Variations in Friction Velocity with Wind Speed and Height for Moderate-to-Strong Onshore Winds Based on Measurements from a Coastal Tower

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ABSTRACT

Variations in friction velocity with wind speed and height are studied under moderate ($\geq 9 \text{ m s}^{-1}$)-to-strong onshore wind conditions caused by three landfalling typhoons. Wind data are from a coastal 100-m tower equipped with 20-Hz ultrasonic anemometers at three heights. Results show that wind direction affects variations in friction velocity with wind speed. A leveling off or decrease in friction velocity occurs at a critical wind speed of $\sim 20 \text{ m s}^{-1}$ under strong onshore wind conditions. Friction velocity does not always decrease with height in the surface layer under typhoon conditions. Thus, height-based corrections on friction velocities using the model from Anctil and Donelan may not be reliable. Surface-layer heights predicted by the model that are based on Ekman dynamics are verified by comparing with those determined by a proposed method that is based on the idea of mean boundary layer using wind-profile data from one of the landfalling typhoons. Friction velocity at the top of the surface layer is then estimated. Results show that friction velocity decreases by about 20% from its surface value and agrees well with previous results of Tennekes.

1. Introduction

Several methods have been developed to calculate air–sea momentum flux exchange. The bulk transfer method has been widely employed because of its convenience by using the drag coefficient (Fairall et al. 2003; Zeng et al. 2010; Edson et al. 2013). As pointed out by Guan and Xie (2004), self-correlation is frequently encountered in studying the variation in drag coefficient with wind speed. According to the bulk transfer method, momentum flux can be calculated as

$$\tau = \rho_a C_{D10,n} u_{10,n}^2 = \rho_a u_*^2, \quad (1)$$

where ρ_a is the density of air; $C_{D10,n}$ and $u_{10,n}$ are the drag coefficient and wind speed, respectively, at 10 m above the sea surface under neutral conditions; and u_* is the friction velocity. The above equation indicates that momentum flux can be obtained from friction velocity if a relationship between $u_{10,n}$ and u_* has been established, with no need to obtain the relationship between $u_{10,n}$ and $C_{D10,n}$. Several studies have showed that $u_{10,n}$ and u_* are well correlated and that the relationship between them can be expressed using piecewise linear functions (Foreman and Emeis 2010; Andreas et al. 2012; Edson et al. 2013). Wind data in the above studies were collected from the open-ocean and nearshore sites. However, the nearshore measurements of Zhao et al. (2015) and the open-ocean measurements of Jarosz et al. (2007) indicate that u_* levels off or decreases at higher wind speeds. To the best of our knowledge, few studies

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have been conducted on variations in friction velocity at higher wind speeds using coastal wind data, which is one of our focuses in this study.

The boundary layer above the sea surface can be viewed as in three sections. The wave boundary layer is the lowest, adjacent to the sea surface. The atmospheric boundary layer (ABL) is the highest, adjacent to the free atmosphere. Between them is the surface layer, with a mean height of about 100 m. However, the surface layer may reach a height of several hundred meters over the ocean under typhoon conditions (Powell et al. 2003). It becomes more complicated and thicker with an increase in magnitude of 20%–30% for nearshore typhoons (Vickery et al. 2009). Constant friction velocity throughout the surface layer is a fairly restrictive assumption. Most often, friction velocity decreases with height. Anctil and Donelan (1996) proposed a model relating friction velocities at the surface to the measurement height (hereinafter the “A&D model”). This model was then used to correct the decrease in friction velocity with height at a nearshore site under neutral conditions. French et al. (2007) showed that the stress at the top of the ABL remains about 50%–75% of that at the sea surface (corresponding to about 70%–85% for friction velocity), and that the A&D model can provide comparable estimates for the decrease of friction velocity with height. Their conclusions were based on aircraft data from mature hurricanes over the open ocean far from the shoreline. Tennekes (1973) also showed that the stress decreases by some 30% from its surface value (corresponding to about 20% for friction velocity). Zhang et al. (2009) studied the turbulence structure in the hurricane boundary layer between outer rainbands using the same dataset. Their work showed that thermodynamic boundary layer heights estimated using virtual potential temperature profiles are roughly half those estimated using momentum flux profiles. Therefore, it is necessary to investigate the boundary layer height or structure and variations in friction velocity with height for the more-complicated surface layer at the coastline as typhoons make landfall.

