

# An In-Situ Observational Study on the Turbulent Characteristics in the Near-surface Layer during the Landfalling Period of Super Typhoon Maria (2018)

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## Key Points:

- The ocean-atmosphere drag coefficient during typhoon landfall is investigated for 10-min average wind speeds extend to  $42.27 \text{ m s}^{-1}$ .
- The relationship between the drag coefficient and wind speed is parabolic during typhoon landfall.
- The drag coefficient extreme drifting as height was mainly caused by the trends of the negative tangential turbulent fluxes with wind speed.

## Abstract

The air-sea exchanges of momentum which are often parameterized by the variation of drag coefficient ( $C_D$ ) and wind speed ( $u_n$ ), is largely uncertain at typhoon-force extreme values of  $u_n$ . This paper investigated the relationship between  $C_D$  and extreme values of  $u_n$  for five different heights using the eddy covariance method from two coastal observation towers during the landfall of Super Typhoon Maria. In particular, our observations include 10-min average  $u_n$  extended to high wind speed of  $42.27 \text{ m s}^{-1}$ . The relationship between  $C_D$  and  $u_n$  was parabolic from regression analysis, and the “roll-off” of  $C_D$  and  $u_*$  appeared at about  $28 \text{ m s}^{-1}$ . From the bottom to top heights, the corresponding  $u_n$  of  $C_D$  extreme were 9.95, 12.72, 22.32, 32.57 and  $38.04 \text{ m s}^{-1}$ , respectively. The trend of negative tangential turbulent flux with  $u_n$  was found to be the main cause for the  $C_D$  extreme drifting with heights.

## Plain Language Summary

The air-sea interaction is critical to the intensification of tropical cyclone because of the exchange of the momentum, humidity and energy between the atmosphere

and the ocean. The exchanges of momentum, which is the most important physical process, is often parameterized by the variation of drag coefficient and wind speed in numerical models, but the magnitude of the corresponding wind speed dependent drag coefficient is largely uncertain at typhoon-force extreme winds. This study investigated the variability of drag coefficient with wind speed at five different heights observations in a more extreme winds ( $> 35$  m/s) during Super Typhoon Maria, results yield that the relationship between drag coefficient and wind speed was parabolic by regression analysis and the maximum of drag coefficient appeared at 30 m height rather than 10 m height using extensively in numerical models. It is the first observation study that revealed that the drag coefficient extreme drifting with height, and the trend of negative tangential turbulent flux with wind speed in onshore direction contributes mainly to the phenomenon. This finding may indicate a new way to improve air-sea interaction in boundary layer scheme of tropical cyclone and thus improve the intensity forecast.

## 1 Introduction

Air-Sea/land exchanges of momentum play an essential role in determining the interaction between the atmosphere and the underlying surface under the bulk transfer relationships based on the Monin-Obukhov similarity theory (MOST) (Monin and Obukhov, 1954) in the sea or land surface processes in weather and climate numerical models and applications in environment sciences and other geoscience (Wyngaard, 2010; Xiao et al., 2013; Zhu et al., 2013). The accuracy of the momentum flux parameter is depended on the drag coefficient ( $C_D$ ) (or the bulk transfer coefficient over land, Nystrom et al., 2020). Over the past few decades, a number of observational and numerical experiments have been conducted to improve understanding of the sea/land-atmosphere exchange processes (Nolan et al., 2009; Zachry et al., 2013; Smith et al., 2017; Yu et al., 2020). These include the Qinghai-Xizhang Plateau Meteorological Experiment (QXPME) in arid/semi-arid areas (Zhao et al., 2017), the Coupled Boundary Layer and Air-Sea Transfer Experiment (CBLAST) in the Atlantic (Black et al., 2007; French et al., 2007), the NOAA Hurricane Forecast Improvement Program and the Intensity Forecasting Experiment (IFEX-HFIP) (Rogers et al., 2012), and other experiments in the Western Pacific (Tang et al., 2015; 2018). Both theoretical work and field observations have investigated the relationship between  $C_D$  and wind speed ( $u_n$ ) in different surface conditions. For extreme wind speeds ( $> 35$  m s<sup>-1</sup>), the trends of  $C_D$  and  $u_n$  are unclear with three different outcomes reported (increase, decrease and constant with changing  $u_{10}$ ) in both observations and laboratory experiments (Alamaro et al., 2012; Cione et al., 2020).

