# High Wind Drag Coefficient and Sea Surface Roughness in Shallow Water

Final Report to the Joint Hurricane Testbed

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## Project Summary

This project examines how the aerodynamic roughness of the sea surface varies between shallow and deep water. All tropical cyclone GPS sonde data collected and post processed 1997-2005 was placed in a modern relational database, organized by water depth, and analyzed to provide values of surface stress, roughness, and drag coefficient Cd as a function of wind speed and water depth. For mean boundary layer winds of 20-29 m $s^{-1}$ shallow water wind profiles show stronger winds than the deep water counterpart but only two levels were significantly different. At higher wind speeds (30-39 m $s^{-1}$ MBL), no significant differences were indicated, however, for the highest winds (40-49 MBL group) there was a suggestion the deep water profiles had stronger winds for a given level than the shallow profiles but the sample size was too small to show any statistical significance. The surface roughness values for all MBL groups profiles showed that shallow water profiles were significantly different roughness than that associated with open terrain. Since open terrain roughness (0.03 m) is the roughness associated with coastal hurricane conditions prescribed by the wind load standard in the U. S., our findings suggest that the code prescribed roughness is too large, and could therefore lead to an underestimation of design winds in hurricane areas. Our results are also applicable to the interpretation of hurricane intensity. The current definition of hurricane intensity, which specifies "unobstructed" terrain, should be revised to recognize the concept of marine roughness since an "unobstructed" roughness can be a factor of five greater over land than over water. This effort is applied towards numerical weather prediction priorities EMC-1 and EMC-2, and is also related to hurricane forecast improvement needs TPC-5 and TPC-6.

## 1. Introduction

In Powell et al., (2003), GPS sonde wind profiles were analyzed to document a logarithmic change of the mean wind speed with height, suggesting the applicability of surface layer similarity in conditions associated with mean boundary layer (MBL) winds up to 70 m/s. A fit of the profiles provided information on the surface stress or friction velocity (slope) and roughness (intercept) as a function of wind speed. This analysis determined a leveling off of the surface stress and drag coefficient (Cd) in wind speeds > 34 m $s^{-1}$ and a reduction in roughness length. The Powell et al., 2003 study involved 330 GPS sondes dropped in 14 storms from 1997-1999. During 2005 and 2006, a related JHT project has focused on updating and extending the Cd values of Powell et al., 2003 using much more available wind profile data (> 2400 profiles). Preliminary results from this research have established Cd for mean boundary layer wind speeds above 70 m $s^{-1}$ and have shown a marked decrease with increasing wind speeds above 33 m $s^{-1}$.

The basis for the method is that each sonde profile is a realization or snap shot of tropical cyclone conditions. By organizing numerous realizations as a function of wind speed, the ergodic hypothesis is invoked to consider each profile as an instance from an ensemble of profiles in identical conditions. The primary feature controlling the turbulence in these conditions is the ocean surface roughness and this quantity is dependent on the wind stress and sea state, hence the organization by wind speed. The profiles are organized by the "mean boundary layer" wind speed, defined as the average of all values below 500 m. Profiles are filtered to remove undersampled flow (turbulent eddies, convective- and swell-related features) and noise due to satellite switching. Averaging the profiles removes larger scale convective features such as transient wind maxima or minima and provides information on the mean state and how it changes with the wind forcing.

Sea surface momentum flux or stress ( $\tau$ ) in numerical weather prediction of tropical cyclones is modeled using the "bulk aerodynamic method" as:

$$\tau = \rho C_D U_{10}^2 = \rho u_*^2 \tag{1}$$

based on a drag coefficient ($C_D$) and the 10 m wind speed ($U_{10}$) which varies logarithmically with height as described by the "log law" :

$$U_{10} = \frac{U^*}{k} Ln\left(\frac{z}{zo}\right) \tag{2}$$

where U* is the friction velocity, k is a constant, z is the height. The aerodynamic roughness length (Zo) is typically modeled through the Charnock (1955) relationship, which implies that the aerodynamic roughness of the sea surface increases with wind speed according to:

$$Zo = \alpha \frac{u_*^2}{g} \tag{3}$$

where g is the gravitational constant. The Charnock coefficient, $\alpha$ in this expression takes on values ranging from 0.015 to 0.035.