Using high-frequency ultrasonic wind data from a 100-m coastal tower at three heights, variations in friction velocity with wind speed and height are studied under moderate-to-strong onshore wind conditions. A method to determine the surface-layer height in typhoons is proposed using wind profiles from global positioning system (GPS) microsonde data. The GPS-based results are used to test the applicability of the existing model on the surface-layer height. Then, friction velocity at the top of the surface layer in typhoons was estimated using the A&D model and the surface-layer height from the existing model. Results indicate that friction velocity

decreases by about 20% from its surface value and is quite close to that reported by Tennekes (1973).

2. Observations and data collection

The tower is located at a coastal site (24°02′08.556″N, 117°53′59.3124″E) in Chihu Town, Fujian Province, China, as indicated by point A in Fig. 1. The altitude of the site is 29 m. The shoreline is roughly oriented from northeast to southwest, as indicated by the line B–A–C in the figure. Thus, open-sea conditions correspond to wind directions of 45°–225°, land conditions correspond to wind directions of 270°–360°, and limited-sea conditions correspond to wind directions of 360°–45° and 225°–270°. Nearshore isobaths adjacent to point A are shown in the inset in the lower-right corner in Fig. 1. In general, the nearshore isobaths are parallel to the line B–A–C. The height of the tower is 100 m. Observational equipment was deployed at heights of 26.6, 42.4, 60.4, and 82.9 m above ground level (first, second, third, and fourth levels from bottom to top, respectively). Each level contained a Gill Instruments, Ltd., WindMaster Pro ultrasonic anemometer (UA) and a Campbell Scientific, Inc., R.M. Young 05106 wind monitor, with sampling frequencies of 20 and 1 Hz, respectively. The cantilever that supported each pair of instruments pointed east. A barometer at 8.5 m above ground level and a thermometer and hygrometer at 10 and 70 m above ground level were also deployed with the output frequency of one data point per minute. More detailed information on the tower and the local topography can be referred to Fang et al. (2018).

Three typhoons, Lionrock (1006), Fanapi (1011), and Megi (1013), made landfall along tracks to the left of the tower in 2010, as shown in the inset in the upper-left corner in Fig. 1. The corresponding landfall times (UTC) were 2300 1 September, 2300 19 September, and 0500 23 October. Their minimum distances from the tower were 33, 40, and 21 km, respectively. Figure 2 shows wind speeds and directions from observations at the fourth level with an averaging time interval (ATI) of 10 min and for wind speeds higher than 10 m s^{-1} for each typhoon. The wind data in Fig. 2a have not been subjected to any quality control. The wind direction changed by nearly 180° when the typhoons made landfall, which implies that the typhoon centers passed close to the tower. The wind data featured by full profiles are shown in Fig. 2b and constitute the analysis dataset used in this study. A full profile is one in which wind data were simultaneously obtained and passed the preliminary quality control at the first, second, third, and fourth levels. A preliminary quality control includes a data loss ratio less than 5% and stationarity

FIG. 1. Location of the coastal site (point A). Lines A–D, A–E, and A–F roughly follow azimuths of 0°, 15°, and 60°, respectively. Nearshore isobaths adjacent to point A are shown in the inset at lower-right corner. Tracks of the typhoons are shown in the inset in the upper-left corner. GPS microsondes were released at point G when Fanapi made landfall.

checking by a run test (Fang et al. 2018). The data loss ratio of a sample is defined as the count of the lost data points divided by the one of the maximum possible data points.

3. Brief description of the data quality control

A brief description of the data quality-control procedure is provided in this section. More detailed information can be found in Fang et al. (2018).

