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Research Article

Drag Coefficient during Strong Typhoons

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Using data from wind towers during typhoons Hagupit and Nuri, drag coefficient was estimated. The relationship between drag coefficient and atmospheric stability was examined. The results indicate that the drag coefficient decreased when atmosphere stability changed from weakly stable or unstable to neutral. Relationship between drag coefficient and wind speed was also examined, and the results indicate that the relationships between drag coefficient and wind speed were similar to other researchers' result, but the wind thresholds were different due to different observation sites. Quantitative expressions between drag coefficient and wind speed were derived.

1. Introduction

Drag coefficient, an important factor to parameterize the wind stress on the sea surface, is widely used in modeling both atmospheric and oceanic dynamics, remote sensing, and other applications. In order to simulate the exact sea surface condition, accurate estimation of drag coefficient is urgently needed. Owing to the complicated water-air interaction on the sea surface, present parameterizations of the wind stress, or equivalently the drag coefficient, over the sea are far from satisfactory [1]. To help resolve this dilemma, there have been many attempts to estimate the drag coefficient. Geernaert et al. [2] reported on the behavior of the drag coefficient in relation to sea state during moderate to high wind speeds based on data collected over a water column depth of 15 m. Rao [3] compared drag coefficient in two different sites using MONTBLEX-90 data. Grachev et al. [4] derived a a new formulation for the neutral drag coefficient in the convective boundary layer, based on the idea that free convection can be considered as a particular case of forced convection. Mahrt et al. [5] examined the dependence of the surface drag coefficient on stability, wind speed, mesoscale modulation of the turbulent flux using data sets collected over grassland, sparse grass, heather, and two forest sites.

Drag coefficients under tropical cyclones have been examined. Powell et al. [6] presented that the drag coefficient levels off and starts to decrease with a further increase in the wind speed at wind speeds increasing above hurricane values of about 33 m/s, which is contrary to the behavior of the drag coefficient parameterizations that are currently used in ocean and atmosphere applications. Moon et al. [7] found that the drag coefficient increased with wind speed at lower winds, but the rate of its increase was significantly reduced at high winds and there was a leveling off or even decrease in certain sectors. Makin [8] predicted the reduction of the drag coefficient for the wind speed exceeding hurricane values of 30–40 m/s in agreement with field data according to a resistance law of the sea surface at hurricane winds.

In order to determine drag coefficient on the sea surface and provide a reference for modeling of typhoon, drag coefficients estimated from the turbulence measurements during typhoons Hagupit and Nuri were analyzed. The main aim of the present paper is to estimate the relationship between drag coefficient and wind speed during typhoon using experimental data.

2. Analytical Data Description and Data Quality Control

2.1. Data Description. Two typhoon cases were selected. Song et al. [9] presented two criteria according to the eddy structure of typhoon and the Beaufort scale of strong typhoon

wind. (i) The wind direction with wind speed exceeding 8th grade Beaufort scale (10 min mean wind speed of 8th grade is 17.2 m/s) successively alters over 120°. (ii) The variation of wind speed with time shows an "M" shape during the passage of typhoons and if a low wind speed less than 11 m/s occurs between two peak values, it can be judged as the typhoon eye area. The two criteria should be fulfilled at the same time to prove whether the typhoon center has passed over the observation site. According to the two criteria, two cases were selected to analyze drag coefficient during strong typhoons: typhoon Nuri (observed from Sanjiao Island) and typhoon Hagupit (observed from Zhizai Island). Both of the two selected typhoon observations captured the passage of typhoon's eye wall and eye, and this representative observation is called typical typhoon [10]. The typhoon tracks and the positions of the observation sites, Sanjiao Island (where typhoon Nuri was observed) and Zhizai Island (where typhoon Hagupit was observed), are showed in Figure 1 and Table 1.

Typhoon Nuri made landfall in the coastal region of the Sai Kung Sea in Hong Kong at 04:55 pm on 22nd Aug 2008 (Beijing time, hereinafter the same). The center of typhoon Nuri passed the tower located in Sanjiao Island at 18:50 on August 22, 2008, and the shortest distance from Sanjiao Island to typhoon center is about 32 km. Data from Sanjiao Island during typhoon Nuri were collected. Sanjiao Island is located on the sea. The distance between northeastern coast of Macao and the island is about 12 km (Figure 1). The surface was covered by grass and bushes (Figure 2(a)). The wind tower was installed on a 93-meter high hill and was equipped by ultrasonic anemometers at the height of 10 m and 60 m. The sonic data from 00:00 am on August 22 to 23:59 pm on August 23, 2008, were chosen to calculate drag coefficient and other parameters. Drag coefficient, mean wind speed, wind direction, and turbulence statistics have been calculated for period of 10 min, and so there are 288 samples of typhoon Nuri observations.