The surface momentum flux is therefore governed by the drag or friction at the sea surface which in turn depends on a roughness which is parameterized as increasing with increasing wind speed. Measurements support this parameterization only up to wind speeds of ~28 m/s. For higher wind speeds the roughness dependence is extrapolated e.g. Large and Pond (1981). The surface enthalpy flux is also modeled using the bulk aerodynamic method and employs an enthalpy exchange coefficient that is dependent on $C_D$. According to the theory of Emanuel (1995), a hurricane is only maintained if kinetic energy is supplied by oceanic heat sources at a rate exceeding dissipation, suggesting a ratio of enthalpy exchange coefficient ($C_E$) to $C_D$ ranging from 1.2 to 1.5 for mature hurricanes. At extreme wind speeds > 50 m/s, the typical extrapolations of wind speed dependent drag coefficients found in most models cause kinetic energy to be destroyed too rapidly to sustain a hurricane (Donelan et al., 2004). The results of the Powell et al., 2003 study have been influencing the parameterization of surface roughness and momentum exchange in extreme winds for the open ocean but we do not know whether the same behavior is typical of sea states associated with shallow water found near the coast.

Studies in non-hurricane conditions (e.g. Anctil and Donelan 1996) suggest that sea surface roughness should be enhanced in shoaling conditions. Taylor and Yelland (2001) found significant changes in roughness associated with shoaling waves with a large increase predicted for depths < 0.2 Lp where Lp is the peak wavelength in the combined wave and swell spectrum. According to Walsh et al, 2002, Lp is on the order of 250 m so a threshold water depth for the affect of shoaling on roughness should be on the order of 50 m. Figure 15 of Walsh et al., 2002 shows a rapid decrease of wavelength with water depth for depths < 35 m. This depth coincides with the region where shallow water creates shoaling conditions where waves slow down, steepen and break as they approach the coast. To evaluate the effect of water depth, we will examine mean profiles in 10 m $s^{-1}$ MBL wind speed groups containing at least 250 mean profiles from locations with water depths above and below 50 m.

Recent observations from a Florida Coastal Monitoring Program (FCMP) coastal tower deployed at Cape Hatteras in Hurricane Isabel (Powell et al., 2005) suggest that marine roughness for onshore flow is similar to that for open terrain over land. If so Cd near the coast might not level off or decrease with wind speed like it does in the open ocean; we hope to accept or reject this (open terrain) hypothesis for coastal regions. If true, distinct water depth dependent air-sea interactions would need to be incorporated in the wave, storm surge, and mesoscale NWP models. A complicating factor will be whether the flow is onshore or offshore. Onshore flow is of most interest for wave and storm surge forecasting and would comprise locations where shoaling is most prevalent. In offshore flow the turbulent advection “shadow” of the land is present such that the surface stress may be large although the winds are weaker and the waves are young and fetch-limited. In either case we expect the coastal marine roughness to be larger than that for the open ocean, however the shoaling effect would be most prominent in onshore flow. If sufficient numbers of shallow water sondes are available, we will attempt to further stratify the sondes in a particular MBL group according to whether the flow is onshore or offshore by plotting the storm splash location and MBL wind vector in H*Wind, and noting the wind direction relative to the coastline.

The specification of roughness and Cd in this region is of extreme importance for forecasting intensity at landfall, for specifying wind forcing of storm surge and waves in shallow water, and for parameterizing surface momentum flux near the coast. Coastal roughness is also extremely important for accurate height and exposure adjustments of wind speed observations and for specification of winds and wind loads for high-rise buildings on the coast. In this one year JHT project, we will organize the available post-processed GPS sonde profiles by water depth and wind speed, determine whether mean wind profiles in shallow water vary from those in deep water for the same mean boundary layer wind speed range, and develop coastal roughness and Cd relationships for use by the modeling community.