Wind data with wind directions of 15°–210°, which were not influenced by the tower body, were considered to be onshore in this study. The wind fetch over the water was at least ~10 km for wind directions of 15°–45°. According to Mahrt et al. (2003), the land upwind of the water body had little effect on the wind data. Wind data with directions of 210°–225° were removed because of possible disturbance by the shoreline at a geographic azimuth of 225°.

Wind speeds in the horizontal plane from the UAs were compared with those from the wind monitors at

the same level. Measurements were nearly identical, suggesting that wind speeds from the UAs are reliable. Sonic temperatures from the UAs were compared with those at the 10- and 70-m levels to evaluate the reliability of the calculated Obukhov lengths. Results indicate that the sonic temperature is affected not only by precipitation, as shown by Zhang et al. (2016), but also by the environmental temperature, which induced the observed abnormalities in sonic temperature from the first and second levels. As a result, the sonic temperature observations from the third and fourth levels were used to calculate the Obukhov lengths for the site.

Effective heights are adopted to describe surface elevation in this situation (Bowen and Lindley 1977). The wind profile for the upper part of the surface layer near the tower, under onshore wind conditions, is assumed to be from the nearshore surface layer:

$$u_z = \frac{u_*}{\kappa} [\ln(z/z_{0,n}) - \psi(z/L)], \quad (2)$$

where u_z is the observed wind speed at effective height z above the sea surface, which is the sum of the altitude at point A (29 m) and the height of the observational equipment above ground level; $z_{0,n}$ is the

roughness length induced by sea waves under neutral conditions; $\kappa = 0.4$ is the von Kármán constant; and $\psi(z/L)$ is the stability function defined as follows (Dyer 1974):

$$\psi(z/L) = \begin{cases} -5z/L, & 0 \leq z/L \leq 0.2 \\ 2 \ln[(1+X)/2] + \ln[(1+X^2)/2] - 2 \arctan(X) + \pi/2, & -1.0 \leq z/L < 0 \end{cases} \quad (3)$$

where $X = [(1 - 16z)/L]^{0.25}$ and L is the Obukhov length, which is defined as follows:

$$L = -u_*^3 T_v / (\kappa g \overline{w' T_v'}), \quad (4a)$$

with the friction velocity defined as

$$u_*^2 = (\overline{u' w'^2} + \overline{v' w'^2})^{0.5}, \quad (4b)$$

where T_v is the virtual temperature (K) and can be replaced by the sonic temperature; $g = 9.8 \text{ m s}^{-2}$ is gravitational acceleration; T_v' is the fluctuation in virtual temperature; and u' , v' , and w' are wind fluctuations in the streamwise, lateral, and vertical directions, respectively. The effect of upwind land fetch near the tower on the lower part of the surface layer was also evaluated (Shir 1972; Rao et al. 1974; Wood 1982; Powell et al. 1996; Grachev et al. 2018). We conclude that the wind speeds at all four levels and turbulence characteristics at the upper three levels are from the nearshore surface layer, despite the tower being located at a coastal site. As a result, the wind speeds at all four levels are used to calculate wind speed at 10 m above the sea surface u_{10} , and the turbulence characteristics at the upper three levels are used to study the variations in friction velocity with wind speed and height.

Using the wind speed at four levels and the mean value of the Obukhov parameter $(z/L)|_{\text{mean}}$ at the third and fourth levels, u_* and $z_{0,n}$ can be obtained from Eq. (2). Thus, u_{10} can be obtained by setting $z = 10 \text{ m}$. The neutral wind speed at 10 m above the sea surface under onshore wind conditions can be calculated as

$$u_{10,n} = u_{10} + \delta u_{10}, \quad \text{with} \quad (5a)$$

$$\delta u_{10} = \frac{u_*}{\kappa} \psi[(z/L)|_{10}] \approx \frac{u_*}{\kappa} \psi[(z/L)|_{\text{mean}}]. \quad (5b)$$

It should be stressed that, in this study, friction velocities calculated by the eddy covariance method of Eq. (4b) and by the wind-profile method of Eq. (2), are comparable when $u_{10,n} \geq 9 \text{ m s}^{-1}$.