The boundary layer of the eyewall region in tropical cyclones (TCBL) often has extremely wind speeds (Emanuel 1986; Kepert 2001). Previous studies point out that the mean  $C_D$  increases approximately linearly with increasing  $u_n$  at low and moderate wind speed in typhoons/hurricanes, but the divergence of the  $C_D$  trend appears during very strong winds. Furthermore, saturation points of

$C_D$  differ from different observations on account of the impact of sea spray and waves and the critical wind speeds at which  $C_D$  levels off are between 15 to 40  $\text{m s}^{-1}$  (Holthuijsen et al., 2012; Potter et al., 2014; Ming et al., 2015; Zhang et al., 2015; Duan et al., 2017; Hsu et al., 2019; Gao et al., 2020; Liu et al., 2020). For the open ocean, Powell et al. (2003, 2008) started to estimate  $C_D$  in tropical cyclones (TCs) by analyzed 2664 global positioning system (GPS) dropsondes and found that  $C_D$  reaches its maximum at wind speeds of about 33  $\text{m s}^{-1}$  (near hurricane-scale strength). Moreover, Richer et al. (2021) used the flux-profile method to improve the result of Powell et al. (2003) and refreshed that the  $C_D$  versus  $u_{10}$  relationship does not actually exhibit a inflection point. Zhao et al. (2020) and Sparks et al. (2019) extended the saturation of  $C_D$  out to 60  $\text{m s}^{-1}$  via the direct aircraft measurements in Pacific typhoons. More recently, unmanned aircraft were used to measure momentum fluxes near the eyewall of TCs with extremely high winds up to 87  $\text{m s}^{-1}$  (Cione et al., 2020). Both of them found the uncertain of the measurements in high winds affect the relationship between  $C_D$  and  $u_n$ . From near shore the corresponding  $u_n$  of the  $C_D$  saturation seems lower than that in open ocean, Bi et al. (2015), Zhao et al., (2015) and Fang et al. (2018) showed that  $C_D$  leveled off when wind speeds around 18-24  $\text{m s}^{-1}$  using the eddy covariance (EC) method, while the trend of  $C_D$  at winds beyond roughly 35  $\text{m s}^{-1}$  is unavailable due to wave breaking and water depth. Hsu et al. (2019) noticed the sea surface wave and estimated its impact on  $C_D$ , and detected the indeterminacy when winds larger than 30  $\text{m s}^{-1}$ . In laboratory, Troitskaya, et al. (2012, 2020) pointed out that  $C_D$  reaches a maximum at a little larger values of  $u_n$  around 25  $\text{m s}^{-1}$  under small-scale surface waves conditions. By using a stepped frequency microwave radiometer (SFMR) measurements on the aircraft, Bell et al. (2012) pointed out that calculations were at least 50% more uncertain at higher wind speeds. To our best knowledge, insufficient experiments have documented the quantitative value of  $C_D$  in ultra-high wind conditions ( $> 35 \text{ m s}^{-1}$ ), especially at height above 10 m nearshore. As a result, the relationship of high  $u_n$  and  $C_D$  at different heights in a typhoon-like circulation has been, until recently, poorly understood to verify turbulent flux parameterizations in TCs (Kepert 2012; Li & Pu, 2020).

Although ample evidence suggests  $C_D$  is affected by fetching, wave breaking, sea spray and foam (Zhao et al., 2015), Mostly  $C_D$  in models is calculated based on  $u_n$  only (Akbar et al. 2017). In order to determine  $C_D$  nearshore and provide a reference for the modeling community, the main objective of this study is thus to find the relationship between the  $C_D$  and  $u_n$  during observations of typhoon via five height levels data of EC measurements from two different EC flux towers (one tower is at the top of an island hill and the other one is nearshore), In particular, an aim is to determine  $C_D$  with extreme values of  $u_n$  from 10 m to 130 m heights during typhoon landfall. In section 2, the data and processing methods used are introduced. Section 3 presents the results of the data analysis. Section 4 includes a summary of the main findings and future work.

## 2 Data and analysis methods

## 2.1 Data overview

In this study, the data analyzed were collected from two onshore EC flux towers deployed along the coastline at Sansha, Fujian, China during the passage of Typhoon Maria (1808). The lower tower (26°55'30" N, 120°13'46" E, 60 m above sea level (a.s.l.)) was approximately 10 m from the coastline, as indicated in Figure 1a, and is referred to as the Low Tower in this study. The High Tower (26°55'25" N, 120°13'54" E, 120 m a.s.l.) was deployed at the top of the hill, as indicated in Figure 1b, and is referred to as the High Tower. The distance between the two towers is about 150 m. The underlying surface of the two towers is grass with less than 0.1 m height.

Four three-dimensional ultrasonic anemometers were mounted on the two towers with 1.5 m cantilever brackets at 10, 30, 50 and 70 m heights above the ground. The four three-dimensional ultrasonic anemometers (WindMaster<sup>TM</sup> Pro 3D, Gill Instruments Limited) and a high-performance data logger with a sampling rate of 20 Hz (CR3000, Campbell Scientific Instruments Inc., Logan, UT, USA) were combined to make a flux measurement system. Unfortunately, the extreme gust wind speed observed is about 50.1 m s<sup>-1</sup> during the landfall of Maria caused the collapse of the High Tower, thus measurements from the sonic anemometers were collected from four levels from the Low Tower nearshore in the period from 0000 local standard time (LST) July 10 to 0000 LST July 12 and a level of 50 m of the High Tower at the top of the hill before landfall (130 m above the nearshore ground and 170 m a.s.l.).