**2. Data organization:**

a. Water Depth data

Water depth information were acquired, stored, and indexed to each sonde profile to allow organization by shallow or deep ocean. Water depth data were obtained from the National Geophysical Data Center using the Oct. 2001 version of the 2-minute Gridded Global Relief Data (ETOPO2) from the World Data Center for Marine Geology and Geophysics in Boulder CO. Database queries implemented to organize the profiles and index to ancillary data. Based on observations from Walsh et al., 2002, a water depth threshold of <= 50 m was chosen to indicate shallow water.

b. Queries

The sonde database was updated to accommodate recently processed sondes and the database was queried as follows:

All data since 1997
All radii between 2 km to 300 km
MBL groups: 20-29, 30-39, 40-49, 50-59, 60-69, 70-79, 80-89 m/s

Each MBL group was sorted by water depth and deep water sondes were eliminated. The shallow water dataset as a function of MBL group breaks down as follows:

*Table 1 Number of shallow and deep water sonde profiles as a function of MBL wind speed group. Numbers exclude post 2000 Air Force sondes, 2005 Wilma, and post 2006 sondes.*

| MBL group (m/s) | Sonde profiles in deep water | Shallow water profiles | Onshore / Open |
|---|---|---|---|
| 20-29 | 224 | 32 | 19 |
| 30-39 | 252 | 65 | 42 |
| 40-49 | 307 | 30 | 19 |

| | | | |
|---|---|---|---|
| 50-59 | 187 | 18 | 9 |
| 60-69 | 118 | 5 | |
| 70-79 | 94 | 0 | |
| 80-89 | 26 | 0 | |

c. Upstream fetch

Shallow water sondes are close enough to shore that the mean wind profiles are affected by the upstream fetch. A sonde with an upstream fetch over land (offshore flow) will exhibit more low level wind speed shear than a sonde with an upstream fetch over open water (onshore flow), leading to very different surface layer quantities and different drag coefficients. Therefore sondes within an MBL group were characterized by upstream fetch as follows:

1) Along-shore: Sonde splash wind direction or last measured wind direction indicates a flow component that is alongshore or within 30 degrees of parallel to shore.

2) Inland: Sonde splash location indicated the sonde drifted over land inland from the coast.

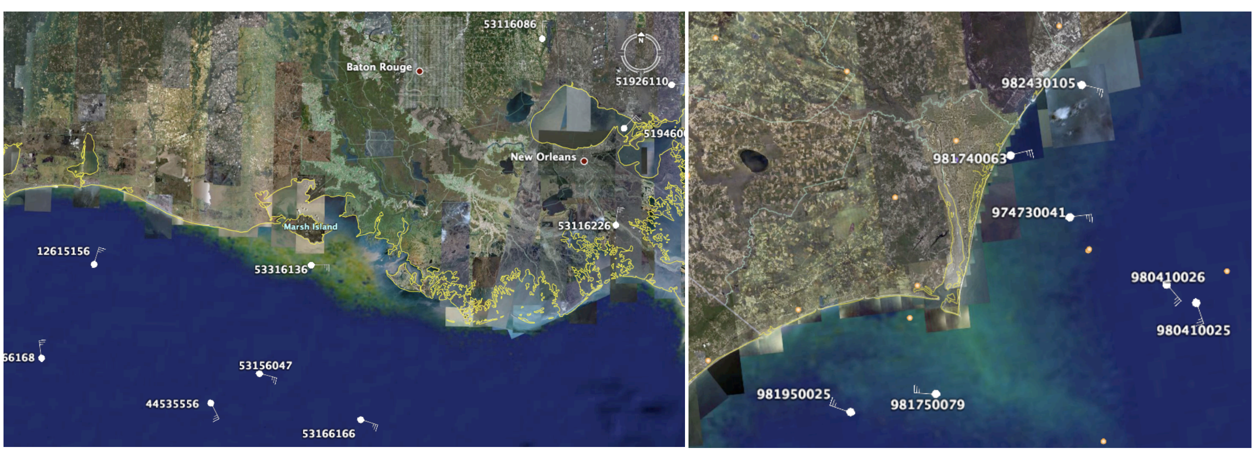


Fig.1 Google Earth images of sondes splash locations and serial numbers in the 40-49 m/s MBL group. Wind barbs show direction last measured wind but speeds are all given a dummy speed of 25. a) Off LA coast (note 3 sondes inland). b) Off Cape Fear NC coast. Onshore or open: Sonde splash wind direction or last measured wind direction indicates a flow component that is either onshore or the sonde is in shallow water or shoals but > 50 km offshore from any land mass.