Strong typhoon Hagupit made landfall in the coastal region of Chencun Town, Dianbai County, Maoming, Guangdong Province, at 06:45 am on September 24, 2008. The center of typhoon Hagupit passed the tower located in Zhizai Island at 05:10 on September 24, 2008, and the shortest distance from Zhizai Island to typhoon center is about 8.5 km. In this paper, data from Zhizai Island during typhoon Hagupit were collected. The wind tower was installed on a 10-meter high hill on Zhizai Island which is located on the sea. The shortest distance between the 100 m high observation tower sites at Zhizai Island and the coast is 4.5 km (Figure 1). The surface was covered by sand and sparse weed. The terrain situation is illustrated in Figure 2(b). An ultrasonic anemometer was placed at the height of 60 m. High frequency (10 Hz) observations of turbulence and the virtual temperature were obtained from the ultrasonic anemometer. The sonic data from 0:00 am to 23:59 pm on September 24, 2008, were chosen to calculate drag coefficient and other parameters. Turbulence statistics have been calculated for period of 10 min, and so there are 144 samples of typhoon Nuri observation. The wind data from the observation tower were classified into "onshore wind" and "offshore wind," and detailed information of the two typhoon observations is showed in Table 1. Considering the complex surface of alongshore direction, along winds were not analyzed in this work.

2.2. Data Quality Control. Before analyzing, all the data were preprocessed as follows [11].

(1) Find the turbulence data spikes. Referring to Højstrup's [12] and Vickers and Mahrt's [13] methods, data satisfying the following formula can be considered as spikes:

$$|dx(i)| \geq 4\sigma, \tag{1}$$

where x is the series of u, v, w, $dx(i) = x(i+1) - x(i)$ and σ is the standard deviation of series x.

(2) Remove and interpolate the spikes by Højstrup's [12] method:

$$x(i) = x(i-1)R_m + (1 - R_m)X_m, \tag{2}$$

where m is a constant ($m = 10$ in this paper), R_m is the correlation coefficient between the series $x(i-m : i-3)$ and $x(i-m+2 : i-1)$, and X_m is the mean value of the series $x(i-m : i-1)$.

3. Analysis and Results

3.1. Wind Characteristics. Using data from the ultrasonic anemometers on the wind tower located in Sanjiao Island, wind speed and direction during typhoon Nuri were calculated and are showen in Figures 3(a) and 3(b). At 60 m height, the maximum wind speed was 32.7 m/s, and the minimum wind velocity was 15.0 m/s. The significant "M-" shaped bimodal distribution was also found. The wind direction altered more than 120° counterclockwise. Compared with the two criteria, typhoon Nuri is a typical typhoon.

Figure 3(c) shows wind speed and direction during typhoon Hagupit. It can be seen that the wind direction altered 120° in the clockwise direction with the wind speed over 8th grade Beaufort scale. The significant "M-" shaped bimodal distribution was found, and the minimum value of wind speed between two peaks was 11.9 m/s, and the maximum value of the whole typhoon was 45.9 m/s. All of the characteristics of the wind speed and direction well satisfied the two criteria mentioned above in Section 2, suggesting that typhoon Hagupit is also a typical typhoon.

3.2. Drag Coefficient during Strong Typhoons. The drag coefficient is found directly by evaluating the ratio of the friction velocity and the mean wind speed difference squared as follows:

