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Observations of Boundary Layer Wind and Turbulence of a Landfalling Tropical Cyclone

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Abstract

This study analyzed the atmospheric boundary layer characteristics based on the multiple level observations by a 350-m height tower during the landfall of Super Typhoon Mangkhut (1822). Mean wind profiles showed logarithmic wind profiles at different wind speed ranges suggesting nearly constant flux layers. The height of the constant layer increased with the wind speed and decreased with the radial distance from the storm centre. This behaviour was supported by flux observations. Momentum fluxes and turbulent kinetic energy increased with the wind speed at all flux measurement levels. The drag coefficient (surface roughness) estimated was nearly a constant with a value of 8×10^{-3} (0.09 m). Both the estimated eddy diffusivity and mixing length varied with height. The eddy diffusivity also varied with the wind speed. Our results supported that the eddy diffusivity is larger over land than over ocean in a same wind speed range.

Introduction

Planetary boundary layer (PBL) physics is closely tied to many aspects of a tropical cyclone (TC) in terms of intensity forecasts. Previous studies have shown that reduction of the vertical eddy diffusivity in the PBL scheme of the Hurricane Weather and Research Forecast (HWRF) model over ocean based on observations helped improve the TC intensity and structure forecasts (Gopalakrishnan et al. 2013, Jun A. Zhang et al. 2015, Jun A. Zhang et al. 2017). Direct flux observations in the TC boundary layer have been limited in the past. Multi-level flux observations in the outer-core (>100 km radius) were made in the TC boundary layer by research aircraft during the Coupled Boundary Layer Air Sea Transfer experiment (Black et al. 2007, Drennan et al. 2007, French et al. 2007, Zhang et al. 2008), Zhang and Drennan (2012) computed the vertical eddy diffusivities for surface wind speeds in range of $18\text{--}30 \text{ m s}^{-1}$. Aircraft measurements in the TC boundary layer near the height of the maximum wind speed (Zhang et al. 2011a, Zhao et al. 2020) showed that the vertical eddy diffusivity for momentum flux increases with wind speed up to $\sim 40 \text{ m s}^{-1}$.

On the other hand, enhancement of the eddy diffusivity over land in the PBL scheme of HWRF helped improve simulations of TC track, rainfall pattern, size, and

structure of landfalling storms (Feimin Zhang and Pu 2017, Feimin Feimin Zhang et al. 2017), although turbulence observations over land are scarce in TCs. Based on turbulence observations from a coastal tower in 3 typhoons during landfall periods, Tang et al. (2018) estimated the vertical eddy diffusivity and mixing length at heights of 10 m to 83 m, in the wind speed range of 6–29 m s⁻¹. They found that the mean vertical eddy diffusivity varies from 5 to 12 m² s⁻¹ and increases slightly with the wind speed. The mixing length fluctuates between 5 m and 40 m. Their results also suggest that the vertical eddy diffusivity and mixing length with landward wind fetch are greater than those with seaward wind fetch by 30-50%.

Although several observational studies have investigated the mean boundary layer structure of landfalling TCs (Lorsolo et al. 2008, Hirth et al. 2012, Ming et al. 2014, Ming and Zhang 2018, Alford et al. 2019, Alford et al. 2020a), how the mean and turbulence structures interact remain to be understood. This study presents collocated wind and flux observations by a high (350 m) tower in the boundary layer of Typhoon Mangkhut (1822). The objective of this study is to document turbulent characteristics of the low-level TC boundary layer and its linkage to the mean kinematic structure. The paper consists of four sections. The second section outlines the data used and methodology. The third section provides the results. Discussions and conclusions are provided in the last section.

Results

Typhoon Mangkhut formed in the northwest Pacific Ocean on 7 September 2018. At 09:00 UTC on 16 September, it made landfall at the coastal area of Jiangmen District, Guangdong Province, China, as a super TC with a maximum surface wind speed of 45 m s⁻¹. The wind speed recorded by a local weather station recorded wind speeds greater than 33 m s⁻¹ in Guangdong Province that lasted for more than 13 hrs.

