pacific Ocean from 2 to 11 November 2013, reaching a maximum intensity on 7 November with a central pressure of 895 hPa and a MSW of approximately 87 m s^{-1} . The lightning activity began at the stage of a tropical depression and lasted 7 days. On 7 November, the daily number of discharges was the greatest at 5704 (Fig. 2). Continuous thunderstorm activity with a number of lightning events per hour over 20 allowed reliable estimates to be obtained of the eyewall characteristics for all BT positions (Fig. 3), as well as implementing calculation procedures in a moving window (Fig. 5) and obtaining estimates for almost any time step.

Figure 3 (lower panel) shows parts of IR imageries from the geostationary Multifunctional Transport Satellite (MTSAT) at 0000, 0600, 1200, and 1800 UTC 7 November and at 0000 UTC 8 November 2013. Images were

FIG. 5. The (a) trajectory and (b) variations of the eyewall characteristics of Super Typhoon Haiyan during 7 Nov 2013. Error bars are standard deviations from Table 3.

obtained from the Tropical Cyclone web page Product Archive (<http://tropic.ssec.wisc.edu/archive/>) of the University of Wisconsin–Madison’s Cooperative Institute for Meteorological Satellite Studies (UW-CIMSS). The sizes of the selected parts of images correspond to the sizes of the TC central areas ($75 \text{ km} \times 75 \text{ km}$), shown in the upper panel of Fig. 3. On these images, we put the discharge points of 2-h samples (i.e., an image time $\pm 1 \text{ h}$), as well as circles with computed eyewall radii of RIN_1 , RIN_2 , RCW , $ROUT_1$, and $ROUT_2$, and center coordinates C , whose numerical values with error estimates are shown in Table 3. The eye of the super typhoon is clearly distinguished on all images for 7 November as a dark region. As seen from the figure, the lightning discharges are located around the eye, forming annular structures. In the last image, for 0000 UTC 8 November, the eye is not as prominent, and points of discharges are scattered throughout the central area, which is possibly related to the entrance of the typhoon to the Philippine Islands (the orange lines) and the partial destruction of the cloud wall. It can be noted that at 0600 and 1800 UTC 7 November, the eyewall center C is located in the center of the dark region, while circles with inner radii of RIN_1 and RIN_2 are quite close to boundaries of the dark area of the typhoon eye. At 0000 and 1200 UTC 7 November, the eyewall center shifts closer to the western border of the TC eye. Circles of the inner and outer boundaries of the eyewall with radii $RIN_{1,2}$ and $ROUT_{1,2}$ circumscribe the main quantity of lightning discharges and give estimates of the eyewall width, D and D_e , (Table 3). As seen in Fig. 3, individual points of discharge fall in the region of the eye, which by definition is free from clouds, and especially from thunderstorm convective clouds (Houze 2010; Shea and Gray

1973) and fall outside the outer boundary of the eyewall. Both can be connected with the random nature of cumulus clouds and lightning, as well as with inevitable errors in coordinate estimates in the WWLLN lightning localization algorithms. Lightning beyond the circles of the outer boundaries may reflect the presence of cumulus clouds that are not associated with the eyewall clouds themselves.

With a fairly dense distribution of the number of lightning discharges throughout the day, it is possible to implement the calculation of the eyewall characteristics as a time- moving window by the methods described in section 2b(4). An example of such calculations according to 1-h samples (windows) with the shift of 30 min for Super Typhoon Haiyan in the day of its maximum intensity (7 November 2013) is shown in Fig. 5. A total of 50 estimates of characteristics were obtained according to 50 samples with volumes from 23 to 678 discharges. Figure 5a shows the trajectory of the eyewall center with coordinates C and Fig. 5b shows corresponding characteristics of RIN_1 , RIN_2 , RCW , $ROUT_1$, and $ROUT_2$. The bars show the standard deviations of our estimates obtained from statistical tests (Table 3 and Table S1).

For comparison, Fig. 5 shows the trajectory of the typhoon center with coordinates of C_{JMA} obtained from the best tracks using spline interpolation at the average times of the WWLLN samples. The 6-h values of C_{JTWC} , $REYE_{JTWC}$ and RMW_{JTWC} are also shown. In addition, the coordinates of the center, C_{ADT} , the radii of the eye, $REYE_{ADT}$, and the radii of maximum winds, RMW_{ADT} , obtained for the super typhoon by the advanced Dvorak technique (ADT; Olander and Velden 2007), available in text form on the website of

TABLE 4. Statistical characteristics of distances between the eyewalls and TC centers (in km) obtained from the data of WLLN, ASCAT, JMA, and JTWC.

