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Lightning Activity and Its Relation to the Intensity of Typhoons over the Northwest Pacific Ocean

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ABSTRACT

Data from the World Wide Lightning Location Network (WWLLN) were used to analyze the lightning activity and the relationship between maximum sustained wind and lightning rate in 69 tropical cyclones over the Northwest Pacific Ocean from 2005 to 2009. The minimum lightning density was observed in the category 2 typhoon Kong-Rey (2007), with a value of only 1.15 d^{-1} $(100\ km)^{-2}$. The maximum lightning density occurred in the category 2 typhoon Mitag (2007), with a value of 510.42 d^{-1} $(100\ km)^{-2}$. The average lightning density decreased with radius from the typhoon center in both weak (categories 1–3) and super (categories 4–5) typhoons. The average lightning density in the inner core of super typhoons was more than twice as large as that for weak typhoons. Both groups of typhoons showed a near-monotonic decrease in lightning density with radius. Results also showed that lightning activity was more active in typhoons that made landfall than in those that did not. The mean correlation coefficient between the accumulated flashes within a 600-km radius and the maximum wind speed in the weak typhoons and super typhoons was 0.81 and 0.74, respectively. For more than 78% (56%) of the super (weak) typhoons, the lightning activity peaked before the maximum sustained wind speed, with the most common leading time being 30 (60) h. The results suggest that, for the Northwest Pacific Ocean, lightning activity might be used as a measurement of the intensification of typhoons.

Key words: lightning, typhoon, intensity, WWLLN

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1. Introduction

Lightning has been used to study the structure and changes in intensity of tropical cyclones over the last two decades by using various lightning networks. Using data from the ground-based National Lightning Detection Network (NLDN), Molinari et al. (1994) studied the spatial and temporal distribution of cloud-to-ground (CG) lightning in hurricane Andrew in 1992 and found that the lightning radial distribution was consistent with the convective structure of mature hurricanes. They also found that eyewall lightning tended to be episodic, occurring prior to and during periods of intensification of the storm. Lyons and Keen (1994) described lightning variations in four tropical storms, and found that two of the storms showed significant outbreaks of lightning near the center before or during their intensification. Molinari et al. (1999) examined nine Atlantic basin hurricanes and the results showed that the outbreaks of eyewall flashes over water always occurred at the beginning of, or during times of, intensification. Their study, however, was limited to storms sampled within a distance of 400 km of the US coastline.

Squires and Businger (2008) used the Long-Range Lightning Detection Network (LLDN) and Tropical Rainfall Measuring Mission (TRMM) dataset to examine the morphology of lightning outbreaks in the eyewall of two hurricanes. Their study showed that outbreaks of eyewall lightning occur during the period of the most rapid intensification, during the eyewall replacement cycles, and during the time period that encompasses the maximum intensity for each hurricane. Shao et al. (2005) found that the eyewall lightning rate was higher during the transition stage from lower to higher hurricane classification categories in both hurricanes Katrina and Rita on the basis of the data from the Los Alamos Sferics Array (LASA). DeMaria et al. (2012) studied the relationship between the spatial evolution of lightning density and tropical cyclone intensity in the Atlantic and East Pacific basins. Zhang et al. (2012) studied the lighting distribution in 33

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Northwest Pacific tropical cyclones during the period of landfall in China and found that lightning outbreaks connect the relationship of eyewall flashes to the changes of structure and intensity of tropical cyclones.

Observations from the World Wide Lightning Location Network (WWLLN) have also been successfully used to study the lightning activity in tropical cyclones. Solorzano et al. (2008) studied two Atlantic hurricanes and three western Pacific typhoons and found that eyewall lightning outbreaks occur prior to or during most major intensity changes for all storms. Price et al. (2009) analyzed lightning frequency and the maximum sustained winds of 56 category 4–5 hurricanes around the globe and found that, in all of these hurricanes, lightning frequency and maximum sustained winds were significantly correlated, where the maximum sustained wind and minimum pressure in hurricanes were preceded by increases in lightning activity approximately one day before the peak wind. Pan et al. (2010) studied seven super typhoons over the western Pacific from 2005–08. Their results indicated that there were three distinct lightning flash regions in mature typhoons. Each typhoon produced eyewall lightning outbreaks during the periods of its intensification, usually several hours prior to its maximum intensity. Thomas et al. (2010) studied the polarity and energetics of inner core lightning in three intense North Atlantic hurricanes, and found episodic inner-core lightning outbreaks prior to and during the most changes of the storm's intensity. A new finding from their results is that positive CG lightning in the inner core increased prior to and during the periods of storm weakening. Abarca et al. (2011) studied 24 Atlantic tropical cyclones (TCs) and suggested that flash density in the inner core was a parameter with potential to distinguish between intensifying versus non-intensifying TCs, particularly in the weaker storm stage when flash density was the largest.

Satellite-based lightning datasets have also been used to study the lightning activity in tropical storms. Cecil and Zipser (1999) and Yang et al. (2011) used data from TRMM, and found no clear relationship between lightning rate and TC intensification. Cecil et al. (2002) and Cecil and Zipser (2002) studied 45 hurricanes, and showed that lightning density maxima were in the eyewall and outer rainband regions, with a lightning density minimum in the inner rainband regions.

Previous studies have shown that there is a significant relationship between inner-core lightning activity and hurricane intensity. Most of these studies, however, were mainly focused on hurricanes over the Atlantic Ocean. Accordingly, the goal of this study is to examine lightning activity in different categories of typhoons, and the relationship between total lightning activity and typhoon intensity of all the typhoons ranging from category 1–5 on the Saffir Simpson scale that occurred over the Northwest Pacific from 2005–09. Lightning that occurred at $<$ 100 km from the center is defined as inner-core lightning (or eyewall lightning); $<$ 600 km is defined as total typhoon lightning; and 100–600 km is defined as outer rainband lightning (refer to section 3). First, the lightning activity in weak typhoons against super typhoons was compared. Then, the relationship between lightning rate and typhoon intensity was analyzed.