Figure 1 shows typhoon Mangkhut's track near the coastal region of South China, from 14:00 UT on 15 September to 18:00 UTC on 16 September 2018. The maximum 10-minute average surface wind of the storm remained above 33 m s⁻¹. This study analyses data acquired by the Shenzhen Meteorological Gradient Observation Tower (referred to as SMT hereafter) with a height of 350-m marked in Fig. 1. The

composite reflectivity was a snapshot at 07:00 UTC September 16 when the SMT was adjacent to Mangkhut's eyewall with the minimum distance of approximately 134 km. The wind fetch over land for the SMT is more than 40 km relative to the location of maximum radar reflectivity, although the distance of the SMT from the nearest coastline is ~ 9 km in the west. Previous studies showed that the transition of the TCBL across the coastal region occurred mainly in the first 5 km over land (Alford et al. 2020b), so the observations here represent the inland surface condition. The underlying of SMT is tropical shrubs. The layout heights of the instruments are given in Fig. 2.

Figure 3 shows the 10-minute averaged wind speed and direction measured by the MST on 16 September 2018. The tower captured strongest winds from 04:00 UTC to 18:00 UTC on 16 September. The distance from the TC center reduced from approximately 200 km to 134 km, and then increased again to 445 km.

Figure. 4 shows the mean vertical wind profiles in a log height scale. The bin averaged wind speed follows a straight line from the surface up to ~ 100 m altitude. This log wind profile supports near neutral stability and constant momentum flux layer.

The lowest 100 m bin-average wind speed in Fig. 4 is fitted by a least-square line according to the following equation

$$U_z = \frac{u_*}{k} \ln \left(\frac{z-d}{z_0} \right) \quad (1)$$

where U_z is the mean wind speed at height z , z_0 is the roughness length, and d is the zero-velocity displacement distance set to be 2 m as the 2/3 the height of surrounding shrubs which is ~3 m. The goodness of the fit is remarkably high, as shown in Table 1. The intercept and slope of the fitted line produce a measure of z_0 and u_* / k , respectively. The drag coefficient (C_D) can be obtained by $C_D = (u_* / U_{10})^2$. Values of u_* , z_0 and C_D are summarized in Table 1. z_0 and C_D almost remain constant, with an average of 0.09 m and 0.008, respectively, while U_{10} varies between 8.3 to 18.0 m/s. The near constant behaviour of z_0 and C_D is as expected over land following the theory of Stull (1988), and similar to the results over rigid vegetation (Liu et al. 2008).

Another interesting feature in these wind profiles is that above 100 m altitude the

wind speed increases more quickly with height than below 100 m altitude. The higher the wind speed range, at a larger altitude the mean wind speed is closer to the best fit line. This feature indicates that the surface layer deepens with the wind speed. The surface layer heights are estimated to be 100, 130 and 180 m in the 3 wind bins, respectively.

Figure 4(b) shows that the mean wind speed increases as the distance from the storm center decreases as expected. Thus, the result in Fig. 4(a) indicates that the surface layer deepens as approaching to the TC center. The mean distances from the TC centre corresponding the 3 wind bins are 330, 168 and 143 km, respectively. The dependence of surface layer height on the distance from TC centre is illustrated in the subpanel of Fig. 4(b).

The trend of the variation of the surface layer height with radius is supported by the eddy-covariance flux result. Figure. 5(a) shows the variations of momentum flux with wind speed at 4 measurement levels (10, 40, 160 and 320 m). As the wind speed increases, the momentum fluxes at 10, 40, and 160 m increase significantly, while the momentum flux at 320 m increases much more slowly than at other heights, with a correlation coefficient of 0.93, 0.87, 0.88 and 0.74 at 10, 40, 160 and 320 m, respectively.

The log-wind profile still exists above 100 m, but with a smaller slope and a much bigger interception, implying that it may be unrealistic to relate the profile transition above 100 m here to the presence of an internal boundary layer (Stull 1988, Hirth et al. 2012, Donaher et al. 2013).