	WLLN – JMA/JTWC		WLLN – JMA/JTWC		WLLN – ASCAT		JMA – JTWC
	$C - C_{JMA}$	$C - C_{JTWC}$	$C - C_{JMA}$	$C - C_{JTWC}$	$C - C_{ASCAT1}$	$C - C_{ASCAT2}$	$C_{JMA} - C_{JTWC}$
	NBT = 86	NBT = 86	NA = 33	NA = 33	NA = 33	NA = 33	NBT = 86
Min	1	1	2.5	1	1	4	0
Max	54	54	68	88	71	73	25
Mean	16	17	16	17	19	23	8
Std dev	12	11	13	18	16	17	8

UW-CIMSS (<http://tropic.ssec.wisc.edu/real-time/adt/archive2013>), are shown. We showed these estimates, since they were received from the analysis of VIS, IR, and MW imageries.

As seen in Fig. 5a, all trajectories are fairly close to each other. Distances between C and C_{JMA} vary within limits of 8–25 km and average 15 km. Distances between C and C_{JTWC} are significantly smaller and range from 2 to 13 km (6.4 km on average), differences of $C - C_{ADT}$ are in the range of 2–19 km (average 11 km).

From Fig. 5b, one can see that radii of the inner boundary of the eyewall during most of the day are less than the eye radii. The $REYE_{ADT}$ values estimated by UW-CIMSS from passive MW imageries were 22.2 km. According to the JTWC data, during the day the radius of the cyclone's eye increased from 19 km at 0000 UTC to 23 km at 0600 UTC, maintained this value until 1800 UTC, and then decreased to 19 km by the end of the day. RIN_2 , in contrast, first decreased from ~26 km at 0000 UTC to ~17 km at 0700 UTC, then until 2100 UTC varied in the range of 16–18 km, and then increased by the end of the day. The value of RIN_1 was characterized by even greater variability, falling from 24 km at 0000 UTC to 9 km at 1200 UTC and then increasing to 17.4 km in the second half of the day. This, as well as the synchronous increase of $ROUT_1$, may be due to large outliers of radii values in the samples (as is clearly seen in Fig. 3, lower panel) and, accordingly, long “tails” in radial distributions giving large values of the mean square distance, σ_p , of the discharge points from the radius of RCW. The use in calculations of the selections using the “ 3σ ” and “ 2σ ” rules led to an increase of 1.5–2 times minimum values of RIN_1 , to a decrease of maximum values of $ROUT_1$ and to “pulling up” the curves to the daily curves of effective radii, RIN_2 and $ROUT_2$, in Fig. 5b (not shown here). At the same time, the estimates of C , RCW, RIN_2 , and $ROUT_2$ did not change much: deviations of these values from the “unfiltered” values did not exceed 1.2 km, and their standard deviations (over all 50 moving windows) were less than 0.4 km, which indicates the stability of these estimates to individual outliers of the discharge points.

Figure 5b shows the low variability in RCW, RMW_{JTWC} , and RMW_{ADT} estimates for most of the day. According to the JTWC data, the radius of maximum winds increased slightly from 28 km at 0000 UTC to 31.5 km at 0600–1800 UTC and decreased to 28 km by the end of the day. At the same time, the eyewall radius decreased from 34.5 to 30.3–26.5 km and then increased to 29.5 km. Thus, the difference between RCW and RMW_{JTWC} was within 1–7 km. It can be noted that our RCW estimates for the periods from 0600 to 1800 UTC are quite close to the RMW_{ADT} values, deviating by no more than 3 km. The significant differences of approximately 12 km at the beginning and the end of the day can also be noted.