2. Data and analysis methods

2.1. *Lightning data*

The lightning data used in this study are from the WWLLN over a 5-yr period from 2005–09. The WWLLN provides almost real-time lightning locations by measuring the very low frequency (VLF) radiation (3–30 kHz) emanating from lightning discharges (Rodger et al., 2004). The efficiency and location accuracy of the WWLLN has been estimated for some regions by comparison to regional ground-based lightning detection systems (Lay et al., 2004; Rodger et al., 2004, 2005, 2006, 2009; Jacobson et al., 2006; Abarca et al., 2010). The WWLLN has been improved over the years and its detection efficiency is increasing. The initial work by Lay et al. (2004) found that the detection efficiency for ground flashes was only 0.3% when comparing the WWLLN with the Brazil Integrated Network (BIN). Rodger et al. (2004, 2005) compared the WWLLN with the Kattron in Australia during 2003 and 2004, and found that the detection efficiency was 1% and 13%, respectively. Rodger et al. (2006) also estimated the detection efficiency with the New Zealand Detection Network and found that 10% of the flashes were detected by the WWLLN. The NLDN (Cummins et al., 1998) and LASA (Shao et al., 2005, 2006) data were also used as the ground truth (Jacobson et al., 2006) to estimate the WWLLN detection efficiency and showed a detection efficiency of about 4%. Rodger et al. (2009) pointed out that the new algorithm in their study has led to WWLLN detection efficiency improvements of 63%. The most recent study found that the detection efficiency was greater than 10% for peak currents larger than $\pm$35 kA, 35% for currents larger than $-$130 kA, and $\sim$ 2% for peak currents between 0 and $-$10 kA (Abarca et al., 2010). The location accuracy was different for different azimuths, with average location errors of 4.03 km in the north–south and 4.98 km in the east–west directions, respectively. The above studies have shown that WWLLN station coverage and detection efficiency have varied from year to year. Therefore, a method is needed to account for this variation. The long-term global lightning density climatology from the Optical Transient Detector (OTD) and Lightning Imaging Sensor (LIS) was used to adjust the detection efficiency of the WWLLN. The flash detection efficiency of the LIS was estimated to be about 90% and 70% for night and noon by Boccippio et al. (2002), which can provide an accurate estimate of the annual mean total typhoon lightning density over the Northwest Pacific. The LIS/OTD High Resolution Full Climatology (HRFC) lightning dataset with a grid resolution of $0.5^\circ \times 0.5^\circ$ was obtained from the Global Hydrology and Climate Lightning Research Team at National Aeronautics and Space Administration (NASA)'s Marshall Space Flight Center, which included OTD data from 1995–2000 and LIS data from 1998–2010 (Cecil et al., 2012).

2.2. *Typhoon data*

The time, location, maximum sustained wind and minimum central pressure of typhoons at 6-h intervals were obtained from the “best-track” data produced by the Joint Typhoon Warning Center. The resolution of 6-h “best-track” data was linearly interpolated to 1-h resolution for convenience of the representations. The radii of the typhoons studied herein varied from 600 to 1300 km according to the MTSAT-1R satellite IR images (Fig. 1) during the maximum intensity of typhoons. Eighty percent of radii of the typhoons within our sample were about 600 km. Therefore, nominal radius values of 600 km were selected to properly represent the size range of typhoons in the sample considered in this study. The lightning data within a 600 km radius were summed with a 30-min period centered at the time of each storm position estimate from the best track.

2.3. *Data analysis methods*

The annual mean lightning density climatology from LIS/OTD in units of strikes per square kilometer per year was used for adjustment (or correction) of the WWLLN detection efficiency. The annual average lightning density from the WWLLN was calculated for each year over the Northwest Pacific domain (0°–45°N, 135°–180°E). These values were compared to the value of mean lightning density climatology from LIS/OTD over the same domain. Table 1 shows the amount of lightning flashes and the adjustment factors needed to make the WWLLN average lightning density equal to that from the LIS/OTD.

Table 1. Number of flashes reported by the WWLLN by year over the Northwest Pacific between 0°–45°N and 135°–180°E and adjustment factors.

Year	Flash number	Adjustment factor
2005	892 185	11.27
2006	926 378	11
2007	803 280	12.46
2008	1 922 511	5.32
2009	3 365 569	3.01

3. Results and discussion

A total of 133 TCs were observed in the Northwest Pacific from 2005–09, 69 of which developed into typhoons. Among them, Typhoon Ioke (2006) initially formed in the eastern Pacific. The typhoons were divided into two different groups according to their intensity based on the Saffir–Simpson scale. During the period considered, 32 weak typhoons (categories 1–3) and 37 super typhoons (categories 4–5) were observed. More than 80% of the 69 typhoons formed between May and November in the Northwestern Pacific. Qie et al. (2013) once briefly introduced the relationship between lightning flashes and the maximum wind speed in typhoons. In the following sections, we will discuss in detail the lightning activity and its relationship with the intensity of the two groups of typhoons.

3.1. *Lightning activity in the two intensity groups of typhoons*

Tables 2 and 3 present a summary of flash rate and lightning intensity within 100 km from the center and the outer rainband (100–600 km) for the weak and super typhoons, respectively. The tables also include typhoon information such as name, year, category and sustained hours. The lightning data in Tables 2 and 3 were adjusted according to the adjustment factors shown in Table 1. The average flash rate means the number of flashes that occurred per day during the whole