After applying the quality-control procedure described above, wind speeds and directions at 10 m above the sea surface with an ATI of 10 min for each

typhoon are shown in Fig. 3. We do not consider variations in wind direction with height and take them as those from the first level. Wind data corresponding to those in Fig. 2b are shown in Fig. 3a. Wind speeds of larger than 9 m s^{-1} and wind directions of 15° – 210° are shown in Fig. 3b. The data in Fig. 3b are further divided into six subdatasets according to typhoon, wind speed, and direction, as shown in Table 1. An interesting phenomenon is that the surface layer seems to be in a nearly neutral state with increasing wind speeds, except that an unstable state exists for the data from MG_200, where the winds are roughly perpendicular to the propagation directions of sea waves with longer wavelength.

4. Observational results

a. Variations in u_* with wind speed

A scatterplot of u_* versus wind speed with an ATI of 10 min is shown in Fig. 4 for the six subdatasets. In general, for wind directions of 30° and 135° (Figs. 4a,e), variations in u_* with wind speed follow or are slightly greater than published results. For wind directions of 60° (Figs. 4b,d,f), variations in u_* with wind speed are slightly smaller than the published results. For a wind direction of 200° (Fig. 4c), variations in u_* with wind speed are noticeably smaller than the published results. Clearly, wind direction has an effect on variations in u_* with wind speed. This phenomenon can be explained by the form-drag theory in the air–sea momentum flux exchange study (Fang et al. 2018). Form drag is a major contributor to sea drag (Kudryavtsev et al. 1999; Makin and Kudryavtsev 1999; Donelan et al. 2012). Sea waves tend to propagate normal to the shoreline or isobaths because of the refraction effect as they approach the shoreline. As shown in Fig. 1, the propagation directions of sea waves in the local region were roughly the same as the wind direction for winds blowing 135° . Under this condition, the form drag caused by sea waves with longer wavelengths is comparable to that in the open-sea conditions. As a result, variations in u_* with wind speed agree with published results (Fig. 4e). For a wind direction of 200° , it is roughly perpendicular to the

FIG. 2. Polar plots of wind speeds and directions from observations at the fourth level with an ATI of 10 min and for wind speeds higher than 10 m s^{-1} for each typhoon: (a) wind data prior to any quality control and (b) wind data featured by full profiles. In (a), landfall times (crosses) are shown for each typhoon with different colors. Wind data to the left (azimuth with small angle) of the crosses are before landfall; those to the right (azimuth with large angle) are after landfall.

propagation directions of sea waves with longer wavelengths, and the form drag contributed by these sea waves is negligible or makes up only a small portion of the total drag. As a result, variations in u_* with wind speed are noticeably smaller than published results (Fig. 4c). The winds and the sea waves are in a cross state for wind directions of 60° (angles from the propagation

FIG. 3. Polar plots of wind speeds and directions at 10 m above the sea surface with an ATI of 10 min for each typhoon: (a) wind data corresponding to those shown in Fig. 2b and (b) wind data for wind directions of 15° – 210° and $u_{10,n} \geq 9 \text{ m s}^{-1}$. Wind speeds at 10 m above the sea surface were obtained using the wind-profile method.

directions of the sea waves to the wind directions are less than 90°). As a result, variations in u_* with wind speed are slightly smaller than the published results (Figs. 4b,d,f). Last, the winds and the sea waves are in a counter state for wind directions of 30° (angles from the propagation directions of the sea waves to the wind directions are larger than 90°). As a result, variations in u_* with wind speed follow or are slightly greater than published results (Donelan et al. 1997). Another reason

TABLE 1. Brief descriptions on the subdatasets. The averaging time interval is 10 min.