## 2.2 Review of Super Typhoon Maria

Super Typhoon Maria (2018) was the eighth typhoon to form in the Northwest Pacific Ocean in 2018. Figure 1 presents the track of Typhoon Maria relative to the location of the two EC flux towers, and shows also the intensity evolution using data from Shanghai Typhoon Institute of China Meteorological Administration (<http://www.typhoon.org.cn/>) (Ying et al., 2014). Maria made landfall over Lianjiang County of the Fujian Province in China at 0850 LST July 11 2018 which was approximately 68 km away from the two observation towers. The towers at this time were located in the inner core region of the circulation, with the radius of maximum wind (RMW) at this time being close to 60 km (Bao et al., 2020). A maximum 10-min average wind speed of 42.27 m s<sup>-1</sup> was observed at 50 m height of the Higher observation Tower. After landfall Maria continued its track northward while weakening rapidly as a result of land effects.

## 2.3 Methodology introduction

In the EC method, a friction velocity ( $u_*$ ) is defined as

(1)

where  $\overline{u'}$  and  $\overline{w'}$  are wind fluctuations in the streamwise. The over bar expresses Reynolds averaging.

The  $C_D$  under the neutral stability condition is estimated by

(2)

where  $u_z$  is the Reynolds-horizontal mean wind velocity at the observation heights  $z$  (Garratt, 1977),  $n$  is the height of measurements taken on the towers.

#### 2.4 Data Processing and Quality Control

The original anemometer data pre-processing in this study mainly involves outlier removing, tilt correction, coordinate rotation corrections and linear detrending (Lee et al., 2004). Schmid et al. (2001) proposed a method to inspect the power spectra of turbulent fluctuations and we followed that method in this study.

(1) The spikes in the data sets were removed by using a criterion of  $X(h) < (X - 4)$  or  $X(h) > (X + 4)$ , where  $X(h)$  denotes the original data,  $X$  is the mean over the averaging interval and  $\sigma$  is the standard deviation.

(2) The calculation of  $C_D$  were omitted when the corresponding  $u_*$  less than  $0.01 \text{ m s}^{-1}$ . No gap filling was taken in this study.

(3) Based on the coastline features near the measurement site, we found that the offshore flow wind direction ranges from  $52.5$ - $227.5^\circ$ , and the offshore flow ranged from  $272.5^\circ$  to  $5^\circ$ . The wind data ( $249$ - $269^\circ$ ) from the back of the measurements from the Lower Tower and the wind data ( $68$ - $88^\circ$ ) from the back of the measurements from Higher Tower were removed due to the turbulent eddies generated by the tower.

### 3 Results and discussions

#### 3.1 The variation of $C_D$ and $u_*$ against $u_n$

Figure 2a-b provides the variation of  $C_D$  as a function of  $u_n$  derived from the five levels of the two towers during Typhoon Maria. Despite the large scattering of  $C_D$ ,  $C_D$  at all levels showed a clear parabolic trend with  $u_n$  when regressed from the median values of  $C_D$  (Figure 2b).  $C_D$  had an increasing trend with an increase in  $u_n$  ( $1$ - $28 \text{ m s}^{-1}$ ), and beyond this range, a saturation or a level off of was observed at higher  $u_n$ . The trends in  $C_D$  with increasing  $u_n$  was similar to the coastal wind measurements from Zachry et al., (2013). From the bottom to top heights, the corresponding  $u_n$  of  $C_D$  extreme were  $9.95$ ,  $12.72$ ,  $22.32$ ,  $32.57$  and  $38.04 \text{ m s}^{-1}$ , respectively.

Figure 2c-d depicts that the variations in  $u_*$  with  $u_n$  at different heights using the bin-averaged method. Like the trend of  $C_D$  with  $u_n$ , the total  $u_*$  also increased with increasing  $u_n$  up to  $28 \text{ m s}^{-1}$ , and decreased for  $u_n$  above  $28 \text{ m s}^{-1}$ . The trends in  $u_n$  agrees reasonable well with previous studies that reported variation in  $u_*$  with  $u_n$  both over open ocean and coastal observations (Zhao et al., 2015; Fang et al., 2020). But the saturation of  $u_*$  at a faster wind speed than that from Fang et al. (2020), it may due to the nearer distance from the core of typhoon center.