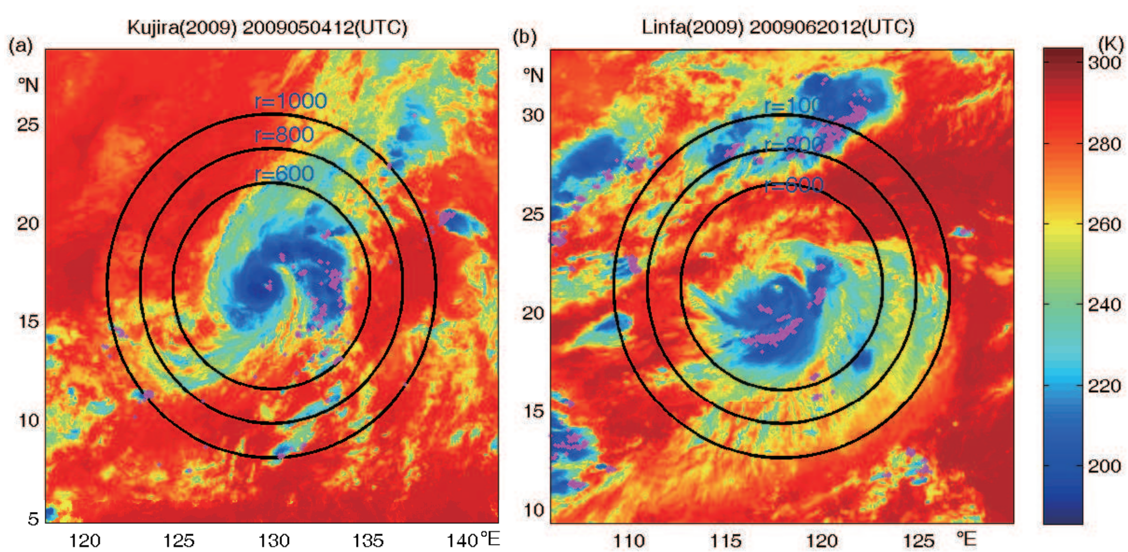

Fig. 1. Cloud top brightness temperature distribution from the MTSAT-1R satellite of typhoons Kujira (2009) and Linfa (2009) and the distribution of flashes (pink dots) within one hour around the time (UTC) of the image; three circles from the inside to outside of radii represent 600 km, 800 km and 1000 km, respectively.

Table 2. List of weak typhoon characteristics and average flash rates and average flash density in the inner core and outer rainband.

Year	Storm	Category	Hours (h)	Inner-core flash rate (fl d^{-1})	Rainband flash rate (fl d^{-1})	Inner-core flash density [fl d^{-1} (100 km)$^{-2}$]	Rainband flash density [fl d^{-1} (100 km)$^{-2}$]
2005	Roke	1	139	611	10 786	193.73	98.05
	Marsa	2	193	195	32 587	60.97	296.29
	Sanvu	1	103	210	55 393	68.18	503.77
	Saola	2	181	120	21 283	39.45	193.51
	Damrey	2	169	66	1042	21.53	9.47
	Kai-Tak	2	138	269	7879	86.10	71.68
	Bolaven	1	211	5513	40 899	1754.18	371.91
2006	Kaemi	2	217	1163	21 629	371.14	196.68
	Prapiroon	1	193	376	44 468	119.02	404.47
	Soulik	2	193	15	1298	3.52	11.77
	Utor	3	217	1060	48 299	336.16	439.23
2007	Kong-Rey	2	145	107	22	35.64	0.25
	Pabuk	1	139	4640	39 206	1475.39	362.34
	Fitow	2	247	39	1141	11.84	10.59
	Lekima	1	121	5578	42 409	1776.80	391.99
	Kajiki	3	97	567	5466	182.41	50.59
	Peipah	1	211	4007	34 606	1277.15	319.85
	Hagibis	2	217	932	13 134	297.42	121.36
	Mitag	2	193	4345	52 526	1384.18	485.44
2008	Neoguri	2	163	129	32 710	40.64	297.44
	Halong	1	145	473	9270	150.72	84.32
	Fengshen	2	205	1565	18 505	497.85	168.27
	Kalmaegi	2	211	1047	10 891	333.62	99.06
	Fung-Wong	2	139	346	27 197	110.07	247.33
	Nuri	2	169	357	14 417	113.48	131.14
	Dolphin	2	241	868	5061	276.00	46.02
2009	Chan-Hom	2	247	991	18 288	315.21	166.33
	Linfa	1	223	233	16 874	73.78	153.45
	Morakot	2	145	48	3392	15.32	30.85
	Koppu	1	103	232	46 922	73.78	426.76
	Ketsana	2	115	357	15 169	114.02	137.95
	Mirinae	2	187	2652	1814	844.09	16.49
	Mean			477.40	11 443.94	150.77	105.18
	Median			424.50	17 581.00	134.87	159.89
	Minimum			15	22	3.52	0.25
	Maximum			5578	55 393	1776.80	503.77

life of one typhoon. The lightning density in Tables 2 and 3 is defined as the number of flashes occurring over unit area in unit time, and expressed as the number of flashes per 100 km^2 per day [in a unit of d^{-1} (100 km)$^{-2}$]. It can be seen from the two tables that the average flash rate and lightning density varied significantly from one typhoon to another. The maximum lightning density occurred in the category 2 typhoon Mitag (2007), with a value of 510.42 d^{-1} (100 km)$^{-2}$. The minimum was observed in the category 2 typhoon Kong-Rey (2007), with a value of only 1.15 d^{-1} (100 km)$^{-2}$.

Table 2 shows that, in the weak typhoon, the outer rainband lightning rate ranged from 22 to 55 393 d^{-1}, and the flash rate within the inner core ranged from 15 to 5578 fl d^{-1}. The outer rainband lightning density ranged from 0.25 to 503.77 d^{-1} (100 km)$^{-2}$ and the inner-core lightning density ranged from 3.52 to 1776.80 d^{-1} (100 km)$^{-2}$. The geometric mean lightning density was 105.18 d^{-1} (100 km)$^{-2}$and 150.77 d^{-1} (100 km)$^{-2}$ in the outer rainband and the inner core, respectively. The median lightning density was 159.89 d^{-1} (100 km)$^{-2}$ and 134.87 d^{-1} (100 km)$^{-2}$ in the outer rainband and the inner core, respectively.

Table 3 shows that, in the super typhoon, the outer rainband lightning rate ranged from 835 to 49 502 d^{-1} and the flash rate within the inner core ranged from 89 to 13 579 d^{-1}. The outer rainband lightning density ranged from 7.60 to 450.12 d^{-1} (100 km)$^{-2}$ and the inner-core lightning density ranged from 27.79 to 4322.72 d^{-1} (100 km)$^{-2}$. The geometric mean lightning density was 70.45 d^{-1} (100 km)$^{-2}$ and 230.25 d^{-1} (100 km)$^{-2}$ in the outer rainband and the inner core, respectively. The median lightning density was 57.70 d^{-1} (100 km)$^{-2}$ and 269.76 d^{-1} (100 km)$^{-2}$ in the outer rainband and the inner core, respectively.

The significant difference in these two groups is that the geometric mean and median lightning density in the inner core of super typhoons is greater than that of weak typhoons. On the contrary, the outer rainband lightning activity shows a

Table 3. List of super typhoon characteristics and average flash rates and average flash density in the inner core and outer rainband.