$$C_d = \left(\frac{u_*}{U}\right)^2, \tag{3}$$

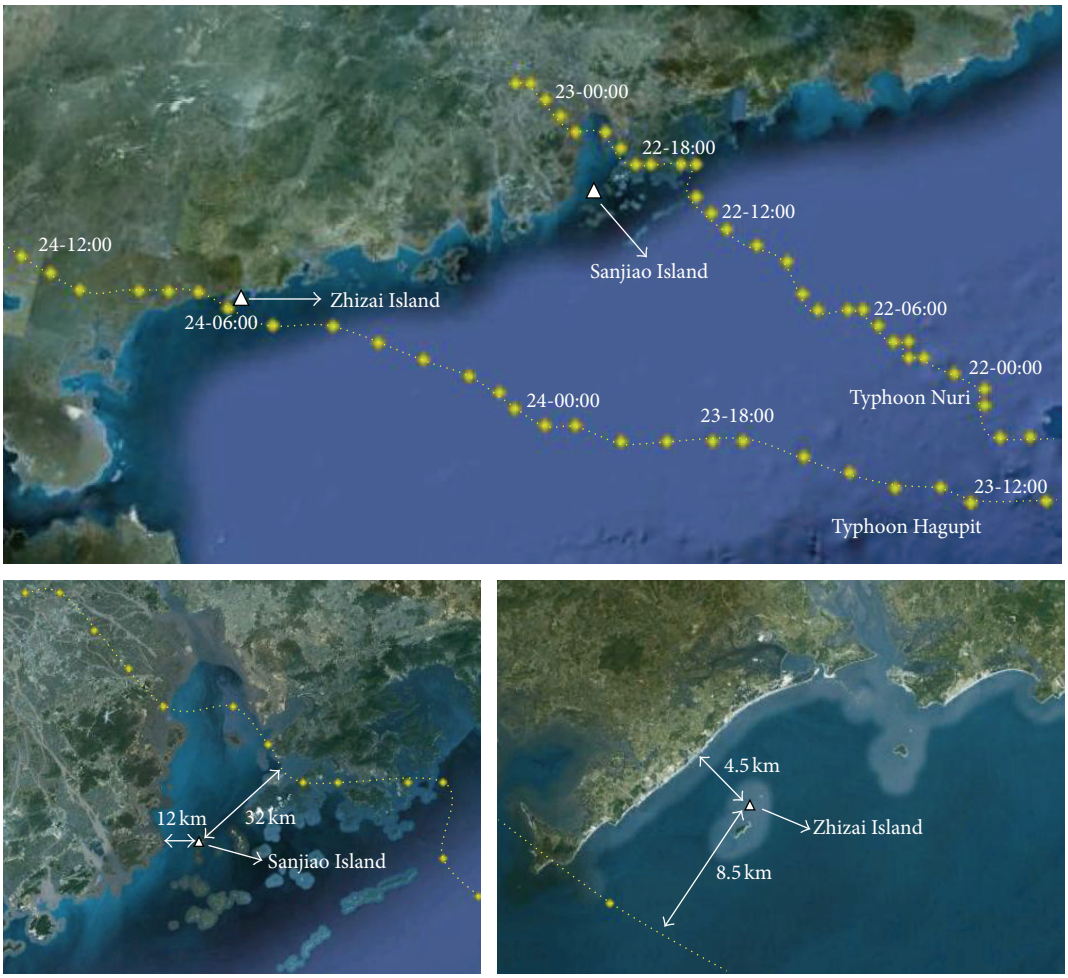

Figure 1: Typhoon tracks (yellow dotted lines) and positions of the observation sites Zhizai Island and Sanjiao Island. The distance between northeastern coast of Macao and the Sanjiao Island is about 12 km, and the shortest distance between the 100 m high observation tower sites at Zhizai Island and the coast is 4.5 km. The center of typhoon Nuri passed the tower at 18:50 on August 22, 2008, and the shortest distance from Sanjiao Island to typhoon center is about 32 km. The center of typhoon Hagupit passed the tower at 05:10 on September 24, 2008, and the shortest distance from Zhizai Island to typhoon center is about 8.5 km.

(a) (b)

Figure 2: Sites of wind tower: (a) Sanjiao Island (where typhoon Nuri was observed) and (b) Zhizai Island (where typhoon Hagupit was observed).