Fig. 2. As in Fig. 1 but for 50-59 m/s MBL group from Hurricane Katrina in 2005. Sonde serial numbers are shown adjacent to the splash location.

Sondes within an MBL group were subgrouped into Keyhole Markup Language (KML) files for plotting their location in Google Earth. A JAVA servlet was written to connect to Google Earth and plot the sonde locations and wind barbs as scalable place marks. The wind direction was then examined relative to the coastline to determine the upstream fetch characterization for each shallow water sonde profile.

Exploratory analysis was conducted on the 30-39 m/s MBL group since this contains the largest number of shallow water sondes.

*1. Offshore flow*

For offshore flow 10 sonde profiles were available. A log Z vs wind speed plot (Fig. 3a) indicates that for several sondes, the lower 50 m of the wind profile shows near constant wind speed profiles with height characteristic of internal boundary layer development. This behavior suggests non stationary conditions associated with the lower levels of the offshore flow accelerating due to a new (sea) underlying surface, whereas the upper levels of the boundary layer are characterized by higher shear associated with flow over land. The specific humidity (Fig. 3b) also show evidence of an internal boundary layer development with relatively sharp decreases above 50-100 m. Such non stationarity makes the offshore flow profiles unsuitable for estimating surface layer quantities.

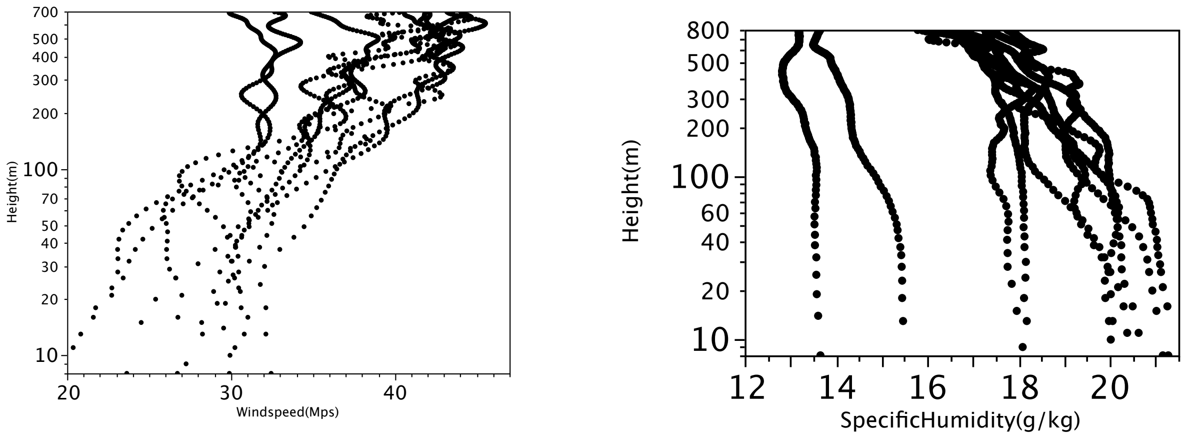


Fig. 3 a) Height vs. Wind speed for offshore sondes showing low shear or near constant wind speed below 50m. b) Height vs. Specific humidity showing a relatively shallow internal bound ary layer with a decrease above the lowest 50 m layer.