Year	Storm	Category	Hours (h)	Inner-core flash rate (d^{-1})	Rainband flash rate (d^{-1})	Inner-core flash density [d^{-1} (100 km)$^{-2}$]	Rainband flash density [d^{-1} (100 km)$^{-2}$]
2005	Sonca	4	247	314	3964	100.42	36.06
	Nesat	4	349	932	6343	297.75	57.70
	Haitang	5	217	505	14 106	161.39	128.37
	Mawar	4	217	3124	33 107	993.68	301.13
	Talim	4	193	7886	49 502	2511.18	450.12
	Nabi	5	223	1476	20 513	469.96	186.52
	Khanun	4	157	13 579	1122	4322.72	10.26
	Longwang	4	211	117	5148	35.84	46.88
	Kirogi	4	217	502	1433	161.39	13.07
2006	Chanchu	4	271	273	25 556	87.56	232.43
	Ewiniar	4	265	1149	6118	364.10	55.66
	Saomai	5	199	1195	7468	381.70	67.98
	Shanshan	4	211	1924	31 188	612.70	283.58
	Yagi	4	223	1080	2609	343.09	23.76
	Xangshen	4	163	570	36 466	182.05	331.65
	Cimaron	5	325	3853	40 248	1225.51	366.08
	Chebi	4	187	2536	22 924	808.83	208.45
	Durian	4	367	2727	17 473	868.34	158.84
2007	Yutu	4	187	166	2595	51.58	23.55
	Man-yi	4	223	89	4310	27.79	39.25
	Usagi	4	199	1370	11 986	436.22	109.03
	Sepat	4	139	2647	21 065	840.80	191.63
	Nari	4	139	116	5196	35.64	47.22
	Wipha	5	211	848	835	269.76	7.60
	Krosa	4	157	213	26 590	67.41	241.85
2008	Rammasun	4	163	291	5228	93.15	47.56
	Nakri	4	193	179	2227	57.56	20.27
	Sinlaku	4	331	247	13 094	77.88	119.06
	Hagupit	4	187	1402	35 227	447.04	320.37
	Jangmi	4	181	177	5013	55.86	45.59
2009	Kujira	4	257	2809	10 705	893.91	97.37
	Vamco	4	247	436	979	138.91	8.91
	Choi-Wan	5	211	245	1808	77.60	16.46
	Parma	4	379	266	3705	84.31	33.71
	Melor	5	253	1119	5989	356.41	54.48
	Lupit	4	319	152	8412	47.92	76.51
	Nida	5	295	2828	4531	900.62	41.21
	Mean			725.50	7742.77	230.25	70.45
	Median			848.00	6343.00	269.76	57.70
	Minimum			89	835	27.79	7.60
	Maximum			13 579	49 502	4322.72	450.12

reverse tendency.

Figure 2 shows the average lightning density as a function of radius for 37 super typhoons and 32 weak typhoons. A total of 195 and 316 samples (days) in weak typhoons and super typhoons were chosen for this study, respectively. This figure shows that the average lightning density in the inner core of super typhoons is more than twice as large as that for weak typhoons. It also shows a near-monotonic decrease in lightning density with radius in both groups of typhoon. A similar structure was shown in the Atlantic and East Pacific by DeMaria et al. (2012). However, the individual case studies show that there is a minimum lightning density region between the inner core and the outer rainband, which was also confirmed by Molinari et al. (1999) and Pan et al. (2010).

Two examples of cloud IR satellite images and flash distribution within ±0.5 h of the image time for typhoons Linfa (2009) (category 1; Fig. 1a) and Kujira (2009) (category 4; Fig. 1b) are shown in Fig. 1. Most of the flashes were located within the cloud region, although a few were located outside the cloud region because of the typhoon's motion (including individual azimuthal cloud motion coupled with the storm forward translation speed) and detection errors. Lightning occurred in deep convective clouds and clustered in outer spiral rainbands in both typhoons. In Typhoon Linfa (2009), lightning was detected in the outer rainband but not in the eyewall region, which illustrates why previous studies have used eyewall lightning to evaluate hurricane intensity (e.g., Molinari et al., 1994, 1999; Squires and Businger, 2008;

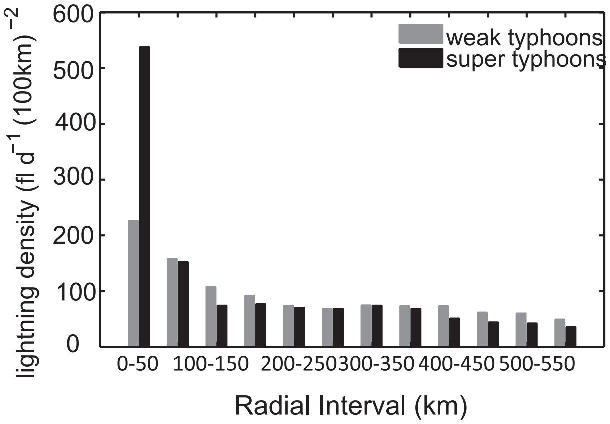

Fig. 2. Mean lightning density as a function of radius from the typhoon center in the two groups of typhoons.

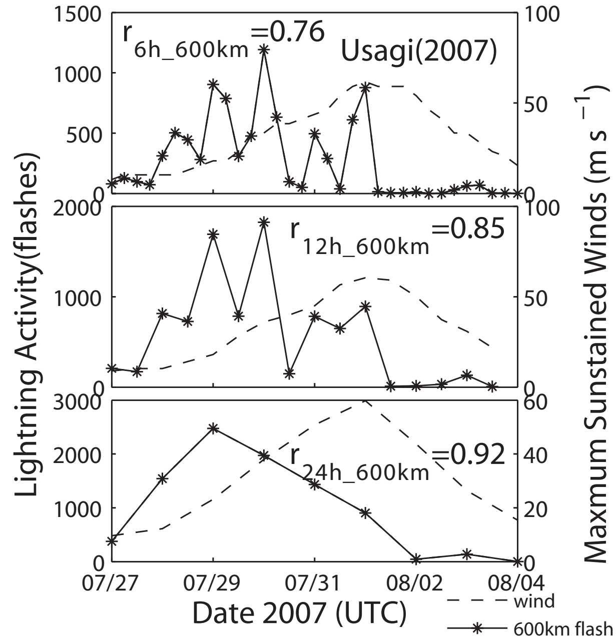

Fig. 3. Evolution of 6-h (top), 12-h (middle), and 24-h (bottom) maximum sustained winds (dashed curve) and accumulated lightning flashes within 600 km (curve with asterisks) observed for Typhoon Usagi (2007).