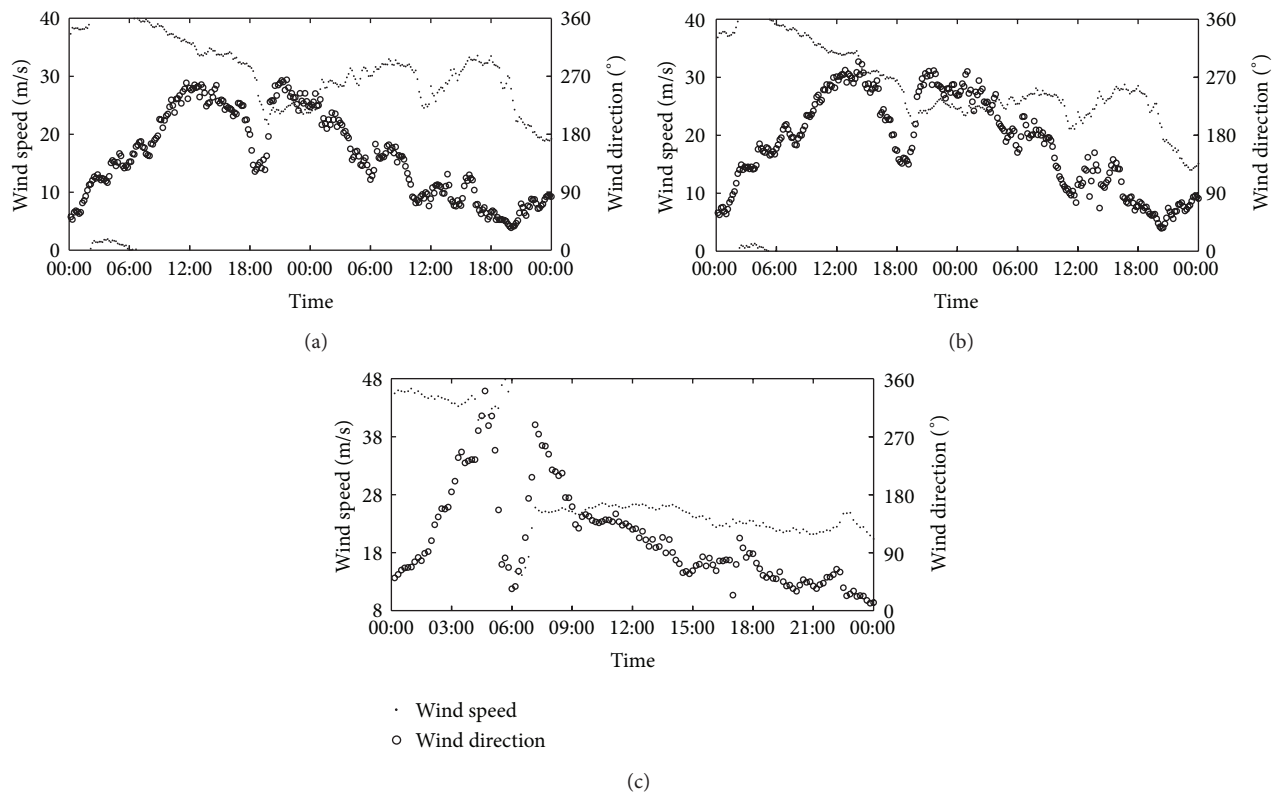

Figure 3: Wind speed and wind direction during strong typhoons: (a) typhoon Nuri from 00:00 am on August 22 to 23:59 pm on August 23, 2008, at 10 m height, (b) typhoon Nuri from 00:00 am on August 22 to 23:59 pm on August 23, 2008, at 60 m height, and (c) typhoon Hagupit from 0:00 am to 23:59 pm on September 24, 2008, at 60 m height.

Table 1: Detailed information of the two typhoon observations.

Observation site	Type of wind	Wind direction	Elevation of the observation site	Area of the observation site
Sanjiao Island (Nuri)	Offshore wind	0–75°, 270–360°	93 m	0.62 km^2
	Onshore wind	75–225°		
Zhizai Island (Hagupit)	Offshore wind	0–75°, 225–360°	10 m	0.0036 km^2
	Onshore wind	75–225°		

where u_* represents the friction velocity calculated from the flux data using the relation

$$u_* = \left(\overline{u'w'}^2 + \overline{v'w'}^2\right)^{1/4} \tag{4}$$

and U is 10-minute average wind speed.

Figure 4 shows drag coefficient during typhoon Nuri. In general, drag coefficients were different at different heights, but the variation trends with time were similar. Before typhoon center passed, drag coefficients at 10 m height were greater than that of 60 m height. When typhoon center passed the wind tower, increments of drag coefficient at the two heights were observed, due to the low wind speed in typhoon eye region. After typhoon center passed, drag coefficients at the two heights made little difference.

Figure 5 shows drag coefficient during typhoon Hagupit. Before the typhoon center passed, there was a peak value (0.0050) of the drag coefficient at 4:10. An hour after the typhoon center passed, the greatest drag coefficient appeared, with a value of 0.0234. During the period from 4:10 to 7:00, the drag coefficients changed dramatically, which may be resulted from low wind speed in typhoon eye region.

3.3. Variations of Drag Coefficient with Atmospheric Stability. The use of sonic data made it possible to calculate atmospheric stability by the fowling formula:

$$\varsigma = \frac{z}{L} = -\frac{kzg\left(\overline{w'\theta'_v}\right)}{\overline{\theta_v}u_*^3}, \tag{5}$$

where ς is atmospheric stability, z is height, and L is the Monin-Obukhov length. The von Karman constant $k = 0.4$ and the Gravitational acceleration $g = 9.8$. $\overline{\theta_v}$ is virtual potential temperature, w is vertical wind speed, and u_* is friction velocity.

Figure 6 is the atmospheric stability during typhoons Nuri and Hagupit. In order to compare atmospheric stability

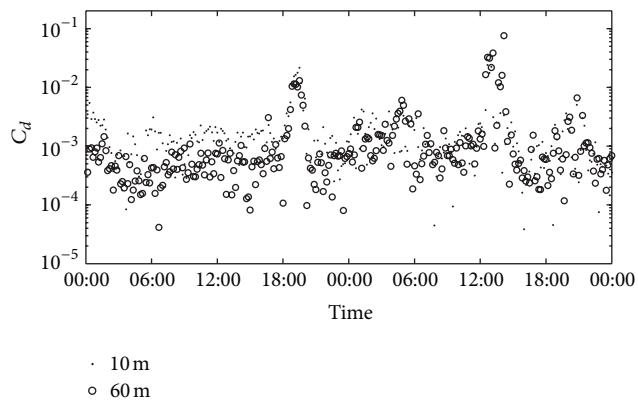

Figure 4: Drag coefficients during typhoon Nuri from 00:00 am on August 22 to 23:59 pm on August 23, 2008, at 10 m and 60 m height.