#### 3.3 Vertical profile of $C_D$ and $u_*$

In order to investigate the structure of  $C_D$  and  $u_*$  with heights, the vertical profile of  $C_D$  and  $u_*$  with varying  $u_n$  for the sixteen hours during Maria landfall's period is analyzed in Figure 3a-b. As Typhoon Maria approached the coastline, the values of  $C_D$  increased rapidly from 02:00 to 07:00 LST 11 July, as the tower was located between 3 RMW and RMW from the typhoon center. It reached a maximum value of  $C_D$  at 30 m height (10.148) at 06:00 LST 11 July (Figure 3a). While the amplitude of  $C_D$  decreased noticeably when the towers were located in the eyewall region ( $< \text{RMW}$ ) from 07:00 to 12:00 LST 11 July. After landfall,  $C_D$  increased again from 12:00 to 14:00 LST 11 July when the towers were located 3-5 RMW from the typhoon center, and the  $C_D$  of 30 m height became the largest of the different levels again. During these times the amplitude of  $C_D$  was much smaller than that during the pre-landfall period. It may be implied that the values of  $C_D$  before Typhoon Maria landfall were bigger than these after landfall, and the values of  $C_D$  from the 2-3 RMW were bigger than those in RMW. Similar to the discussions above, the vertical variation of  $u_*$  was highly consistent with  $C_D$  before the Maria landfall and  $u_*$  in the 2-3 RMW is bigger than that in RMW (Figure. 3b). That is to say, the momentum exchange flux was more severe in the 2-3 RMW is bigger than that in RMW. It was consistent with the expected behavior of these physical quantities in the typhoon boundary layer (Kepert 2001).

#### 3.4 The variation of $C_D$ and $u_*$ with $u_n$ at each height from regressed results

To understand further the details of the variations of  $C_D$  with  $u_n$  at different heights, regressed from the median and mean numbers were completed by generating groups at each height and are plotted against  $u_n$  in Figure 4a-e. According to the regression curves, the relationship between the median or mean values of  $C_D$  and wind speed were parabolic from 10 m to 70 m height, while  $C_D$  presented as a curve of two peaks from 130 m height. The first peak appeared in the wind speed section of 10-20  $\text{m s}^{-1}$  under the offshore winds, the second peak arose at the wind speed section of 28-38  $\text{m s}^{-1}$  under onshore winds.

From the bottom to top height, the  $C_D$  saturation points were 0.06, 0.05, 0.62, 0.17 and 0.01 from 10, 30, 50, 70, 130 m heights, respectively, and the corresponding wind speeds were about 18, 18, 23, 28 and 38  $\text{m s}^{-1}$ . The saturation values of  $C_D$  decrease along with the increasing wind speeds from 30 m to 130 m height, it seems that the regression curves of the median and mean  $C_D$  had a drifting of saturation as height. The values of  $C_D$  reached their maximum with wind speeds of 18  $\text{m s}^{-1}$  at 30 m height rather than 10 m height currently used in various surface flux parameterization of models. In other words, one might conclude that surface roughness had less impact on airflow when the height exceeds 30 m.

In a comparison of the saturation values of  $C_D$  from the Lower Tower at nearshore with those on the same height of the Higher Tower on the hilltop (50 m height), we see that the saturation  $C_D$  value at 50 m height from the Higher Tower was smaller than those from the same height at the Lower Tower from nearshore. According to Eq.2,  $u_n$  from the Higher Tower was higher than

that from the Lower Tower, while the  $u_*$  from the Higher Tower was lower than that from the Lower Tower. This could explain the lower  $C_D$  from the Higher Tower. This may imply although  $u_n$  increased with height, the momentum fluxes were not always similarly increasing with height, and the weaker influence of the ground and the higher wind speed led to a decreasing  $C_D$  with height. Topography may also affect the decrease rate of  $C_D$  with heights. The surface of the earth exerts a frictional drag on the air blowing just above it, the difference in terrain conditions directly affects how much friction is exerted. Hills affects the wind speed and/or change wind direction much more, so that the  $u_*$  values from the Higher Tower clearly decreased leading to decreasing  $C_D$ .

Similar to the analysis of  $C_D$ , the variations of  $u_*$  with  $u_n$  at different heights calculating by the bin-averaged method are shown in Figure 4f-j. The median, mean and maximum  $u_*$  are also plotted in Figure 4f-j. From the bottom to top heights, the  $u_*$  saturation points were 2.74, 2.88, 5.453, 3.35 and 1.99  $\text{m s}^{-1}$  at 10, 30, 50, 70, 130 m height, respectively, and the corresponding  $u_n$  were about 18, 23, 28, 33 and 38  $\text{m s}^{-1}$  regressing from the mean and median  $u_*$  data. This finding indicates that the drifting in saturation of  $u_*$  was responsible for the drifting in saturation of  $C_D$  with height. The  $u_*$  maximum increased from 10 m to 50 m height, then it decreased at larger heights. The maximum  $u_*$  occurred at 50 m height with a value of 5.6134  $\text{m s}^{-1}$ , which was higher than to the maximum of  $C_D$  appeared at 30 m height. The vertical variation trend of  $u_*$  is consistent with Fang et al. (2020), and it indicates that  $u_*$  does not always decrease with height under typhoon condition. However, French et al. (2007) reported that  $u_*$  has a decreasing trend with height above 70 m and below 400 m height under typhoon conditions. The different results obtained in this study from ground to 170 m height suggest that the boundary layer structure is complicated and it needs more observations of the  $u_*$  vertical profile to confirm.