Furthermore, the momentum flux varies with height. At wind speeds of $\sim 10 \text{ m s}^{-1}$, the momentum fluxes at 10 and 40 m are not statistically significantly different with a 95% confidence level. The constant flux layer assumption is approximately applied to a layer of 40 m. When the wind speeds are greater than 10 m s^{-1} , the momentum fluxes at 160 altitudes are close to those at 40 m. When the wind speeds are greater than 15 m s^{-1} . The mean flux at the 160 m is not statistically significantly different from that at the 40 m altitude with a 95% confidence interval. This result suggests that the top of constant momentum flux layer increases with the wind speed. This trend of variation of the surface layer depth with wind speed based on the direct flux measurements are consistent with that based on the wind profile data illustrated in Fig. 4(a). Given the negative correlation between the mean wind speed and radial

distance, both measurements suggest the increasing surface layer height with radius. This result is different from the radial variation of the boundary layer height over the ocean as shown by dropsonde composite of Zhang et al. (2011).

Figure. 5(b) shows the turbulence kinetic energy (e) as a function of the measurement-level mean wind speed. The e at each level appears to increase with the wind speed (with a mean correlation coefficient of 0.85). The values of e at wind speeds >20 m/s are comparable to those in large eddy simulations of a landfall hurricane given by Zhu (2008) as well those based on Doppler radar observations given by Lorsolo et al. (2010) and Kosiba and Wurman (2014). The result in Fig. 7b suggests that e decreases with height in agreement with flight-level and radar observations (Zhang et al. 2009; Lorsolo et al. 2010; Zhang and Drennan 2012).

In Figure. 6(a), the strain rate is plotted against height in a log scale. The maximum strain rate appears at 10 m altitude with an average value of 0.16 s^{-1} . The strain rate decreases with height up to about 100 m and reaches a local minimum of 0.029 s^{-1} at 200 m. This vertical variation of strain rate is similar to that of Zhang and Drennan (2012) obtained by aircraft observations over the ocean, but the values of strain rates are much greater than theirs. Vertical profiles of the estimated vertical eddy diffusivity (K_m) (Fig. 6b) shows an increase of K_m with height between 10 m and 160 m, and then a trend of decrease with height above 160 m. At 10 m and 40 m, the mean values of K_m are 11 and $38 \text{ m}^2 \text{ s}^{-1}$, respectively. It peaks at 160 m with an average of $96 \text{ m}^2 \text{ s}^{-1}$. At 320 m, the mean value of K_m decreases to $78 \text{ m}^2 \text{ s}^{-1}$. A maximum of K_m may appear between 160 m and 320 m. The general trend of vertical variation of K_m with height is similar with that of Zhang and Drennan (2012) who reported a maximum K_m at approximately 190 m height over the ocean with surface wind speeds ranging from 18 to 30 m/s. However, our values of K_m are 50% greater than those of Zhang and Drennan (2012) at an equivalent height and wind speed on average.

According to equation (4), with the approximation of a constant momentum flux layer, K_m should have a maximum at the height of minimum strain rate. The minimum strain rate is located between 200 m and 250 m altitudes as shown in Fig. 6(a). Thus, it is speculated that the maximum of K_m appears at this height range. Furthermore, from the K -profile parameterization in equation (7), K_m maximum is located at $\sim 1/3$ of the boundary layer suggesting the boundary layer height ranges

from 600-750 m. We use 675 m as the top of the boundary layer in the following K_m parameterization evaluation based on equation (5).

As shown in Fig. 6(b), using $\alpha=1$ in Eq. (5), gives K_m values being much lower than the observed values. Setting $\alpha=1.5$ makes the parameterized K_m to be consistent with observations. This result supports the enhancement of vertical mixing from ocean to land as assumed by Zhang and Pu (2017).

According to eqs. (3) and (4), the mixing length l can be calculated directly, and its vertical profiles are shown in Fig. 6(c). The mean values of l at 10 and 40 m altitudes are 8 m and 27 m, respectively. Tang et al. (2018) reported that smaller values of l at 27 and 42 m altitudes of 10 - 20 m in their observations near the coastline. The average value of l at 160 m and 320 m altitudes are 55 m and 49 m, respectively, which are greater than those (~40 m) in Zhang and Drennan (2012) at similar altitudes. If the mean profile is fitted according to eq. (6), a value of 104 m is obtained for l_∞ , while a value of 67 m is obtained for l_∞ according to eq. (7). The root mean squared error of the former fit is nearly twice the later. The shape of the l profile is much closer to that using eq. (7) than using eq. (6).