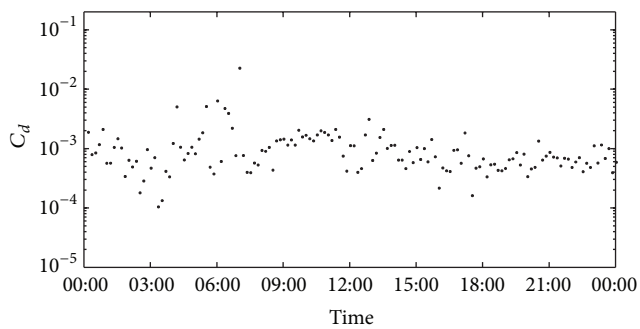

Figure 5: Drag coefficients during typhoon Hagupit from 0:00 am to 23:59 pm on September 24, 2008, at 60 m height.

between different typhoons before and after typhoon center passed, samples from 07:00 am on August 22 to 07:00 am on August 23, 2008, during typhoon Nuri were selected. During the period, the absolute values of atmospheric stability at 10 m height were close to zero, indicating the atmosphere stratification was nearly neutral. At 60 m height, the atmospheric stability varied from −2 to 2, indicating weak stable or weak unstable stratification. Before typhoon eye passed the difference of atmospheric stability between 10 m and 60 m height it was small. As winds were from the land before typhoon center passed, the small difference between the two heights indicated that the influence of land surface on atmospheric stability was similar at different heights. After typhoon center passed, atmospheric stability of most samples at 10 m height was greater than zero, while at 60 m height was smaller than zero. After typhoon center passed, winds were from the sea, with the large difference of atmospheric stability indicating that the influences of the sea surface on atmospheric stability were different at different heights.

Figure 7 shows variations of drag coefficient with atmospheric stability in onshore direction during typhoons Nuri and Hagupit. During typhoon Nuri (Figure 7(a)), atmospheric conditions are different at different heights. At 10 m height, ς is greater than zero, and drag coefficient reduces regularly as atmospheric stratification changes from neutral to weakly stable. At 60 m height, ς is lower than zero, and drag coefficient reduces regularly as atmospheric stratification changes from neutral to weakly unstable. The curve which can describe the regular variation of drag coefficient was derived from these observation data as follows:

$$C_d = \begin{cases} \exp\left(0.8660\varsigma^2 + 3.6106\varsigma - 6.0184\right), \\ \exp\left(13.0547\varsigma^2 - 15.8059\varsigma - 5.9793\right). \end{cases} \quad (6)$$

During typhoon Hagupit, variation of drag coefficient with atmospheric stability is not so regular like typhoon Nuri, and no relationship was found between drag coefficient and atmospheric stability during typhoon Hagupit.

3.4. Variation of Drag Coefficient with Wind Speed in Onshore Direction. The data pairs (C_d, U) in onshore direction are graphically presented in Figure 8. In general, variation trends of drag coefficient with wind are similar for the two typhoons. It can also be seen that variation trends of drag coefficient with wind are accordant at different heights during typhoon Nuri. Drag coefficient increases until wind speed reaches a certain threshold and decreases when wind speed is greater than the threshold. For different typhoons, the thresholds are different. The threshold is about 15 m/s for typhoon Nuri, 25 m/s for typhoon Hagupit, and 40 m/s for other researchers' [6].

During typhoon Nuri, drag coefficient assumes very large values in the onshore direction for the wind speed reaches about 25 m/s at both 10 m and 60 m height. The relationship between drag coefficient and wind speed in onshore direction can be described by the following formulae:

$$C_d = \begin{cases} 10^{-3}\left(0.0284U^2 - 3.9000U + 14.2000\right), & U \le 15\,\text{m/s}, \\ 10^4 \times 8.4061U^{-5.5597}, & U > 15\,\text{m/s}. \end{cases} \quad (7)$$

During typhoon Hagupit, drag coefficient ranges from 0.0007 to 0.003. Drag coefficient increases slowly until wind speed reaches about 25 m/s. When wind speed is greater than 25 m/s, there are only several samples; nevertheless, it could be seen that drag coefficient decreases regularly with wind speed. A least squares analysis on the data pairs in onshore wind direction produced the following "best fit" regression equation:

$$C_d = \begin{cases} 10^{-3}\left(0.0063U^2 - 0.1499U + 1.500\right), & U \le 25\,\text{m/s}, \\ 3.0541U^{-2.3837}, & U > 25\,\text{m/s}. \end{cases} \quad (8)$$

Figure 9 shows the average drag coefficient of typhoons Hagupit and Nuri in onshore direction. Here drag coefficients from different sites at the same height are compared. In the onshore direction at 60 m height, drag coefficient during typhoons Hagupit and Nuri makes some difference for different speed bins. In general, when wind speed is greater than 10 m/s and lower than 25 m/s, drag coefficient of typhoon Nuri is far greater than that of typhoon Hagupit. When wind speed is greater than 25 m/s, drag coefficient of typhoon Nuri reaches the same order of magnitude as typhoon Hagupit.