From our dataset, the critical  $u_n$  located nearshore at 10 m height (20.5456  $\text{m s}^{-1}$ ) was similar to the leveling off point of 22  $\text{m s}^{-1}$  from Fang et al. (2018), but it a little bit smaller than that of 26-30  $\text{m s}^{-1}$  reported by Zhao et al. (2015). The differences in critical wind speed from the different sectors in TCBL and different underlying surfaces.

### 3.5 The variation of the turbulent flux ( $\overline{w'u'}$ , $\overline{w'v'}$ ) with $u_n$ at each height

In order to explore which part of turbulent flux generates the drifting of saturation and extreme in  $C_D$  and  $u_*$  with height, Figure 5 presents scatters plot of positive turbulent fluxes ( $\overline{w'u'}$ ,  $\overline{w'v'}$ ) and negative turbulent fluxes ( $-\overline{w'u'}$ ,  $-\overline{w'v'}$ ) against  $u_n$  from the five heights. The trend of negative tangential component fluxes ( $-\overline{w'u'}$ ) with  $u_n$  was agree well with the trend of  $u_*$  and  $C_D$  again  $u_n$ , rather than the trend of radial components flux ( $\overline{w'v'}$ ) with  $u_n$ . The corresponding  $u_n$  with extreme  $-\overline{w'u'}$  in each height were constant with extreme  $C_D$  highly. Furthermore, the extreme wind conditions ( $> 35 \text{ m s}^{-1}$ ) in onshore direction concentrated at the negative component fluxes, it may be concluded that the variation of the  $-\overline{w'u'}$  in onshore direction was the main factor of  $C_D$ .

drifting with  $u_n$ .

#### 4 Summary and Conclusion

In this study, high frequency wind data was collected by two EC flux towers located on the coastline of the East China Sea to study the turbulent characters and eddy transportation during the passage of Super Typhoon Maria. In contrast to most previous studies on turbulence in high wind speeds at low levels ( $<50$  m a.s.l), this study investigates the values of the  $C_D$  from five height levels at two towers from the near surface (70, 90, 110, 130 and 170 m a.s.l). The extreme 10-min average  $u_n$  is  $42.27 \text{ m s}^{-1}$  and the minimum distance to the landing point of typhoon is less than 70 km which shows the relationship between  $C_D$  and  $u_n$  in a more extreme environment ( $> 35 \text{ m s}^{-1}$ ) in the upper surface layer (170 m a.s.l). Furthermore, comparing the near shore observational results with the hilltop observations at high winds, it is confirmed that the dependence of  $C_D$  on  $u_n$  is modified by elevation. Some preliminary conclusions are offered as follows.

According to regression from the median of total data, the relationship between  $C_D$  and  $u_n$  was parabolic, the “roll-off” of  $u_*$  also appeared at about  $28 \text{ m s}^{-1}$ . From the bottom to top heights, the corresponding  $u_n$  of  $C_D$  extreme were 9.95, 12.72, 22.32, 32.57 and  $38.04 \text{ m s}^{-1}$ , respectively. The  $C_D$  saturation points were 0.06, 0.05, 0.62, 0.17 and 0.01 at 10, 30, 50, 70, 130 m heights, respectively, and the corresponding wind speeds were 18, 18, 23, 32 and  $38 \text{ m s}^{-1}$ . For the first time observed, the saturation and extreme values of  $C_D$  had a drifting with heights based on in-situ observations. Moreover, the regression curve of the median and mean  $u_*$  also had a drifting of saturation  $u_*$  with height like  $C_D$ . Furthermore, the trends of the extreme negative tangential turbulence fluxes in onshore direction was the main cause for  $C_D$  extreme drifting with  $u_n$ .

It is worth noting that the maximum  $C_D$  appeared at 30 m height rather than 10 m height currently used in various surface flux parameterization of models. An obviously decreases in  $C_D$  in upper level ( $>30$  m height) of the lower boundary layer was found. This may imply that due to the increasing height, there is a weaker influence from the ground. The values of  $C_D$  from the 2-3 RMW was bigger than that in RMW. These information would enhance our understanding of the turbulent process in the TCBL.

Observations in high winds are relatively rare, and more in-situ observations needed to confirm the drifting of extreme  $C_D$  in the future. In addition, further work will explore the enthalpy exchange coefficient from different sectors of typhoon/hurricane structure to update in the understanding of the air-sea drag under extreme wind conditions, and thus improve the turbulent process in the typhoon numerical models.

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### Data Availability Statement

The eddy covariance observation data in this paper are available online [https://figshare.com/articles/dataset/EC\\_observation\\_data\\_during\\_Typhoon\\_Maria\\_rar/16566162](https://figshare.com/articles/dataset/EC_observation_data_during_Typhoon_Maria_rar/16566162) (DOI:10.6084/m9.figshare.16566162).