Name ^a	Typhoon	Range of wind speed (m s^{-1})/wind direction ($^{\circ}$)	Before or after landfall time	Sample count
LR_060_B_10	Lionrock	15.0–20.1/33.9–94.1	Before	12
LR_135_A_10	Lionrock	9.1–11.4/130.8–140.2	After	14
FN_060_B_10	Fanapi	11.7–17.7/82.5–101.0	Before	10
MG_030_B_10	Megi	9.0–16.8/16.1–41.5	Before	152
MG_060_B_10	Megi	16.8–22.4/30.8–87.0	Before	13
MG_200_A_10	Megi	9.2–23.5/176.1–208.7	After	22

^a Naming rules: for UU_XXX_V_YY, UU is the typhoon name (LR is for Lionrock, FN is for Fanapi, and MG is for Megi), XXX is the mean observation azimuth (030 is for 30° , 060 is for 60° , 135 is for 135° , and 200 is for 200°), V is the observation time (A is for after landfall, and B is for before landfall), and YY is the ATI (10 is for 10 min, and 01 is for 1 min) (see Fig. 5 for 01).

may be the perturbed influence of the land upwind of the water body as wind blowing from the limited sea conditions. The altitude of the land upwind of the water body is about 200 m (indicated by the Google Map). As pointed out by Tieleman (1992), the turbulent characteristics may be enhanced by the large-scale topographic features' upwind fetch of about 100 km. Thus, the assumption that the land upwind of the water body had little effect on the wind data may not be appropriated in this study. García-Nava et al. (2012) found that the relative direction of the wind and sea waves affects the air–sea momentum flux exchange via form drag. Shabani et al. (2014) found a similar decreasing tendency going from winds blowing in the onshore direction (normal to the shoreline) to those blowing in the alongshore direction (parallel to the shoreline). The underlying surface is the surfzone, and the wind speed is lower than 14 m s^{-1} , as compared with the underlying nearshore zone and wind speeds are higher than 9 m s^{-1} in this study.

Wind data with higher wind speeds are required to investigate the leveling off or decrease phenomenon on the variations in u_* with wind speed. This can be realized by choosing an ATI of 1 min. The rationale behind choosing an ATI of 1 min is as follows: the variation in friction velocity with wind speed, or the quantity $u_*/u_{10,m}$, is controlled by the roughness induced by sea waves under the assumption of a logarithmic wind profile. To the best of our knowledge, most published sea-wave spectra have a peak wave period no less than 0.5 rad s^{-1} , corresponding to a period of 12.56 s. Thus, an ATI of 1 min can be considered relatively long and can capture the representative characteristics of variations in friction velocity with wind speed, thereby extending the wind speed range of the observations. Figure 5 shows a scatterplot of u_* versus wind speed with an ATI of 1 min. Wind data from Megi and Fanapi were selected because they have a maximum wind speed higher than 25 m s^{-1} and thus provide a relatively larger range in wind speed. The friction velocities here are the

mean values at the second, third, and fourth levels. As a result, variations in u_* with wind speed can be taken as the mean variation in a thin layer from the second to fourth levels. It is evident that the friction velocity levels off at wind speeds of about 20 m s^{-1} in Fig. 5a, and it has a tendency to level off or decrease at wind speeds of about 20 m s^{-1} in Figs. 5c and 5d. The friction velocity may have a decrease tendency in Fig. 5b, although we cannot determine the critical wind speed for this phenomenon. The wind speed range may still be too small to make generalizations; however, our conclusions are supported by the fact that the wind data are from various subdatasets and wind directions. Figure 5 also shows a lower critical wind speed of $\sim 20 \text{ m s}^{-1}$ as compared with the nearshore results of $26\text{--}30 \text{ m s}^{-1}$ reported by Zhao et al. (2015). This may be caused by enhanced wave breaking induced by decreasing sea depth that lowers the critical wind speed as sea waves propagate toward the shoreline. This mechanism is discussed in detail by Zhao et al. (2015) and Fang et al. (2018).

b. Variations in u_* with height

The boundary layer theory predicts that the friction velocity is zero at the top of the boundary layer or decreases with height. Banner et al. (1999) and French et al. (2007) showed that u_* generally decreases with height under typhoon conditions and reported that the A&D model can provide realistic estimates of the decrease in friction velocity with height. The mean rate of decrease from its surface value for u_* in the lowest 100 m above the sea surface using the A&D model is provided in Table 2. According to the A&D model, the method for calculating the mean rate of decrease involves first obtaining the surface friction velocity u_{*s} using each sample of the friction velocity. Then, the rate of decrease in the lowest 100 m above the sea surface can be obtained for the sample. Finally, the mean rate of decrease at each level is obtained by averaging the rates of decrease for all samples from that level. There is negligible difference among the various levels shown in

FIG. 4. Variations in u_* with wind speed. The averaging time interval is 10 min. Only moderate-to-strong wind speed range ($u_{10,n} \geq 8 \text{ m s}^{-1}$) was plotted for the results from Foreman and Emeis (2010).