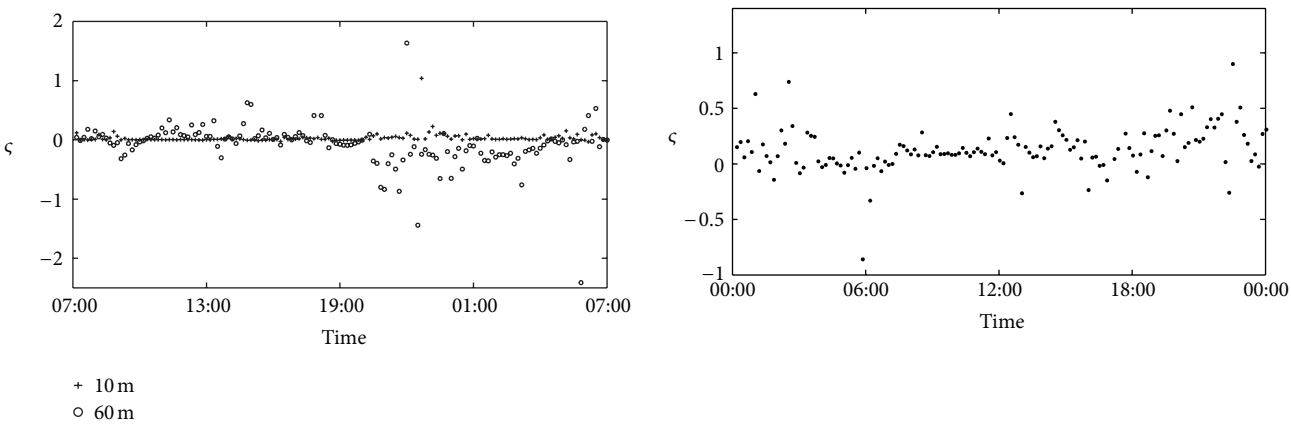

Figure 6: Atmospheric stability during strong typhoons: (a) typhoon Nuri from 00:00 am on August 22 to 23:59 pm on August 23, 2008, at 10 m and 60 m height and (b) typhoon Hagupit from 0:00 am to 23:59 pm on September 24, 2008, at 60 m height.

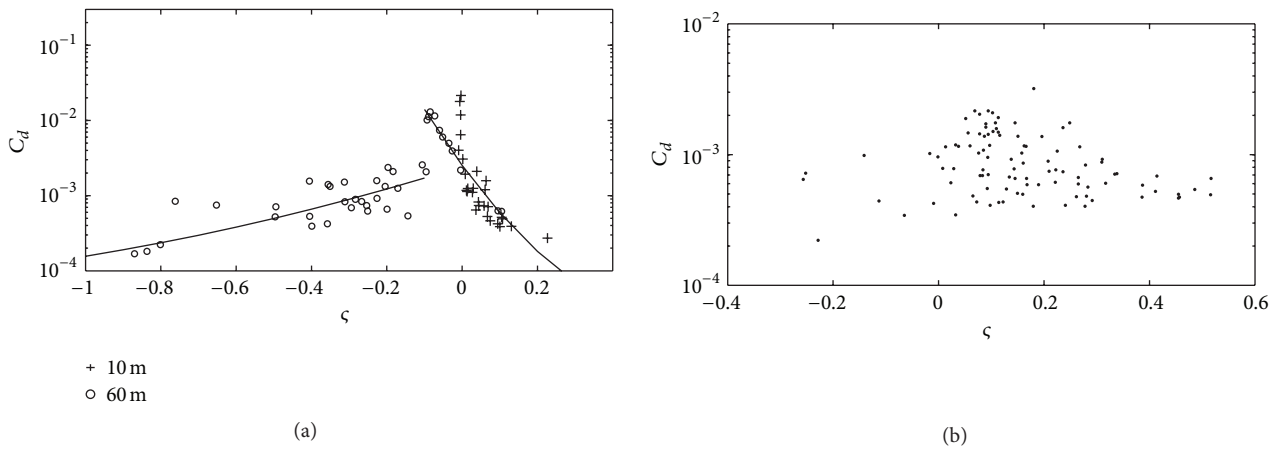

Figure 7: Variations of drag coefficient with atmospheric stability in onshore direction during strong typhoons: (a) typhoon Nuri at 10 m and 60 m height and (b) typhoon Hagupit at 60 m height.