Pan et al., 2010; Thomas et al., 2010). Similar to the finding of Fierro et al. (2011), lightning in the TCs is associated with deep convective clouds. Those results are very similar to those found by DeMaria et al. (2012). The amount of flashes that occurred within the inner core was very small for a number of samples. Therefore, total typhoon lightning ($<$ 600 km) was used to study typhoon intensity in this work.

3.2. *Relationships between typhoon lightning activity and maximum sustained winds*

Figures 3–5 show the evolution of maximum sustained winds and total typhoon lightning frequency within 600 km at 6-h intervals for typhoons Usagi (2007) (Fig. 3), Roke (2005) (Fig. 4), and Pabuk (2007) (Fig. 5). Lightning flash counts accumulated over 12-h and 24-h intervals are also shown.

The evolutions of 6-h, 12-h, and 24-h maximum sustained wind and accumulated flashes within 600 km of the typhoon center are shown for the entire lifetime of Typhoon Usagi (2007) in Fig. 3. Usagi (2007) attained its maximum intensity at 0000 UTC 1 August 2007 with a maximum sustained surface wind of 61.7 m s^{-1}. The peaks of 6-h and 12-h total typhoon lightning within 600 km peaked at 0000 UTC 30 July, 48 h prior to the wind maximum. However, the peak of 24-h lightning preceded that of maximum wind by three days rather than two days. The linear correlation coefficients (r) between 6-h, 12-h, and 24-h accumulated total typhoon lightning activity and the maximum sustained winds 48 h later are 0.76, 0.85, and 0.92, respectively. The minimum surface pressure within Typhoon Usagi (2007) dropped abruptly by 31 hPa between 0000 UTC 28 July and 0000 UTC 30 July. The hourly flash rate soared during this intensification stage, suggesting that vigorous convective activity during this period produced multiple lightning events.

The maximum sustained wind speed of Typhoon Roke (2005) (Fig. 4) peaked at 41.2 m s^{-1} at 0000 UTC 16 July 2005 and persisted through 1200 UTC 16 July. The 6-h, 12-h, and 24-h 600-km lightning activity peaked simultaneously with the maximum wind speed. The correlation coefficients between 600-km lightning activity and simultaneous maximum wind are 0.64 at 6-h, 0.76 at 12-h, and 0.95 at 24-h intervals. The minimum surface pressure in Typhoon Roke (2005) dropped only 6 hPa between 0000 UTC 12 March and 0000 UTC 14 March. Lightning activity was weak during this period, and remained weak relative to the intensification period of other observed typhoons.

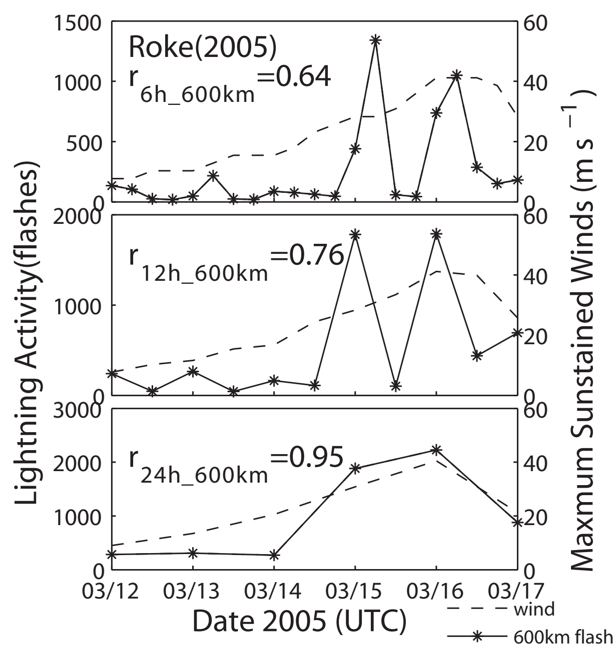

Fig. 4. The same as Fig. 3, but for Typhoon Roke (2005).

Figure 5 shows the evolution of lightning activity and maximum wind in Typhoon Pabuk (2007). The maximum wind peaked at 36 m s^{-1} at 1200 UTC 7 August 2007. The 6-h total typhoon lightning activity peak occurred 18 h after the maximum wind peak. The peaks of 12-h and 24-h 600-km lightning activity also lagged behind that of maximum wind, by 12 h and 24 h, respectively. The lag correlation coefficients between 600-km lightning activity and maximum wind are 0.69 at 6-h (18-h lag), 0.71 at 12-h (12-h lag), and 0.82 at 24-h (24-h lag). There were no lightning outbreaks during the intensification stage of Typhoon Pabuk (2007), but a lightning outbreak occurred during the dissipation stage.

Recent studies have shown that eyewall lightning bursts often occur prior to hurricane intensification (e.g., Molinari et al., 1994, 1999; Shao et al., 2005; Squires and Businger, 2008). On the basis of WWLLN observations, DeMaria and DeMaria (2009) suggested that lightning outbreaks in the outer rainband might be a better proxy for hurricane intensity than lightning outbreaks in the eyewall. Our results show that total typhoon lightning activity is strongly correlated to lightning outbreaks during periods of dramatic change in typhoon intensity.

Typhoon Kirogi (2005) (Fig. 6) also experienced lightning outbreaks during periods of dramatic changes in intensity. Lightning activity in Typhoon Kirogi (2005) was weak from 0000 UTC 13 October to 0000 UTC 15 October 2005, when the maximum sustained wind speed was roughly constant. By contrast, lightning activity was strong during periods when the maximum wind speed was changing. The evolution of lightning activity during Typhoon Fitow (2007) (Fig. 7) was similar: the number of lightning flashes soared during the intensification period (0000 UTC 28 August to 0000 UTC 30 August, 2007), but the lightning activity was weak for several days as the intensity of the typhoon remained roughly constant.