*2. Onshore flow*

For shallow water onshore flow 42 sonde profiles are available (Fig 4a) and a mean profile fit suggests a roughness length of about 0.7 mm. A mean profile constructed from all 294 sondes in the 30-39 MBL group (Fig. 5) suggests a smaller roughness length of about 0.3 mm. However this plot includes all the shallow water sondes. The differences should be larger once we separate out the shallow water sondes. However, another factor to consider will be the storm relative azimuth of the deep water sondes since in our April 2007 JHT report we indicated enhanced roughness in the storm-relative, left-front portion of the storm. By separating the shallow water profiles from the deep ones, we should be able to determine whether the higher roughness values observed to the front left are associated with shallow water or interaction between the flow and the wave motion. Furthermore we hope to determine whether onshore flow in shallow water exhibits different surface layer characteristics than open ocean flow over deep water.

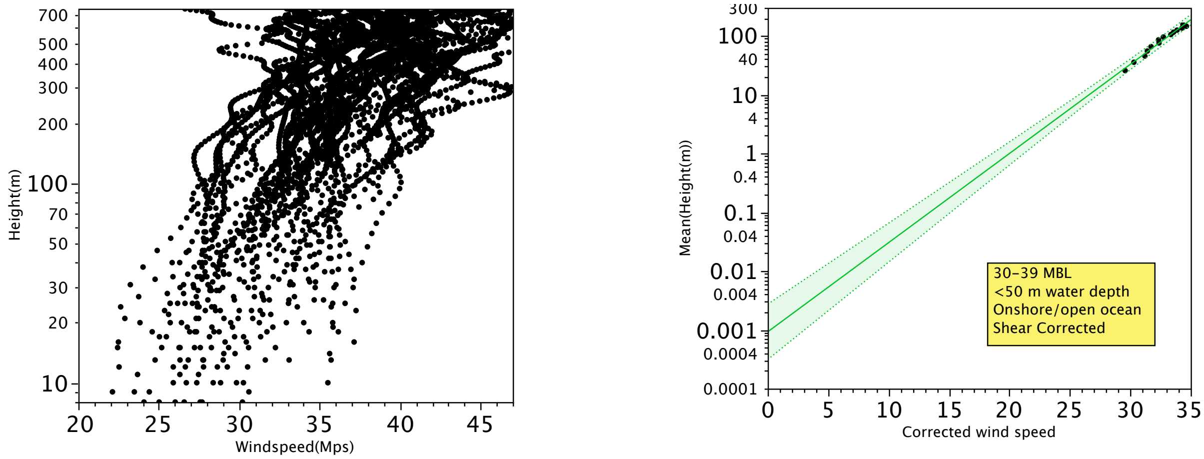


Fig. 4 a) Height vs. Wind speed for onshore flow sondes in the 30-39 m/s MBL group. b) Log fit to the bin mean wind profile in the lowest 20-160 m (lowest two points not used in the fit). Intersection with the height axis determines the roughness length (~ 0.7 mm).

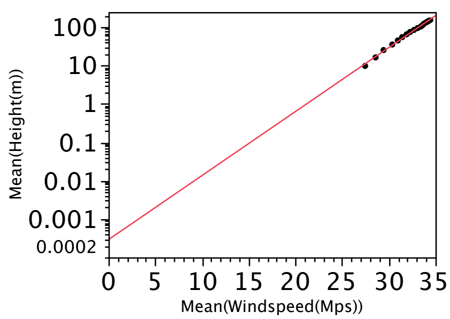


Fig. 5 As in 4b but mean profile for 20-160 m layer from all sondes in the 30-39 MBL group.

*3. Along shore flow*

For along shore flow in the 30-39 m/s MBL group, eight sonde profiles are available. Examination of individual plots (Fig. 6) indicates profiles with characteristics of the offshore flow as well as onshore flow. These profiles may be examined more closely to see if some can be associated with the onshore and offshore profile categories.