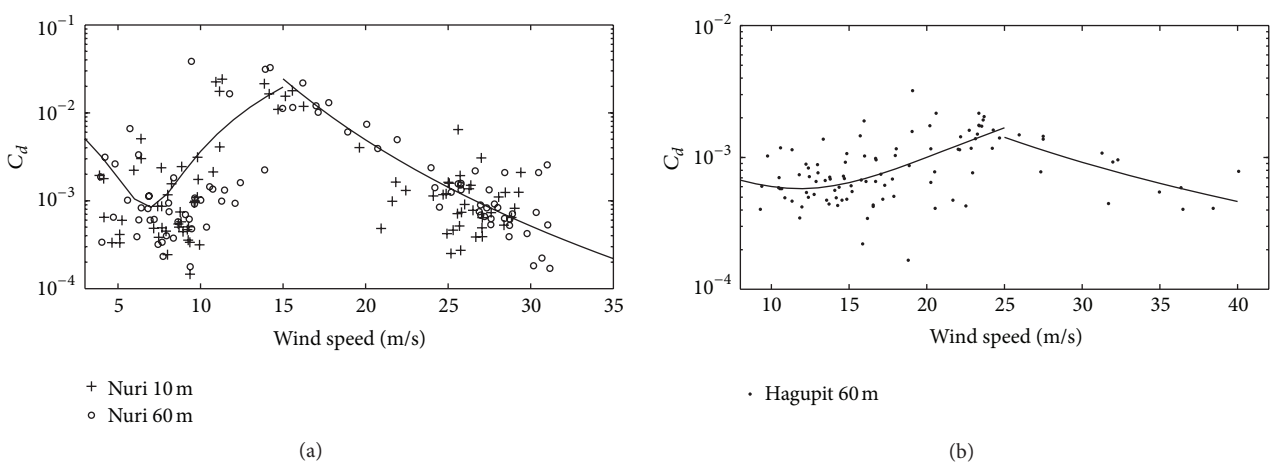

Figure 8: Drag coefficient as a function of wind speed during strong typhoons in onshore direction: (a) typhoon Nuri and (b) typhoon Hagupit.

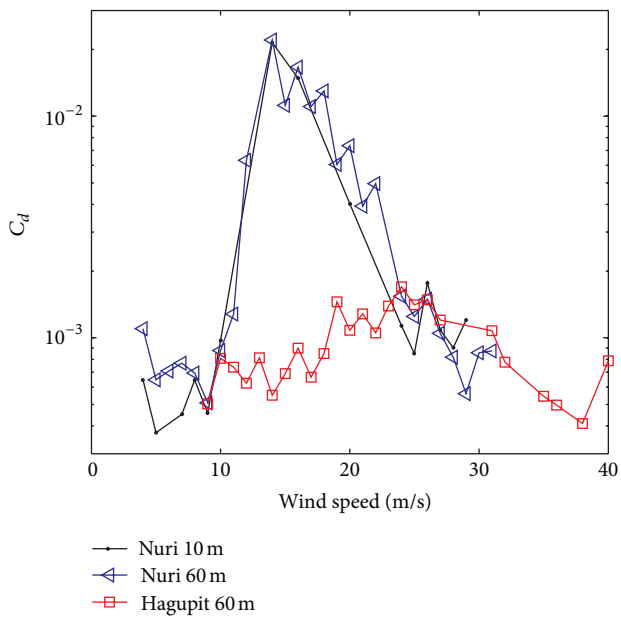

Figure 9: Average drag coefficient of typhoons Hagupit and Nuri in onshore direction, and the wind speed bin is 1 m/s.

By comparing drag coefficients at the two heights during typhoon Nuri, it can be found that the relationships between drag coefficient and wind speed are similar at different heights.

Another fact which is worth noting is that wind thresholds for typhoon Nuri and typhoon Hagupit are different from other researchers' result [6]. It is maybe resulted from different observation sites. Typhoon Nuri was observed from a tower located on a 93-meter high hill, while typhoon Hagupit was observed from a tower located on a 10-meter high hill. Furthermore, Sanjiao Island where typhoon Nuri was observed covers an area of 0.62 km^2, while Zhizai Island only covers an area of 0.0036 km^2. The average distance from the tower to the edge of Sanjiao Island is about 840 m and to Zhizai Island is about 45 m in the onshore direction. Winds from the onshore direction are mainly affected by the sea surface but are also influenced by the land where the tower is located. These observation environments make the sea surface roughness length, arisen from wave or other factors from open sea surface produce lesser effect on drag coefficient during typhoon Nuri. That is to say, relationships between drag coefficient and wind speed derived from typhoon Nuri and typhoon Hagupit are not from real open sea surface. Powell et al.'s [6] experiment was conducted in open sea, and was not affected by land. These different observation sites may be why the wind thresholds are different for different typhoons. Consequently, whether the observation data are affected by land may be a key factor which determines the threshold. Considering other researchers' experiments from open sea and these experiments from islands in this work, it can be concluded that the larger area of the land where observation data are collected is responsible for the lower threshold of wind speed.

3.5. Variation of Drag Coefficient with Wind Speed in Offshore Direction. Figure 10 shows the variation of drag coefficient with wind speed during typhoons Nuri and Hagupit in offshore direction. It can be seen that drag coefficient fluctuates obviously from 0.0001 to 0.001 during typhoons Nuri and Hagupit, and no regular relationship is found between drag coefficient and wind speed. It may be resulted from the distance from the observation tower to shore and complex land surface in offshore direction.

4. Conclusion

Using data from wind towers during typhoons Hagupit and Nuri, drag coefficient was estimated. The relationship between drag coefficient and atmospheric stability was examined, finding that the drag coefficient decreased when atmosphere stability changed from weakly stable or unstable to neutral. Relationship between drag coefficient and wind speed was also examined, and the result indicated that the relationships between drag coefficient and wind speed were similar to other researcher's result, but the wind thresholds were different due to different observation sites. Some preliminary conclusions are obtained as follows.