Table 2. However, there exist some differences among the subdatasets, even for the same wind direction. The largest rate of decrease is observed for subdataset MG_200_A_10, for which the wind is roughly parallel to sea waves with longer wavelength.

Scatterplots of u_* versus height are shown in Fig. 6 for the six subdatasets. We do not consider the effects of wind speed on the variations because each subdataset has a relatively small range of wind speed, except the subdataset shown in Fig. 6c. Boxplots and the mean

value for each level are also shown in the figure. The mean and median values for each level are nearly identical, which implies that the distribution of dataset is symmetrical. Thus, the mean value can be used to describe the mean variations in u_* with height as a first step. In general, the friction velocity does not always decrease with height from the second to fourth levels. This conclusion can also be supported by the scatterplot of friction velocity differences between the fourth or third levels and the second level, as shown in Fig. 7.

FIG. 5. Variations in u_* with wind speed. The averaging time interval is 10 min, and the wind speed bin size is 3 m s^{-1} . Only moderate-to-strong wind speed range ($u_{10,n} \geq 8 \text{ m s}^{-1}$) was plotted for the results from Foreman and Emeis (2010). Friction velocities reported by Zhao et al. (2015) were obtained using the wind-profile method with wind speeds from 13.4, 16.4, 20.0, 23.4, and 31.3 m above the sea surface. The lower and upper whisker caps in the boxplots correspond to the 10th and 90th percentiles, respectively. The lower and upper box edges correspond to the 25th and 75th percentiles, respectively. Boxplots may lack caps for sample counts between 3 and 8.

The positive relative value indicates that the friction velocity increases with height. It can be seen that a large portion of the samples has a positive relative value and can be even one time larger than the friction velocity at the second level (Fig. 7c). On the other hand, friction velocity decreases with height at higher friction velocities or wind speeds (Figs. 7a,e,f) or remains constant (Figs. 7b–d) in the thin layer. The mean rate of decrease in the lowest 100 m is also calculated based on the A&D

model using the mean friction velocity at each level shown in Fig. 6, and comparable results can be obtained as those shown in Table 2. These differences in the variation in friction velocity with height between the model and observations suggest that the boundary layer structure is complicated and that further investigation is needed in the future. In addition, it is not a reliable practice to simply adjust friction velocity using the A&D model, at least for the dataset used in this study. We do

TABLE 2. Mean rate of decrease from its surface value for u_* in the lowest 100 m above the sea surface (%) for different typhoons and wind directions based on the A&D model. Standard deviations are shown in parentheses. The averaging time interval is 10 min.

Level (height above the sea surface)	Lionrock		Fanapi		Megi	
	LR_060_B_10	LR_135_A_10	FN_060_B_10	MG_030_B_10	MG_060_B_10	MG_200_A_10
Second (71.4 m)	5.22 (0.95)	8.06 (1.05)	7.60 (2.91)	7.93 (3.34)	4.33 (0.40)	9.73 (4.69)
Third (89.4 m)	5.61 (1.30)	7.51 (0.94)	8.15 (3.79)	8.73 (3.75)	4.37 (0.95)	10.11 (4.22)
Fourth (111.9 m)	5.06 (0.84)	7.62 (1.25)	6.67 (1.52)	8.30 (3.81)	4.24 (0.78)	10.80 (6.53)

FIG. 6. Variations in u_* with height. The averaging time interval is 10 min. The left and right whisker caps in the boxplots correspond to the 10th and 90th percentiles, respectively.

not estimate surface-level values using linear regression because only three data points for each observation are available in this complicated boundary layer.