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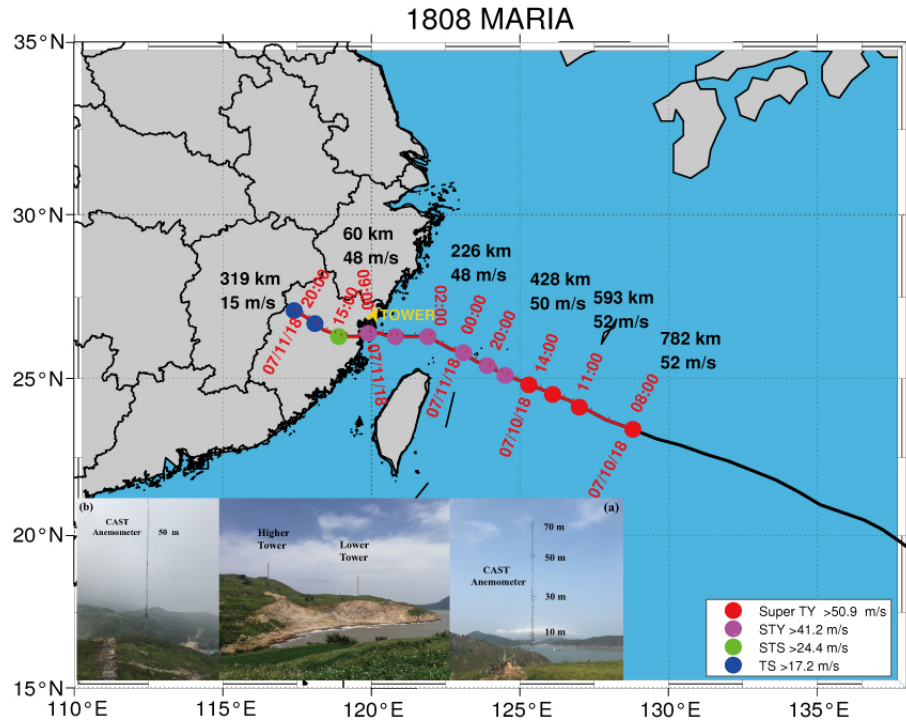
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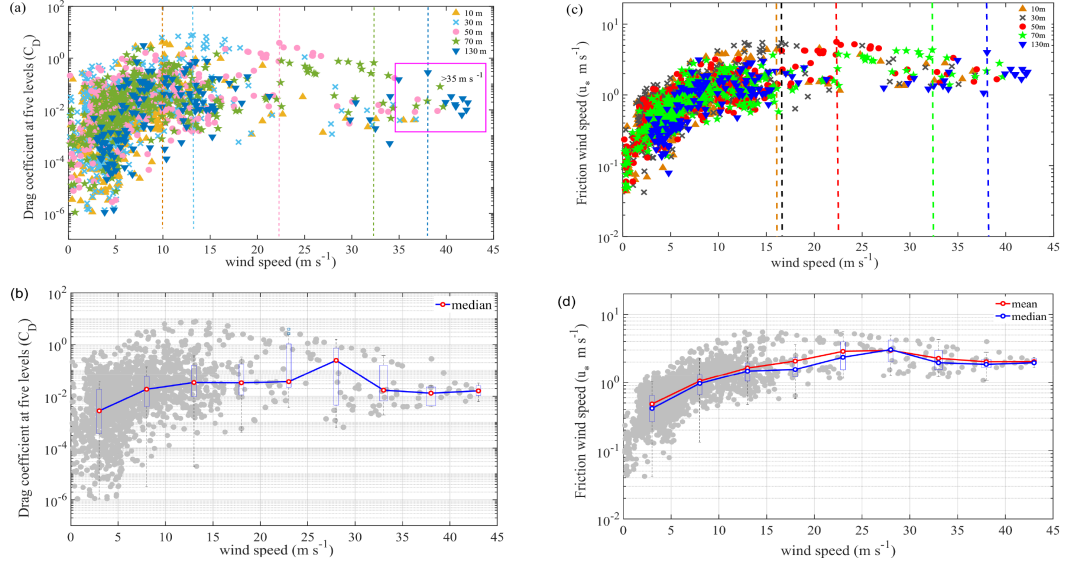
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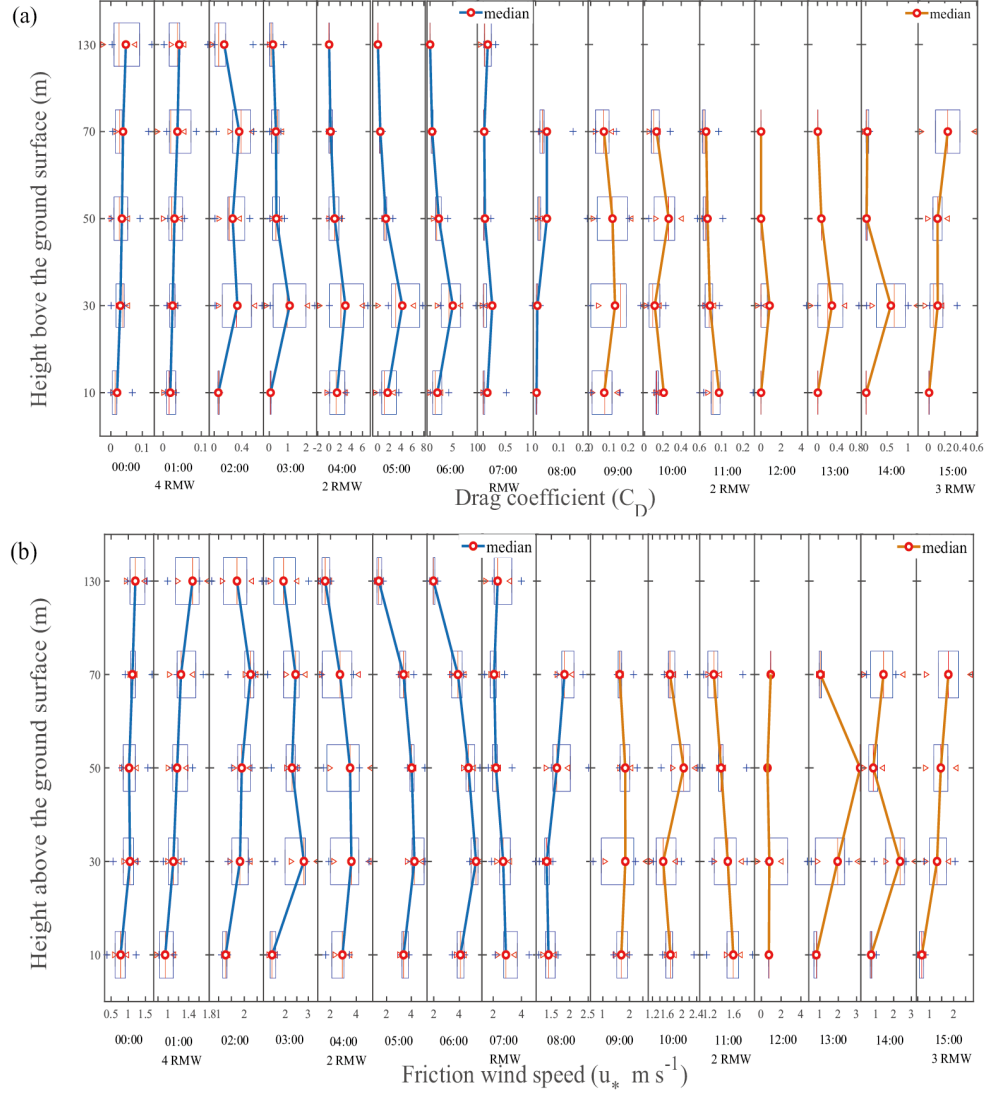
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**Figure 1** Track of typhoon Maria, the location, exposure and instruments of the two eddy covariance flux towers. The coastal observation towers are denoted by yellow arrow. (a) A photo of coastal observation tower approximately 10 m from the coastline, as indicated in Figure 1a, and is referred to as the Lower Tower in this study. The four levels of CAST anemometers on Lower Tower are 10 m, 30 m, 50 m and 70 m above the ground (70 m, 90 m, 110 m and 130 m a.s.l). (b) A photo of the coastal observation tower at the top of the hill, as indicated in Figure 1b, and is referred to as the Higher Tower in this study. The CAST anemometers on Higher Tower is 50 m above the ground (170 m a.s.l).