(1) By comparing atmospheric stability at the two heights during typhoon Nuri in onshore direction, it is found that atmospheric conditions are different at different heights. At 10 m height, $\varsigma > 0$, and drag coefficient reduces regularly as atmospheric stratification changes from neutral to weakly stable. At 60 m height, $\varsigma < 0$, and drag coefficient reduces regularly as atmospheric stratification changes from neutral to unstable. The curve which can describe the regular variation of drag coefficient is derived from these observation data as follows:

$$C_d = \begin{cases} \exp\left(0.8660\varsigma^2 + 3.6106\varsigma - 6.0184\right), \\ \exp\left(13.0547\varsigma^2 - 15.8059\varsigma - 5.9793\right). \end{cases} \quad (9)$$

(2) In onshore direction at 60 m height, drag coefficient during typhoons Hagupit and Nuri makes some difference for different speed. In general, when wind speed is greater than 10 m/s and lower than 25 m/s, drag coefficient of typhoon Nuri is far greater than that of typhoon Hagupit. When wind speed is greater than 25 m/s, drag coefficient of typhoon Nuri reaches the same order of magnitude as typhoon Hagupit. By comparing drag coefficients at the two heights during typhoon Nuri, it can be found that the relationships between drag coefficient and wind speed are similar at different heights.

(3) In onshore direction, relationships between drag coefficient and wind speed are derived from observation data of different typhoon cases, showing considerable difference between different typhoons.

During typhoon Nuri, the relationships between drag coefficient and wind speed are similar at 10 m and 60 m height:

$$C_d = \begin{cases} 10^{-3}\left(0.0284U^2 - 3.9000U + 14.2000\right), & U \le 15\ \text{m/s}, \\ 10^4 \times 8.4061U^{-5.5597}, & U > 15\ \text{m/s}. \end{cases} \quad (10)$$

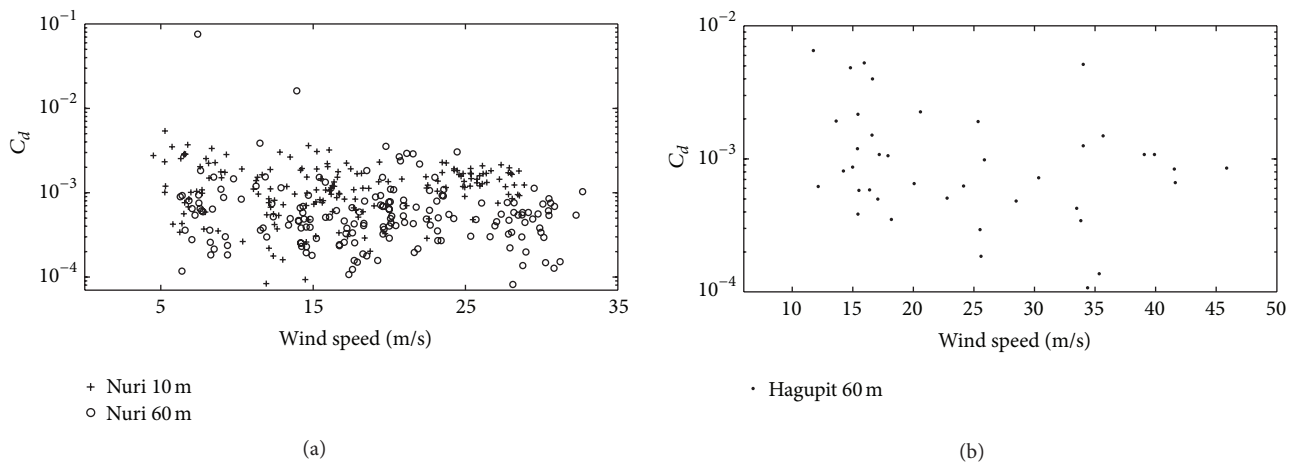

Figure 10: Variation of drag coefficient with wind speed during strong typhoons in offshore direction: (a) typhoon Nuri and (b) typhoon Hagupit.

During typhoon Hagupit at 60 m height,

$$C_d = \begin{cases} 10^{-3}\left(0.0063U^2 - 0.1499U + 1.500\right), & U \leq 25\,\text{m/s}, \\ 3.0541U^{-2.3837}, & U > 25\,\text{m/s}. \end{cases} \tag{11}$$

Considering the same expression of typhoon Nuri at different height, the relationship at 60 m height during typhoon Hagupit can be thought to work at 10 m height.

(4) Variation trends of drag coefficient with wind in this work are similar to other researcher's result, but the wind thresholds are different. Whether the observation data are affected by land may be a key factor which determines the threshold. Considering other researchers' experiments from open sea and these experiments from islands in this work, it can be concluded that the larger area of the land where observation data are collected is responsible for the lower threshold of wind speed. Here, the wind threshold is a value. Drag coefficient increases until wind speed reaches a certain threshold and decreases when wind speed is greater than the threshold.

Acknowledgments

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