c. Value of u_* at the top of the surface layer

Although the A&D model has some deficiency as described above, we estimate the friction velocity at the top of the boundary layer according to the mean rate of decrease provided in Table 2. We believe that this will reduce the uncertainty by using the mean value. The boundary layer height must be known in advance for this

estimation; however, various definitions of the boundary layer have been proposed (Zhang et al. 2011; Vickers and Mahrt 2004). The A&D model is primarily validated in the surface layer. The surface-layer height h can be estimated on the basis of Ekman theory as follows:

$$h = C_n u_* / f, \quad (6)$$

where C_n is a nondimensional coefficient with values ranging from 0.01 to 0.05 (larger values are associated with neutral conditions) and f is the Coriolis parameter.

FIG. 7. Relative values of friction velocity differences between the fourth or third levels and the second level. The averaging time interval is 10 min. The difference is defined as the friction velocity at the fourth or third levels minus that at the second level. The relative value is defined as this difference divided by the friction velocity at the second level.

We assume that the surface-layer height is about 10% of the ABL height, and thus $C_n = 0.03$ (Tennekes 1973). For a specific site (constant f), Eq. (6) shows that the surface-layer height increases with higher friction velocity. This leads to controversial results for surface-layer height within typhoons because higher friction velocity exists in the maximum wind speed zone near the eyewall, thus causing higher surface-layer heights according to Eq. (6). However, surface-layer heights are

lower near the maximum wind speed zone than in the outer zones in typhoons, as demonstrated by Vickery et al. (2009). These lower surface-layer heights are also supported by the result from the wind profiles obtained by the GPS microsonde data as shown in Fig. 8a. The release sites of the GPS microsondes relative to the typhoon center are shown in Fig. 8b. A detailed description of the GPS microsonde measurements and the method used to obtain surface-layer heights in the

FIG. 8. (a) Temporal evolution of the surface-layer height around the time when Fanapi made landfall, and (b) typhoon-relative plots of the release sites of GPS microsondes. The averaging time interval is 10 min. The release time is used for the GPS microsonde data shown in (a). The radial distance of the release sites (positions of the crosses) to the typhoon center (center of the figure) in (b) is normalized to the radius of the maximum wind speed (RMW). The radius of the maximum wind speed is from the Joint Typhoon Warning Center best-track data. The typhoon center location is from the China Meteorological Administration best-track data. Release times (UTC) for each GPS microsonde are as follows [from top to bottom in (b) for numbers 1–7]: 1113 19 Sep, 1417 19 Sep, 1718 19 Sep, 2019 19 Sep, 2308 19 Sep, 0221 20 Sep, and 0511 20 Sep 2010.

typhoon can be found in the [appendix](#). The temporal evolution of the surface-layer height around the time when Fanapi made landfall is calculated using Eq. (6) and also shown in Fig. 8a. The mean values of surface-layer height predicted by Eq. (6) for the second, third, and fourth levels are 232.73, 242.29, and 238.13 m, respectively. The mean value from the GPS microsonde

data is 224.31 m. In general, results from Eq. (6) and from the GPS microsonde data are comparable, at least for the mean values. Thus, mean values for surface-layer height based on Eq. (6) can be used to predict the friction velocity at the top of the surface layer, as shown in Table 3. The results in Table 3 are very close to that from Tennekes (1973) and comparable to that from French et al. (2007). This suggests that the friction velocity at the top of the surface layer in typhoons can be estimated by combining the A&D model with the surface-layer height model [Eq. (6)], at least in a mean sense, considering the impossibility of accurate determination of the surface-layer height and the difficulty of direct observation of the friction velocity at the top of the surface layer.