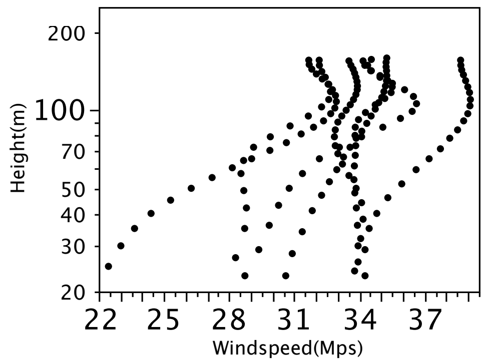


Fig. 6 Height vs. Wind speed for Along-shore flow sondes in the 30-39 m/s MBL group.

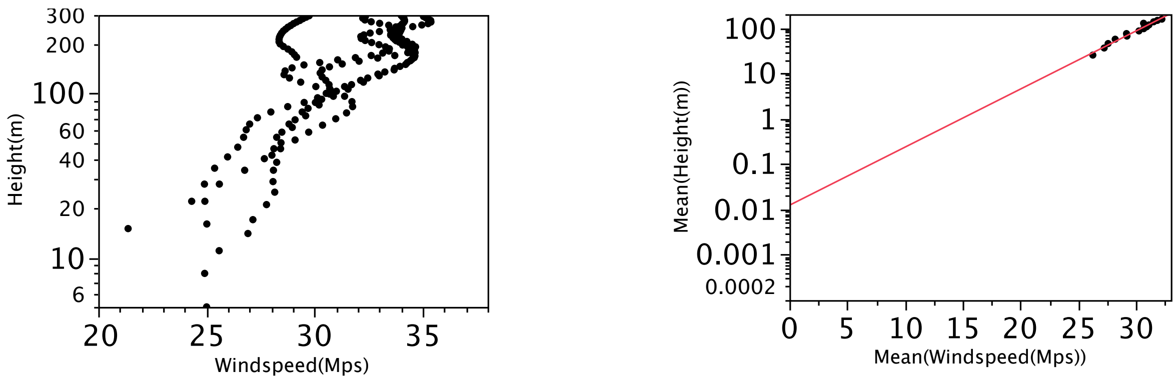


Fig. 7 Wind profiles over land from the 30-39 m/s MBL group. a) individual profiles. b) Bin-mean profiles and log fit over the 20-260 m layer.

*4. Inland Wind Profiles*

Four sondes (Fig. 7) in the 30-39 m/s MBL group drifted inland and were characterized by large wind speed shear over the lowest 150 m, resulting in a roughness length near that associated with open terrain (15 mm). We would need > 10 profiles over land to substantiate the differences with onshore flow over shallow water and open ocean flow over deep water in the MBL group. However, sondes are not permitted to be launched over land so it is rare that such profiles are available (apparently the inland sondes shown here were advected inland from offshore or from a bay, sound, or lake (e.g. Onslow Bay, Pamlico Sound, Lake Ponchartrain).

## 3. Statistical analysis for differences between shallow and deep water wind profiles

Once the mean profiles were established for the shallow water groupings of profiles according to the four MBL groups with sufficient samples, testing was conducted to determine whether the shallow water profiles differ from those conducted in deep water. Subsets of the complete shallow and deep files for a given MBL group were concatenated to create files containing all shallow and deep samples for each height bin in a given MBL group. Distributions of the wind speed observations were examined for each height bin using oneway analysis with the water depth as the categorical variable. Finally the shallow and deep water wind profiles were compared for each MBL group.

*a. 30-39 m/s MBL Group*

Oneway analysis tests how a continuous response (wind speed) distributes differently across groups defined by a categorical factor (water depth, shallow or deep). Student's t tests for the difference of means depend on the data in each category being independent, random samples and having characteristics of a normal distribution.

Independence was achieved by categorizing shallow profiles according to sondes that splashed in water < 50 m with onshore flow relative to the coast or with splash locations in shallow water well (> 50 km) offshore, while all deep water profiles comprised sondes that splashed in water deeper than 50 m. The proximity of deep water sondes close to shore was not examined. While the data within each water depth category are independent from each other, sonde post processing includes a 5 s filter to remove spikes associated with undersampled scales and satellite switching. Since the sondes fall at about 10-12 m/s and sample at 2 Hz, a 5 s filter will include about 10 samples with the capacity to influence a particular wind speed value. A ten m bin would typically include two filtered samples from the same sonde so only about half the samples for a particular height bin are independent sonde measurements. Since the sonde profiles in shallow water are completely independent from the profiles in deep water, the t test independence requirement is satisfied. Individual samples within a height bin are not completely independent of samples in the same or neighboring height bins. However, this should have no bearing on the results because all height bins are affected similarly.