Calculating the characteristics of the eyewall in Haiyan and then comparing them with the typhoon parameters available from other sources showed their significant consistency, although they reflect fields of different physical natures. Our estimates are related to the deep convection field in the eyewall, but the JTWC radii are mainly estimated by analyzing cloudiness in IR and VIS images, reflecting the cloud top fields. In the following three subsections, the results from calculations for all typhoons, where annular lightning structures were observed, as well as their comparison with characteristics from different sources, are given.

b. The comparison of the eyewall and typhoon center positions

This subsection presents the results of a comparison of the positions of the eyewall centers obtained using the data from WLLN (C) and typhoon centers received according to the data from ASCAT (C_{ASCAT1} and C_{ASCAT2}), JMA (C_{JMA}), and JTWC (C_{JTWC}). Table 4 summarizes the statistical characteristics of distances between them, obtained both at the time of the BT positions (the number of estimates NBT = 86 for 24 TCs) and ASCAT data (the number of estimates NA = 33 for 19 TCs).

As seen from Table 4, distances between centers, ($C - C_{JMA}$) and ($C - C_{JTWC}$), at BT positions ranged from 1 to 54 km and averaged 16 and 17 km, respectively. It should be noted that the distances between C_{JMA} and C_{JTWC} in some cases reach 25 km (on the average

FIG. 6. (a)–(c) The ASCAT (*MetOp-A*) wind speed and (d)–(g) the MTSAT-2 1-km VIS imagery of Typhoon Dolphin at 0032 UTC 16 May 2015 with the eyewall characteristics according to data from WWLLN, ASCAT, and JTWC/JMA.

approximately 8 km, Table 4) due to differences in the algorithms used in JMA and JTWC. It is interesting to compare locations of the eyewall centers and TCs centers obtained at the times of the ASCAT data. As an example, Fig. 6 shows the Typhoon Dolphin characteristics received at 0032 UTC 16 May 2015 and plotted to fields of the ASCAT (*MetOp-A*) wind speed and 1 km visible imagery from the MTSAT-2, available on the tropical cyclone web page of U.S. Naval Research Laboratory (<https://www.nrlmry.navy.mil/TC.html>). The center of the eyewall with coordinates $C = (142.22^{\circ}\text{E}, 15.27^{\circ}\text{N})$ was located in the typhoon core with a minimum ASCAT speed of approximately 20 m s^{-1} (Figs. 6a,e). Very close, at distances of 1 and 3 km, the TC centers with $C_{\text{JTWC}} = (142.22^{\circ}\text{E}, 15.26^{\circ}\text{N})$ and $C_{\text{ASCAT1}} = (142.25^{\circ}\text{E}, 15.27^{\circ}\text{N})$, respectively, were located. The largest discrepancies, 21 and 12 km, were obtained with estimates of $C_{\text{JMA}} = (142.41^{\circ}\text{E}, 15.24^{\circ}\text{N})$ and $C_{\text{ASCAT2}} = (142.32^{\circ}\text{E}, 15.32^{\circ}\text{N})$, respectively, which may be due to rounding and interpolation errors in the first case, and large errors in the ASCAT wind speed vorticity fields in the second. As seen from Table 4, the distances of $(C - C_{\text{ASCAT1}})$ and $(C - C_{\text{ASCAT2}})$ varied in the range of 1–71 and 4–73 km and averaged 19 and 23 km, respectively. Distances of $(C - C_{\text{JMA}})$ and $(C - C_{\text{JTWC}})$ for the time of the ASCAT data varied in the ranges of 2.5–68 and 1–88 km and averaged 16 and 17 km, respectively. The largest discrepancies (from 50 km and above) were obtained in only three cases, for TCs Soulik (2013), Utor (2013), and Rammasun (2014). It should be noted that such situations were accompanied by the unrealistic values of

other characteristics of the eyewall which were subsequently excluded when evaluating the regression relationships. Thus, in the case of Rammasun at 0142 UTC 17 July 2014, the discharge points that formed a small part of the annulus (less than the radian) were approximated by an anomalously large radius of ~ 100 km with the center at a distance of ~ 68 – 88 km from the typhoon center according to best tracks and ASCAT (Fig. S1). Most likely, these lightning discharges were not associated with the eyewall but reflected a secondary eyewall or rainband (Houze 2010). After ~ 4.5 h, a sufficient number of discharge points formed an annulus with a radius of $\text{RCW} \sim 40$ km and a center close to the values of RMW_{JTWC} and C_{JTWC} , C_{JMA} .

c. The comparison of radii of the eyewall and maximum wind in TCs

In mature typhoons and hurricanes, the positions of the eyewall and areas of maximum winds are very close (Houze 2010; Shea and Gray 1973). The WWLLN data provide an opportunity for estimates of the eyewall parameters, which can be related to characteristic scales in the wind field. This primarily refers to searching for the connection between the eyewall radius and the radius of maximum winds, especially according to the ASCAT data, since they directly reflect the wind field, unlike the data of operational centers, which mainly use satellite images.