5. Conclusions

Variations in friction velocity with wind speed and height were studied under moderate ($\geq 9 \text{ m s}^{-1}$)-to-strong onshore wind conditions caused by three landfalling typhoons. Observations were made at a coastal site where a 100-m tower was equipped with 20-Hz ultrasonic anemometers at three heights. The four main conclusions of this study are as follows:

- 1) Wind direction has an effect on variations in friction velocity with wind speed. The variation in friction velocity with wind speed follows published results when the wind direction is normal to the shoreline in the local region and is lower than that when the wind direction is parallel to the shoreline. This phenomenon can be explained by the form-drag theory in the air–sea momentum flux exchange study. Lower critical wind speeds of $\sim 20 \text{ m s}^{-1}$ exist for strong onshore winds because of the enhanced wave breaking induced by decreasing sea depth.
- 2) Friction velocity does not always decrease with height in the surface layer; however, friction velocity decreases or remains constant with height at higher friction velocities or higher wind speeds. A simple correction to the decrease of the friction velocity caused by height, based on the model in Ancil and Donelan (1996), is not reliable in this study.
- 3) GPS microsondes were released at a site located about 40 km southwest of the tower where Fanapi made landfall. A method to estimate surface-layer heights using wind-profile data is proposed based on the idea of mean boundary layer. Typical feature that lower surface-layer height near the typhoon centers was captured by the proposed method. Surface-layer heights calculated using the existing model based on Ekman dynamics are comparable to the results estimated using the proposed method, at least in terms of mean values.

TABLE 3. Ratio of decrease in friction velocity at the top of the surface layer to the value at the surface for different wind directions. The averaging time interval is 10 min.

Items	Lionrock		Fanapi	Megi		
	LR_060_B_10	LR_135_A_10	FN_060_B_10	MG_030_B_10	MG_060_B_10	MG_200_A_10
Mean rate of decrease per 100 m (%) ^a	5.30	7.73	7.47	8.32	4.35	10.21
Surface-layer height (m)	342.92	228.67	260.86	240.82	418.92	206.32
Ratio of decrease (%)	18.2	17.7	19.5	20.0	18.22	21.1

^a Mean rate of decrease per 100 m is calculated by averaging the rate of decrease at the second, third, and fourth levels, shown in Table 2.

4) Friction velocities at the top of the surface layer generally decrease by about 20% from the surface value under typhoon conditions, which is quite close to that from Tennekes (1973) and comparable to that from French et al. (2007).

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FIG. A1. Typical wind-profile structures for (a),(b) a constant wind speed layer over the surface layer and (c),(d) a sheared wind speed layer over the surface layer, using (left) linear coordinates and (right) logarithmic-linear coordinates. Surface-layer heights are also shown.

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APPENDIX

GPS Microsonde Measurements and the Method Used to Obtain Surface-Layer Heights

Seven GPS microsondes (Mark II) were released from a site (Gulei Harbor) located about 40 km southwest of the tower, where Fanapi made landfall (Fig. 1a). The microsondes were manufactured by Sippican. The rising speed of the microsondes was $4\text{--}5\text{ m s}^{-1}$, and the sampling frequency was 1 Hz. Thus, a microsonde will need less than 2 min to reach a height of about 500 m.

The method proposed to estimate the surface-layer height in typhoons is based on the idea of the average or mean boundary layer. The idea is widely used in wind field models for typhoons (Vickery et al. 2000) and was originally developed by Chow (1971). Our practice differs from Vickery et al. (2000) in that the average is made on the upper part of the boundary layer or above the surface layer in typhoon. For the upper part of the typhoon boundary layer, the wind field conforms to a gradient or geostrophic balance and moves horizontally with constant wind speed in depth. Gusts can be superimposed on the constant wind speed to describe a real wind field, as shown by Franklin et al. (2003). A surface layer exists below the constant wind speed layer. In this case, surface-layer height can be easily estimated for four wind profiles from the GPS microsonde data (numbers 4, 5, 6, and 7). A typical structure of the wind profiles (number 6) is shown in Figs. A1a and A1b. Furthermore, the layer may contain sheared wind speed rather than a constant wind speed in depth. Under these conditions, surface-layer heights can be identified for three wind profiles (numbers 1, 2, and 3). A typical structure of these wind profiles (number 1) is shown in Figs. A1c and A1d. All wind profiles (seven) were analyzed using this method. It seems that surface-layer height can be identified easily near the typhoon center. The general applicability of the proposed method should also be tested with more GPS microsonde data in future.

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