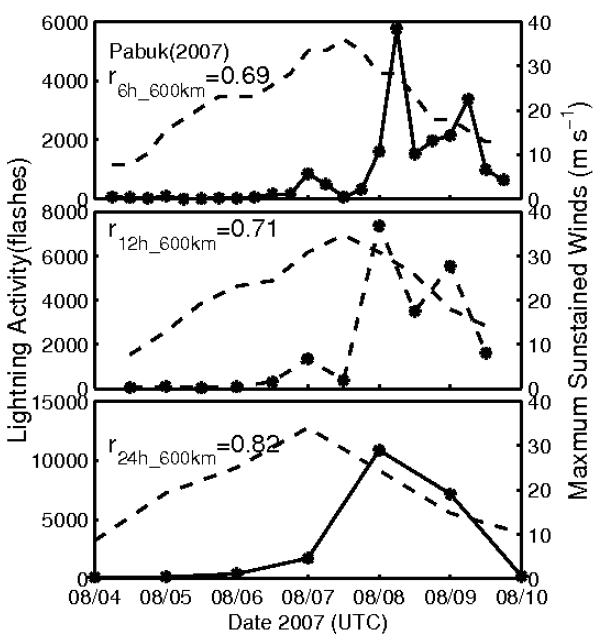

Fig. 5. The same as Fig. 3, but for Typhoon Pabuk (2007).

Price et al. (2009) performed a correlation analysis for 56 super hurricanes and reported a mean correlation between lightning activity and wind speed of 0.82. This study used a similar method. Figure 8 shows distributions of the lag time between maximum lightning activity and maximum sustained winds for weak (category 1–3) typhoons and super (category 4–5) typhoons (Fig. 8). These lag times were obtained by identifying the maximum lag correlation between

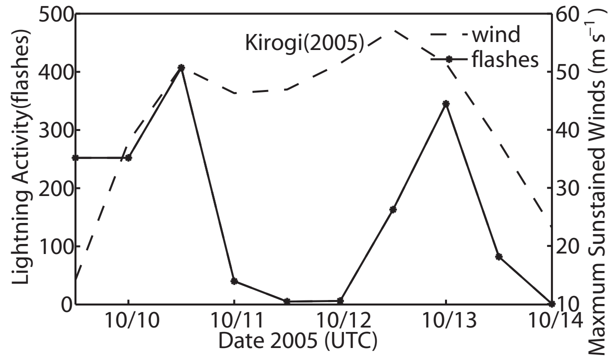

Fig. 6. Evolution of total accumulated lightning within 600 km over 24 h (solid curve) and maximum sustained winds (dashed curve) during Typhoon Kirogi (2005).

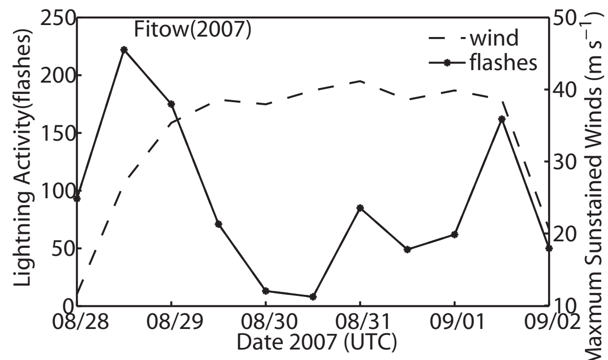

Fig. 7. The same as Fig. 6 but for Typhoon Fitow (2007).

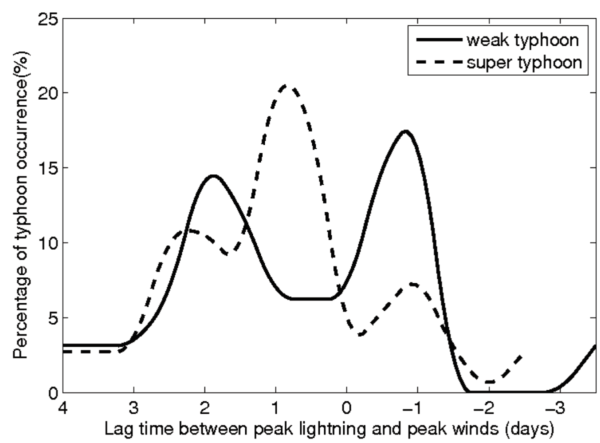

Fig. 8. Distributions of lag times between maximum lightning activity and maximum sustained winds in 32 weak typhoons and 37 super typhoons.

the two datasets. Lag correlations were calculated by shifting the lightning activity time series relative to that of maximum sustained wind by 12-h increments within the range from −4 to +3.5 days. A positive lag time indicates that lightning activity peaked prior to the maximum wind intensity, while a negative lag time indicates that lightning activity peaked after the maximum wind intensity.

Lightning activity peaked before maximum wind intensity in nearly 56% of the weak typhoons, with an average lag of 60 h (geometric mean). Lightning activity peaked before maximum wind intensity in 78% of super typhoons, with a geometric mean lag of 30 h.

Lightning activity peaked after maximum sustained winds in about 15% of weak typhoons. This result seems to be related to intensification of convection after landfall in these storms. Table 4 provides a statistical summary of 10 weak typhoons that made landfall; as expected, peak lightning activity generally occurred within one day of typhoon landfall.

Table 5 provides additional information on these 10 land-

Table 4. Information regarding 10 weak typhoon cases.

Storm	Year	Landfall location	Lanfall time	Wind speed peak time	Lightning peak time
Sanvu	2005	Philippines	12 Aug	1200 UTC 12 Aug	0000 UTC 13 Aug
		Guangdong, China	0445 UTC 13 Aug		
Kaemi	2006	Taiwan, China	1645 UTC 24 Jul	1200 UTC 21 Jul	0000 UTC 25 Jul
		Fujian, China	0750 UTC 25 Jul		
Pabuk	2007	Taiwan, China	1700 UTC 7 Aug	1200 UTC 07 Aug	0000 UTC 8 Aug
		Hong Kong, China	0800 UTC 10 Aug		
		Guangdong, China	1030 UTC 10 Aug		
Halong	2008	Philippines	17–18 May	1200 UTC 17 May	1200 UTC 18 May
Fengshen	2008	Philippines	21–22 Jun	0000 UTC 21 Jun	0000 UTC 22 Jun
		Guangdong, China	1930 UTC 23 Jun		
Fung-Wong	2008	Taiwan, China	1830 UTC 27 Jul	1800 UTC 27 Jul	1200 UTC 28 Jul
		Fujian, China	1400 UTC 28 Jul		
Chan-Hom	2009	Philippines	7–8 May	1800 UTC 06 May	0000 UTC 8 May
Linfa	2009	Philippines	16 Jun	1200 UTC 20 Jun	0000 UTC 21 Jun
		Fujian, China	1230 UTC 22 Jun		
Morakot	2009	Taiwan, China	1550 UTC 7 Aug	0600 UTC 07Aug	0000 UTC 8 Aug
Koppu	2009	Guangdong, China	2300 UTC 14 Sept	1800 UTC 14 Sept	0000 UTC 15 Sept