As an example, Figs. 6b and 6f show circles with the radius of the eyewall and the radii of maximum winds obtained for Typhoon Dolphin at 0032 UTC 16 May

TABLE 5. Statistical characteristics of the eyewalls and maximum wind radii in TCs (in km) obtained from the data of WWLLN, ASCAT, and JTWC.

	WWLLN		ASCAT		JTWC	
	RCW		RMW _{ASCAT1}	RMW _{ASCAT2}	RMW _{JTWC}	
	NA = 33	NBT = 86	NA = 33	NA = 29	NA = 33	NBT = 86
Min	15	14	25	18	13	13
Max	100	82	98	89	38	57
Mean	36	34	46	38	26	27
Std dev	18	15	15	16	6	8

2015. The eyewall radius was $RCW = 34$ km and the radii of maximum winds were $RMW_{ASCAT1} = 44$ km, $RMW_{ASCAT2} = 35$ km, and $RMW_{JTWC} = 31$ km. As seen from Fig. 6b, circles with these radii pass through the area of maximum winds shown in gradations of red color, and, with the exception of the circle with radius of RMW_{ASCAT1} , almost merge in the figure.

Table 5 presents statistical characteristics of the eyewall and maximum wind radii obtained for all selected typhoons according to the data from WWLLN, JTWC, and ASCAT. The RCW values calculated at time of the JTWC data (NBT = 86 for 24 TCs) varied from 14 to 82 km and averaged 34 km. The radii of maximum winds, RMW_{JTWC} , were smaller than RCW and ranged from 13 to 57 km and averaged 27 km. The rmsd between the RCW and RMW_{JTWC} values was 14.8 km. As seen from the scatter diagram of RCW and RMW_{JTWC} values (Fig. 7a), it is difficult to discuss any relationship between them, since the RMW_{JTWC} values are clearly grouped around values with intervals of 3 and 6 km, which is due to specifics of the estimating techniques used by the agency JTWC (Velden et al. 2006).

Values of RCW obtained at the time of RMW_{ASCAT1} estimates (NA = 33 for 19 TCs) varied over a wider

range from 15 to 100 km and averaged 36 km (Table 5). RMW_{ASCAT1} values, calculated by the correlation method, varied from 25 to 98 km and averaged 46 km. RMW_{ASCAT2} values estimated through the radial wind speed distribution (number of NA = 29 due to the rejection of four values) were less than RMW_{ASCAT1} and varied from 18 to 89 km and averaged 38 km. Figures 7b and 7c show scatter diagrams of estimates of RCW and $RMW_{ASCAT1,2}$. Black lines show orthogonal regression lines calculated after rejecting a pair of values of RCW and $RMW_{ASCAT1,2}$ for the super typhoons Utor (2013) and Rammasun (2014), marked in the diagrams as cross symbols. These values were excluded because their deviations from the initial orthogonal regression line exceeded two standard deviations (criterion of “ 2σ ”). This is the so-called regression with the data selection. The correlation coefficient r between estimates of RCW and RMW_{ASCAT1} is 0.87, and they can be connected by the linear relation $RMW_{ASCAT1} = 2.4 + 1.4RCW$. The same close relationship between RCW and RMW_{ASCAT2} ($r = 0.89$) gives the regression ratio $RMW_{ASCAT2} = 1.3 + 1.1RCW$. The rmsd values between RCW and $RMW_{ASCAT1,2}$ were ~ 7 km, which is half the rmsd between RCW and RMW_{JTWC} .

FIG. 7. Scatter diagrams of estimates of the eyewall radii according to the WWLLN data and maximal wind radii according to the (a) JTWC and (b),(c) ASCAT data. Black lines are orthogonal regressions; cross marks are the rejected estimates.

TABLE 6. Statistical characteristics of inner radii of the eyewalls and TC eye radii (in km) obtained from the data of WWLLN, ASCAT, and JTWC.