Figure. 7(a) shows K_m at each measurement-level as a function of the wind speed. Besides the altitude dependence shown in Fig. 6(b), K_m also shows a wind speed dependence. At 10 m, 40 m and 160 m altitudes, K_m increases nearly logarithmically with the mean wind speed. However, at 320 m altitude, the dependence of K_m on the wind speed is much weaker than at other altitudes. This may be due to that the lowest 3 levels are within the surface layer, while the 320 m level is above the surface layer. This increasing trend of K_m with the wind speed in our observations generally agrees with previous studies (e.g., Zhang et al. 2011a; Tang et al. 2018) as shown in Fig.9a.

The estimated mixing lengths l at the 4 vertical levels as a function of the wind speed are as shown in Fig. 7(b). There is no significant relationship between l and the wind speed at each level. Of note, the result of Tang et al. (2018) showed a weak dependence of l on the wind speed, while Zhang et al. (2011a) result showed no dependence of l on the wind speed. .

Discussions and conclusions

In this study, tower observations of the low-level boundary layer structure of a landfalling TC were presented. Both mean and turbulence structures of the low-level boundary layer were investigated. The mean wind profile data showed that the depth of the surface layer, or the nearly constant flux layer, was larger than 100 m for the 10-m mean wind speed of 8.3 m s^{-1} , and this depth increased to $\sim 200 \text{ m}$ as the 10-m mean wind speed increased to 18 m s^{-1} . The eddy-covariance method derived flux data also showed that the constant flux layer deepens with the increasing wind speed and decreasing radius.

Turbulence parameters, including the momentum flux, e , drag coefficient, roughness length, strain rate, mixing length, and vertical eddy diffusivity were calculated at four vertical levels. The dependence of these parameters on height and wind speed are examined. The drag coefficients and roughness lengths were nearly constant with values of 0.008 and 0.09 m, respectively. The vertical eddy diffusivity at each observational height increases with the wind speed. The dependence of the mixing length on wind speed is very weak at all levels. The mean values of l are 8 m, 27 m, 55 m and 49 m, while those of K_m are 11, 38, 96 and $78 \text{ m}^2 \text{ s}^{-2}$ at 10 m, 40 m, 160 m and 320 m levels, respectively. K_m increases with height up to 160 m altitude and then weakly decreases with height. The vertical mixing length increases with height up to 160 m and then becomes nearly constant above this height. Using the observational estimates of vertical eddy diffusivity and mixing length, the nonlocal K -profile parameterization (KPP) scheme and the Blackadar (1962) mixing length scheme were evaluated, respectively. Results showed that an enhancement factor 1.5 is needed to improve the KPP parameterization scheme of the vertical eddy diffusivity over land compared to that over the ocean. The Blackadar scheme test result showed that the mixing length varies as a function of z close to 10 m altitude, rather than the usual $l \approx kz$ relationship.

Observations over the ocean (Vickery et al. 2009, Zhang et al. 2011b) suggested that the boundary layer became shallower as approaching to the storm center. However, our result suggested a reverse trend of boundary layer height varying with the distance from the storm center. The theoretical definition of the

boundary layer height has the form of:

$$D = \sqrt{2K_m / I} \quad (2)$$

where I is the inertial stability, which increases with the increase of wind speed from its definition (e.g., Kepert, 2001). Given that K_m increases with the wind speed over both ocean and land, our result suggested that the degree of the increase of K_m with wind speed is much larger than that of I over land, but vice versa over the ocean. Of note, we assumed the boundary layer height variation with the radius is similar to that of the surface layer height. This assumption requires to be evaluated when collocated high-resolution Doppler radar or Doppler profile observations with the flux observations are available. Future field experiments will be designed to test this hypothesis and the variation of boundary layer height with radius in landfalling TCs.