Table 5. Information and correlation coefficients (r) between lightning (600-km) and maximum wind for 11 typhoons that did not make landfall. Lightning activity in the inner core and within 600-km of the center is also summarized for the 11 no-landfall typhoons and 10 landfall typhoons.

				Flashes (h^{-1})	
Storm	Year	Lag time (h)	r	100 km	600 km
No landfall					
Sonca	2005	24	0.87	13.1	178.27
Nesat	2005	12	0.79	38.85	303.13
Kirogi	2005	60	0.63	20.93	80.66
Yagi	2006	36	0.6	44.99	153.7
Soulik	2006	80	0.8	0.63	54.72
Kong-Rey	2007	12	0.75	4.47	5.32
Yutu	2007	12	0.8	6.93	113.04
Kajiki	2007	12	0.9	23.64	250.6
Rammasun	2008	12	0.78	12.11	229.93
Nakri	2008	−60	0.78	7.47	100.25
Dolphin	2008	36	0.8	36.18	247.04
Landfall					
Sanvu	2005			8.75	2316.81
Kaemi	2006			48.46	949.65
Pabuk	2007			193.35	1820.85
Halong	2008			19.7	405.97
Fengshen	2008			65.19	836.23
Fung-Wong	2008			14.43	1147.63
Chan-Hom	2009			41.31	803.3
Linfa	2009			9.69	712.76
Morakot	2009			1.99	143.34
Koppu	2009			9.67	1964.77

fall weak storms and 11 storms that did not make landfall and that were consistently located far from land. Of the 11 typhoons that did not make landfall, 10 of them had peak lightning activity that preceded the maximum wind speed, while only one typhoon had peak lightning activity that lagged behind the maximum sustained wind speed. The mean correlation coefficient is 0.77. Table 5 also shows that lightning activity is typically substantially greater in landfalling typhoons than in typhoons that do not make landfall. This difference was observed in both the inner cores and within 600 km of the storm centers. A number of factors are responsible for the different lightning activity between landfall and no-landfall typhoons. One possible reason is the amount of cloud condensation nuclei (CCN), which greatly increases close to land, and influences the microphysics and drop size distribution greatly by favoring the nucleation of more small drops. This can also enhance the production (through riming on frozen drops) of ice pellets and graupel aloft compared to fewer larger drops over water produced via efficient coalescence (Rogers and Yau, 1989; Williams and Stanfill, 2002), as fewer CCN compete for an abundant supply of moisture. Another possible reason is the east–west SST gradients in the western Pacific, which will enhance the lightning activity during the landfall of typhoons. And the third possible reason is the orographic forcing of clouds and the lifting due to topography and the convective available potential energy (Qie et al., 2003) as the storms make landfall.

Figure 9 shows correlation coefficients between lightning activity and maximum sustained wind speed for 32 weak typhoons (Fig. 9a) and 37 super typhoons (Fig. 9b), taking into account the lag times identified for each storm. The names of the typhoons are shown along the x-axis and the correlation coefficients are shown using different symbols to represent different levels of statistical significance. The mean correlation between lightning activity and maximum sustained winds is stronger for weak typhoons (0.81) than for super typhoons (0.74). The correlation in this study for the super typhoons is lower than the value $(r = 0.82)$ calculated by Price et al. (2009) because we used 12-h accumulated total typhoon lightning activity within 600 km instead of mean daily lightning activity. If we instead consider a fixed lag time of 24 h between the lightning activity peak and the maximum wind speed peak in all typhoons, 37 out of 69% (54%) of the typhoons show a positive correlation among them, with a mean correlation of 0.72.

The intensity of a tropical storm is controlled by many factors, and in many cases it is difficult to isolate the effects of one factor from those of another. Changes in TC intensity are governed mainly by internal dynamics (e.g., eyewall contraction, eyewall replacement cycles, and interactions between the inner core and outer rainband) and environmental conditions (e.g., vertical wind shear, moisture distributions, sea surface temperature, and ocean mixed layer temperature and depth). Fierro et al. (2011) showed the relation between lightning bursts and the existence of deep convective clouds in mature hurricanes using in-situ tail Dopper radar data from aircraft reconnaissance. The results from DeMaria et al. (2012) suggested that the rainband lightning flash rate could be a better proxy for imminent TC intensification while eyewall lightning bursts were essentially more correlated with the end of an intensification cycle. They also found that TC intensification would be expected via axisymmetrization of convective heat from a newly formed vertical hot tower around the eyewall. Gallina and Velden (2002) noted time lags between changes in the vertical wind shear and changes in TC intensity. The detrimental effect that vertical wind shear exerts on a TC has been explained as "ventilation" (Gray, 1968): the wind shear advects upper-level warm air away from the low-level center. The low-level moisture inflow provides moisture to the upper-level. If the upper-level outflow is too strong, ice and snow will be taken away from upper-level regions and consume the supercooled water in the mixed phase region. Lightning is related to the vertical wind shear, which modifies TC intensity through its influence on microphysical processes within the storm.