	WWLLN				ASCAT	JTWC	
	RIN ₁		RIN ₂		REYE _{ASCAT}	REYE _{JTWC}	
	NA = 13	NBT = 64	NA = 14	NBT = 64	NA = 14	NA = 14	NBT = 64
Min	1.2	1	7	4	6	5	5
Max	44	64	51	67	19	23	28
Mean	16	18	18	20	13	16	16
Std dev	12	14	11	14	4	5	6

d. The comparison of the inner eyewall radii and the radii of the TC eye

The “typhoon eye” is commonly understood as a cloudless area, which allows it to be highlighted on satellite images in the visible and infrared bands (Kossin et al. 2007; Olander and Velden 2007) or on radar images (Squires and Businger 2008). In addition, the typhoon eye is associated with the field of wind speed and is characterized by its low values. This gave us reason to compare inner radii of the eyewall obtained according to the WWLLN lightning distribution with the typhoon eye radii from the JTWC archives and evaluated using the ASCAT data. Table 6 presents statistical characteristics of all these radii, calculated both at the time of BT positions and at the time of the ASCAT data.

At the time of BT positions, NBT = 64 estimates (for 24 TCs) of RIN₁, RIN₂, and REYE_{JTWC} were received (Table 6). Note that this number is significantly lower than the number in the above estimates due to the rejection of three negative RIN₁ values and 19 zero REYE_{JTWC} values, which are given by JTWC in the cases of an indistinct or too small eye, on the order of 1–2 pixels (a so-called “pinhole”) (Olander and Velden 2007). RIN₁ and RIN₂ had close values (rmsd = 3.7 km),

consistently varying from 1 to 67 km and averaged 18 and 20 km, respectively. The REYE_{JTWC} values were significantly smaller and varied from 5 to 28 km and averaged 16 km. There is almost no relationship between the estimates of RIN_{1,2} and REYE_{JTWC} ($r < 0.35$ and rmsd = 13 km). As already noted in section 3c, this may be due to the specifics of the JTWC procedures, as evidenced by the grouping of REYE_{JTWC} around discrete values at intervals of ~4–5 km on the scatter diagram of RIN₁ and REYE_{JTWC} estimates (Fig. 8a).

Table 6 also gives the statistical characteristics of RIN_{1,2} (and for comparison, REYE_{JTWC}) values obtained at the times of REYE_{ASCAT} estimates. In total, we received 14 estimates of REYE_{ASCAT} (for 10 TCs) synchronous with RIN₂ and 13 values of REYE_{ASCAT} synchronous with RIN₁ due to the rejection of negative values of the latter. It can be noted that the values for REYE_{ASCAT} are lower than for RIN_{1,2} and for REYE_{JTWC} and vary from 6 to 19 km and averaged 13 km. For example, for the abovementioned Typhoon Dolphin, at 0032 UTC 16 May 2015 REYE_{ASCAT} = 13 km, RIN₁ = 22 km, RIN₂ = 23 km, and REYE_{JTWC} = 23 km, and can be seen from Figs. 6c and 6g, the circles with last three radii merge and circumscribe the region with the lowest wind speeds. Figures 8b and 8c show the scatter

FIG. 8. Scatter diagrams of estimates of inner radii of the eyewall according to the WWLLN data and the eye TC radii according to the (a) JTWC and (b),(c) ASCAT data. Black lines are orthogonal regressions; cross marks are the rejected estimates.

diagrams of $RIN_{1,2}$ and $REYE_{ASCAT}$ estimates. Black lines show lines of the orthogonal regressions calculated after removing values for the super typhoons Utor (2013) and Nuri (2014) from the samples according to the criterion of “ 2σ ”. The correlation coefficient between estimates of RIN_1 and $REYE_{ASCAT}$ is 0.84, and they can be linked by the linear relation $REYE_{ASCAT} = 6.15 + 0.4RIN_1$ (Fig. 8b). The correlation coefficient between values of $REYE_{ASCAT}$ and RIN_2 is 0.75 and they can be linked by the linear relation $REYE_{ASCAT} = 3.13 + 0.57RIN_2$ (Fig. 8c). The rmsd values between $RIN_{1,2}$ and $REYE_{ASCAT}$ are 6.2 and 4.6 km, respectively.