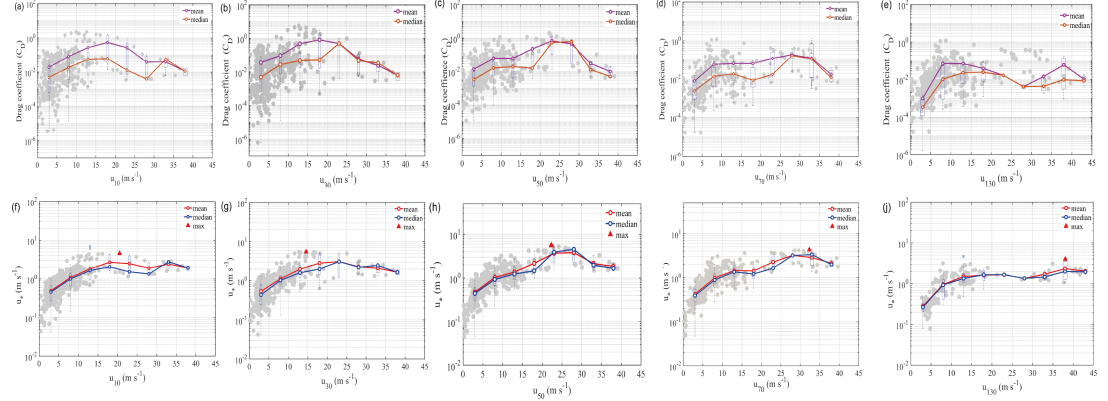


**Figure 2** (a) Scatterplots of drag coefficient ( $C_D$ ) versus wind speed ( $u_n$ ) from the five levels during Typhoon Maria, as well as for the samples of 10 m (yellow triangles), 30 m (light blue crosses), 50 m (pink circles), 70 m (green star) and 130 m (blue circles). (b) Relationship of  $C_D$  versus  $u_n$  (gray dots), the blue line with red circle is the bin median averaged  $C_D$  with 5 m s<sup>-1</sup> interval of  $u_n$  from observations. (c) Scatterplots of friction wind speed ( $u_*$ ) versus  $u_n$  from the five levels during Typhoon Maria, as well as for the samples of 10 m (yellow triangles), 30 m (gray crosses), 50 m (red circles), 70 m (green star) and 130 m (pink circles). (d) Relationship of  $u_*$  with  $u_n$  (gray dots), the blue line with blue circles indicates the bin median averaged  $u_*$  with 5 m s<sup>-1</sup> interval of  $u_n$  from observations, the red line with red circle represents the bin mean averaged  $u_*$  with 5 m s<sup>-1</sup> interval of  $u_n$  from observations.

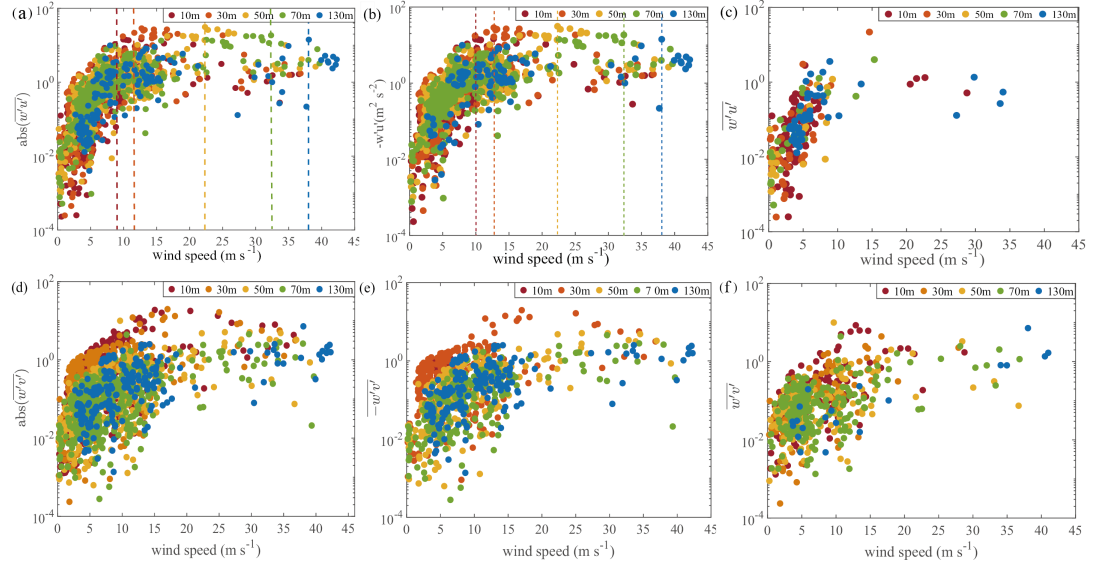


**Figure 3** The vertical profile of (a) 10 min averaged drag coefficient ( $C_D$ ) and (b) friction velocity ( $u_*$ ), for sixteen hours before and for six hours after Maria landfall. The light blue line of (a) is the median of  $C_D$  at five heights. The blue line in (b) is the median of  $u_*$  at five heights. The left and right boundary lines are 25% and 75% percentage points.





**Figure 4** Variation in  $C_D$  (a-e) and  $u_*$  (f-j) with  $u_n$  at five different levels using the bin-averaged method from the two EC flux towers during Typhoon Maria. The purple and the orange lines in a-e are the regression line of mean and median  $C_D$ , respectively. The red and blue lines in f-j are the regression line of mean and median  $u_*$ , respectively. The red triangle in f-j are maximum of  $u_*$  in each groups (every 5  $\text{m s}^{-1}$ ).



**Figure 5** Relationships of turbulent components ( $\text{abs}(\overline{w'u'})$  and  $\text{abs}(\overline{w'v'})$ ) as function of  $u_n$  from the five levels from the two towers during Typhoon Maria. The overbar indicates time averaging over 10 min.  $-\overline{w'u'}$  indicates the negative tangential component fluxes,  $\overline{w'u'}$  represents the positive tangential component fluxes,  $-\overline{w'v'}$  is the negative radial components flux and  $\overline{w'v'}$  is the positive radial components flux. The purple circles are the samples of 10 m, the orange circles are the samples of 30 m, the yellow circles are the samples of 50 m, the

green circles are the samples of 70 m and the blue circles are the samples of 130 m.