Data and methodology

The meteorological observation unites include a wind gradient observation system and a flux observation system. The gradient observation system consists of 13 levels of wind measurements using anemometers (i.e., 10, 20, 40, 50, 80, 100, 150, 160, 200, 250, 300, 320 and 350 m, respectively). The flux observation system is deployed at four levels, 10, 40, 160, and 320 m, respectively. Note that the observed winds by a Vaisala anemometer (WAA15) and wind vane (WAV15) are consistent with those measured by a Vaisala ultrasonic wind sensor (WMT703) during the period of observations. At each level, fast-response observations of three-dimensional wind velocities, air temperature, and humidity are obtained. Turbulent fluxes of momentum, sensible heat, and latent heat are calculated directly using the eddy covariance method. Here, only the wind and momentum flux data are presented.

The quality-controlled data during this 16-hour period were analyzed when the wind speed at 20 m height exceeded 7 m s^{-1} . Data of each 30-minute intervals were discarded if the outliers or missing data account for more than 1% of the total data. Otherwise, a linear interpolation is performed to replace the missing values. Subsequently, the data was subjected to a stationarity test (Foken and Wichura 1996). Furthermore, spectra, cospectra and their cumulative sums (ogives) were checked to evaluate the data quality following Zhang et al. (2009). If the spectral curve against

the frequency in the log-log plot has a slope of -5/3 in the inertial sub-range, the data of the 30-min leg was considered reliable, as shown in Fig. 8, which was used in a subsequent flux calculation. The ogive curves of the cospectra approach a stable value at both low and high end of the frequencies, as show in Fig. 9. The final cumulative sum values represented the total covariance or flux. The ogive curves are also used to estimate the spatial scales of turbulence eddies that contribute to the total fluxes.

The momentum flux τ and friction velocity u_* were calculated using the standard eddy-covariance method

$$\tau = \rho \left(-i \overline{w'u'} - j \overline{w'v'} \right) = \rho u_*^2 \quad (3)$$

where ρ is the air density, and u' , v' , w' are the perturbations of wind component in the zonal, meridional and vertical directions, respectively, and the overbar denotes averaging over the flux leg.

The momentum flux and strain rate S are used to directly calculate the vertical eddy diffusivity K_m in the form of:

$$K_m = u_*^2 / S \quad (4)$$

Here, the strain rate S is calculated as

$$S = \sqrt{\left(\frac{\partial \bar{u}}{\partial z} \right)^2 + \left(\frac{\partial \bar{v}}{\partial z} \right)^2} \quad (5)$$

Where the overbar denotes averaging over the leg. The vertical mixing length l can be estimated using the eddy diffusivity and strain rate,

$$l = \sqrt{\frac{K_m}{S}} \quad (6)$$

To obtain g , the method used by Zhang and Drennan (2012) was followed. First, the individual wind speed and direction profiles were averaged at each 30-minute interval. Second, weighted linear least squares were adopted to smooth the average profiles plotted against the log height. These smoothed profiles were then used to calculate the vertical gradients of the wind components.

The widely used non-local planetary boundary layer parameterization scheme or K profile parameterization scheme (i.e., Hong et al. 2006), was revised in HWRF in recent studies (Zhang et al. 2015, Bu et al. 2017, Zhang et al. 2017) in the form of:

$$K_m = \kappa z u_* [\alpha (1 - z/h)^2] \quad (7)$$

where κ denotes the von Karman constant which is 0.4, z is the observation height, u_* is the friction velocity, h is the height of the boundary layer, α is a nonzero constant to adjust the magnitude of K_m artificially. Over ocean (Zhang et al. 2015), α was set to be 0.7 to reduce the vertical mixing, while it is 1.2 to enhance the vertical mixing over land in Zhang and Pu (2017). It is noted that the boundary layer was assumed to be neutral in these studies, which will be validated by observations in Section 3.