When comparing the inner radii of the eyewall and the radii of the TC eye according to different data, one should take into account the level to which these estimates can be attributed and the possible influence of the slopes of the typhoon’s eyewall (funnel). Radii derived according to CG lightning discharges from the WWLLN data are integral estimates for the lower atmosphere layer, ~ 5 – 10 km thick, occupied by powerful cumulus clouds in the eyewall (Houze 2010, Fig. 27). $REYE_{JTWC}$ (or diameter) values in the case of a cloudless area on VIS and IR images refer to the level of the lower boundary of cumulonimbus clouds in the eyewall. In the presence of stratified (stratocumulus) cloudiness in the TC eye (Houze 2010, Fig. 9), the diameter of the eye is associated with the level of its upper boundary. RIN_1 and RIN_2 will differ even more and most likely, will exceed, $REYE_{JTWC}$ due to the inclination of the cloud funnel. Our estimates of the “dynamic” radius of the eye, $REYE_{ASCAT}$, refer to the level 10 m from the ocean surface. Naturally, these estimates will also differ from RIN_1 and RIN_2 but, as seen from Fig. 8, they generally change consistently.

The WWLLN data allows estimation of two more important parameters of the eyewall, the radius of its outer border and its width, which can be typhoon and hurricane characteristics as important as the radius of the eye and the radius of maximum winds. In total, 86 values of D for 24 TCs were obtained over the period of 2011–15. Values of D varied from 15 to 69 km and averaged 30 km (std dev = 11 km). Values of the effective width of the eyewall, D_e , changed in a smaller range, from 21 to 34 km and averaged 25 km (std dev = 2.4 km). Estimates obtained are consistent with the size of areas of maximum radar reflectivity in the eyewall, given, for example, in the figures of the work by Squires and Businger (2008).

4. Conclusions

This paper presents and discusses methods for estimating characteristics of the eyewalls of typhoons

according to the WWLLN data—the center positions, the radii and the widths, and the radii of the inner and outer boundaries. These methods were applied to the typhoons in the northwestern Pacific during the period from 2011 to 15, and for those typhoons in the central region of which the annular structures in fields of lightning discharges were observed. Locations of the eyewall centers, radii of the eyewalls and their inner boundaries were compared with the TC centers, radii of maximum winds and eyes, obtained from the data of BT and ASCAT. It is shown that the characteristics of the eyewall are most closely related to characteristics of ASCAT wind speed fields: the radii of the eyewall and its inner boundaries are linearly related to the radii of maximum wind and eye with correlation coefficients reaching approximately 0.9 and 0.8, respectively. It is shown that distances between locations of centers of the eyewalls and typhoons, estimated according to the WWLLN and those of ASCAT, JMA, and JTWC data, are on average 19, 16, and 17 km, respectively.

An advantage of the presented methods is the ability to evaluate the geometric characteristics of an eyewall with sufficiently high accuracy, since points of discharges recorded by the WWLLN are directly related to the position of powerful cumulus clouds in the eyewall. Acceptable accuracy is due to the WWLLN data structure (only coordinates and discharge times), which allows the use of gridless (or pixel-free) numerical methods in an analysis of distributions of discharge points. This paper shows that the accuracy of estimates can be higher than the estimates from satellite images, achieving the accuracy of radar methods, and can be controlled by a simple bootstrap method. Methods allow estimating the radius of the outer boundary of an eyewall and its width, which traditional satellite methods do not provide, and can be directly applied to data from other lightning localization systems (LLS). It is also shown for the example of Super Typhoon Haiyan that, in the case of high density and frequency of the WWLLN data, it is possible to receive estimates with the discreteness of 15–30 min, comparable to the discreteness of TCs images from geostationary satellites.

However, the listed advantages of methods for evaluating the eyewall characteristics according to the WWLLN (or other LLS) data can be realized only with a sufficiently high lightning density in the central region of intense, mature TCs. The annular lightning structures are not present in all TCs and the methods described cannot always be applied. As our statistics showed, only 72% of typhoons observed an annular lighting structure in the eyewall, and Vagasky (2017) noted that only 32 of 82 TCs (wind speed over 58 m s^{-1}) had such an EEL signature. However, the absence of annular lightning

structures may be due, among other things, to the insufficiently high efficiency of registration of lightning by the global network WWLLN, which depends on many factors—its constructive features, time of day, geographical conditions, the state of the ionosphere.

However, we note that the described methods and algorithms can be applied to the data from any LLS with higher lightning detection efficiency than in WWLLN. This allows them to be used as an additional tool to the traditional ones in the practice of hurricane and typhoon monitoring.

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