4. Summary and conclusions

The lightning activity in 69 typhoons over the Northwest Pacific during 2005–09 was investigated, with particular focus on the relationships between lightning frequency and typhoon intensity. The 69 typhoons were classified into weak and super typhoons according to their intensity based on the Saffir–Simpson scale, and 32 weak typhoons (categories 1–3) and 37 super typhoons (categories 4–5) were observed. The average flash rate and lightning density varied significantly from one typhoon to another. The maximum lightning density occurred in the category 2 Typhoon Mitag (2007), with a value of 510.42 d^{-1} $(100\ km)^{-2}$. The minimum was observed in the category 2 typhoon Kong-Rey (2007) with a value of only 1.15 d^{-1} $(100\ km)^{-2}$. The average lightning density in the inner core of super typhoons is more than twice as large as that for weak typhoons. Both groups of typhoons showed a near-monotonic decrease in lightning density with radius. There was a significant difference between these two groups insofar as that the geometric mean and median lightning density in the inner core of super typhoons were greater than those of weak typhoons. On the contrary, the outer rainband lightning activity showed a reverse tendency. The average lightning density decreased with radius from the typhoon center. Lightning activity was more active in typhoons that made landfall than in those did not.

Comparisons of correlations between lightning activity accumulated over 6-h, 12-h, and 24-h intervals and corresponding maximum wind speeds revealed that correlations were stronger at longer time intervals (i.e., 24-h); however, 12-h 600-km correlation coefficients were found to be capable of truly representing the relationship between lightning activity and maximum sustained winds. Mean correlation coefficients between 12-h accumulated flashes within 600 km of the storm center were 0.81 for weak typhoons and 0.74 for super typhoons. Lightning activity peaked before maximum wind intensities in more than 78% (56%) of super(weak) typhoons with a geometric mean lag of 30 (60) h. Thirty-seven

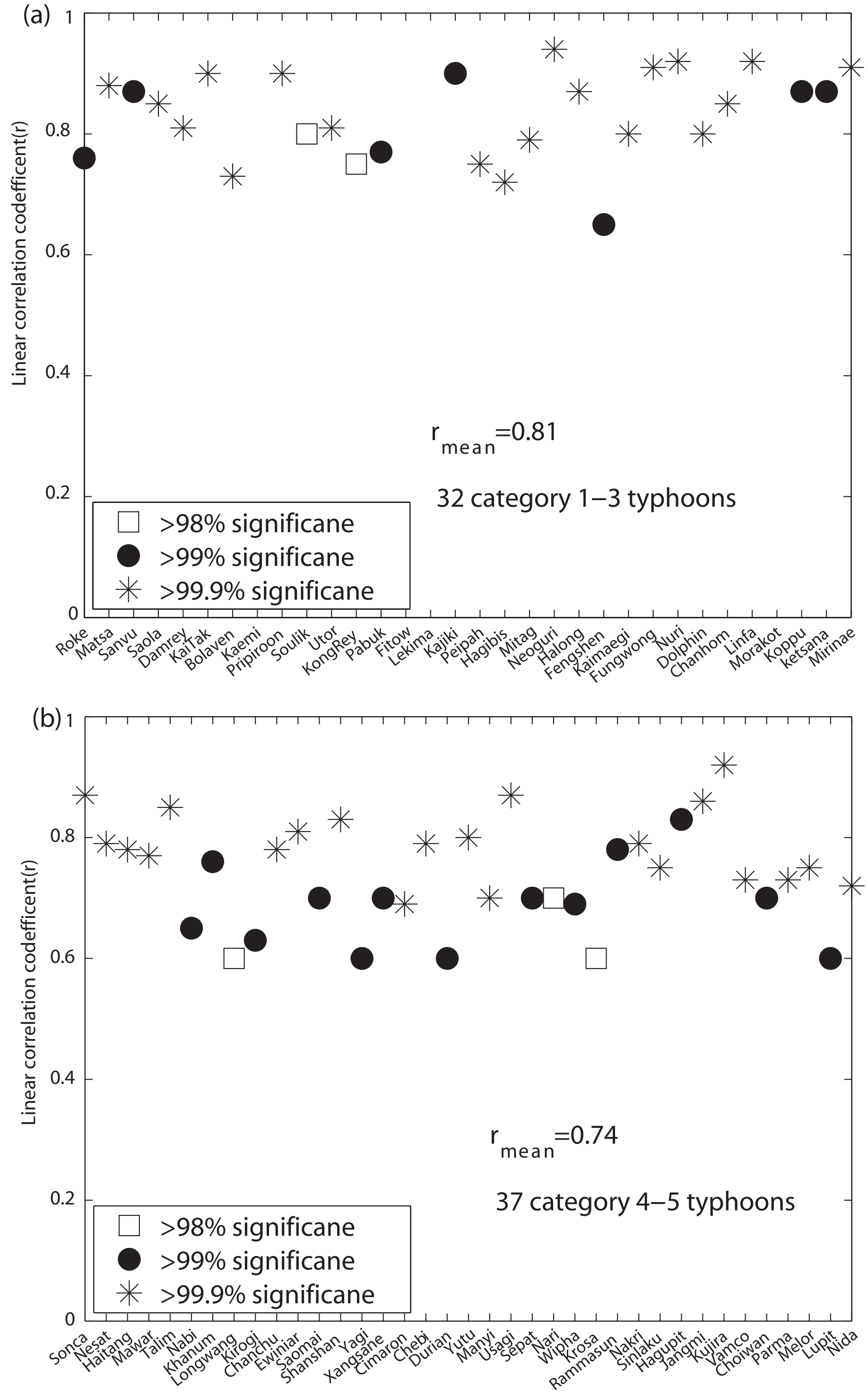

Fig. 9. Correlation coefficients between maximum sustained winds and lightning activity. Each point represents one typhoon, and different symbols represent different levels of statistical significance.

out of 69% (54%) of the typhoons showed a positive correlation between lightning activity peak and the maximum wind speed peek with a constant lag time of 24 h, and with a mean correlation of 0.72. Due to the physical relationship between the lightning flashes and updraft, ice particles, and supercooled water within a convective storm (Lang and Rutledge, 2008; Yuan and Qie, 2008; Liu et al., 2011), lightning information could be used as an early indicator of a strengthening updraft within a thunderstorm (Schultz et al., 2009; Qie, 2012), and hence the intensity of typhoon. Regional ground-based total lightning networks [e.g., NLDN, Lightning Detection and Ranging (LDAR) etc.], while highly accurate and useful in terms of regional observation, are limited in range and have very minimal coverage over oceanic regions. Therefore, the WWLLN data, together with the ongoing Geostationary Lightning Mapper (GLM) aboard future geostationary satellite platforms, will help to advance understanding of the lightning activity in TCs, and could be used as an early warning system for the strengthening of typhoons.

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