The mixing length is usually formulated by half of the harmonic mean of κz and the asymptotic mixing length l_∞ (Blackadar 1962, Louis 1979)

$$\frac{1}{l} = \frac{1}{\kappa z} + \frac{1}{l_\infty} \quad (8)$$

This formula limits the mixing length to κz when approaching the surface. As a comparison, we modified (8) and fit the observations using the following equation

$$\frac{1}{l} = \frac{1}{z} + \frac{1}{l_\infty} \quad (9)$$

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Author contributions

ZZK analysed the data and wrote the draft. GRQ took the tower observations. JZ and CPW revised the draft. ZY,QLW and LCX supplied financial supports.

Competing interests statement

The authors declare that they have no competing financial interests.

Figure legend

Fig. 1 The composite radar reflectivity is at 07:00 on September 16 when the tower was nearest to the typhoon center. Real-time track (bold solid line) of Typhoon Mangkhut (1822) in the coastal area of South China from 14:00 UTC on September 15, 2018, to 18:00 UTC on September 16, 2018. The real-time data are from the National Meteorological Centre of China. The symbol denotes the Shenzhen Meteorological Tower

Fig. 2 Photograph of the Shenzhen Meteorological Tower (SMT). The heights of the devices for measuring the vertical profiles and turbulence fluxes are as labelled. The water beneath the SMT is a reservoir. The subpanel shows the local topography, and the marker denotes the SMT

Fig. 3 Observations obtained at the 13 layers of the Shenzhen Meteorological Tower from 04:00 to 18:00 on 16 September 2018: (a) 10-minute average wind speed and (b) 10-minute average wind direction. In panel (b), the thick black line shows the average wind direction over the 13 layers. The axis between the two panels shows the relative distance of SMT to the TC centre (km) according to the real-time track data from China Meteorology Administration

Fig. 4 (a) Vertical profiles of 10-minute average wind speed. Symbols are mean of each vertical bin. The wind speed data are grouped into 3 bins according to the 10-m wind speed, 7-10 m/s (red), 10-15 m/s (green) and 15-20 m/s (blue); (b) Multiple-level mean wind speed (dot) and the fitting line (solid blue line) as a function distance from the TC center. The subpanel in (b) shows the dependence of the surface layer height (SFCH) on the distance from TC center. SFCHs are estimated from the fitted lines in panel (a). The horizontal bars indicate the standard deviations of the distances grouped into 3 bins according to the 10-m wind speed, as in panel (a)

Fig. 5 Relationships of (a) the vertical flux of horizontal momentum τ , (b) turbulence kinetic energy (e), with the wind speed at the four heights, 10, 40, 160 and 320 m. The 4 couples of dashed lines in same color in (a) denote the corresponding 95% confidence intervals, respectively. Panel (a) and (b) share the same legends

Fig. 6 Vertical profiles of (a) the strain rate, (b) the vertical eddy diffusivity K_m , and (c) vertical mixing length l . The average values (bold $\bigcirc$), the standard deviations (error bars) on different layers. Panel (b) and (c) also show the fitted lines. ZD12 denotes the results of Zhang and Drennan (2012)

Fig. 7 Variations of (a) the vertical eddy diffusivities K_m , and (b) the mixing length, at different layers with the wind speed. TZAML18 stands for Tang et al. (2018), and ZMML11 for Zhang et al. (2011a). In (b), the trend line at each level is also shown

Fig. 8 Along-wind velocity spectrum at (a) 320 m, (b) 160 m, (c) 40 m and (d) 10 m. The red lines with a slope $-5/3$ help indicate the inertial subrange. The record time is 2018-09-16 07:30

Fig. 9 Ogive curves of the two components of momentum fluxes verse the horizontal wavenumber at height (a)320 m, (b)160 m, (c) 40 m, and (d)10 m. The record time is 2018-09-16 07:30

Table

Table 1. Observations of friction velocity u_* and aerodynamic roughness length z_0 obtain by a logarithmic fit to each bin. Also shown are the goodness of fit R-square.

U_{10} (m/s)	u_* (m/s)	z_0 (m)	$1000 \times C_D$	R-square
8.3	0.70	0.08	7.1	0.98
12.1	1.13	0.11	8.7	1.00
18.0	1.59	0.08	7.8	1.00

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Figures

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