Statistical moments (Table 2) indicated that a slightly right skewed distribution with typical skewness values of 0.25, with small or negative kurtosis indicative of a flattened distribution (relative to normal). Wind speed vs Quantile plots indicated relatively straight lines (similar to normal distributions) except for the tail regions, which were relatively thin at the low wind speed end relative to the normal distribution, and relatively fat at the high wind speed end (more high wind observations than expected from a normal distribution. Goodness of fit tests for the normal distribution were only significant for a couple of the shallow height bins where the small sample size was probably the determining factor.

*Table 2 Statistical moments of the 25 m height bin wind speed data*

| Water Depth | N | Mean | Sigma | Skewness | Kurtosis |
|---|---|---|---|---|---|
| Deep | 350 | 29.49 | 3.86 | 0.32 | 0.02 |
| Shallow | 64 | 29.71 | 3.49 | 0.37 | -0.37 |

The variance of the low sample (shallow) data set was always less than the larger sample set but the shallow water mean standard errors were over twice as large as the deep water sample and did not show other distribution characteristics that would tend to influence the t test (such as skewness of a different sign to the deep water group, or fat tails relative to the deep water group. The mean of the shallow wind speed data set was not always less than that of the deep water data set and the variance did not depend on the magnitude of the mean. Even though the distributions differed from normal, a t test was conducted assuming unequal variances for each water depth category height bin of a given MBL group. No evidence of significant differences of mean wind speeds was indicated for shallow water vs. deep water. Due to the non-normal characteristics of the wind speed distributions for a given height bin, nonparametric tests were also conducted to determine whether the group means or medians are located differently across water depth groups. The nonparametric tests do not assume normality. The Wilcoxon nonparametric test is powerful when the actual distribution of the differences between the observations and the mean do not follow a normal distribution. Nonparametric testing gave no indication that the means of the 30-39 MBL distributions were significantly different from each other.

To illustrate the statistical analysis for testing whether the mean wind speeds for a particular height bin are significantly different, we show the data for the 25 m bin which comprises all observations in the 30-39 m/s MBL group with wind speeds >= 20.0 and < 30.0 m/s. First we examine the distributions of the observations.

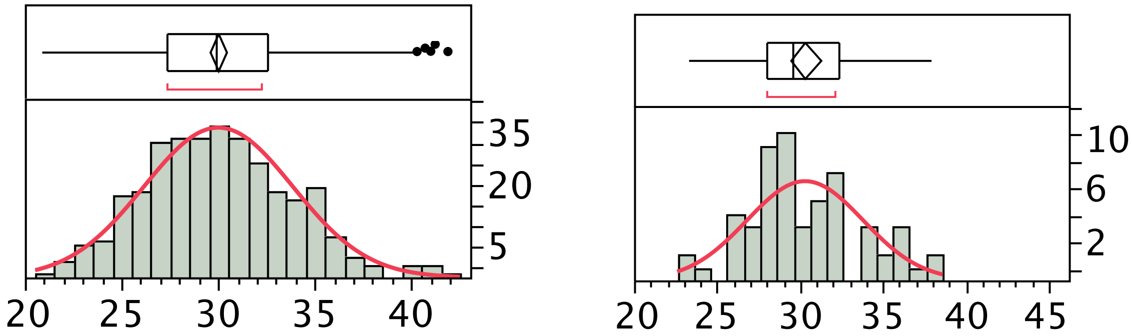


Fig. 8 Histogram of wind speed at the 25 m height bin for the 30-39 m/s MBL group between a) deep (left) and b) shallow (right) water depths. Red line indicates fit of normal distribution.

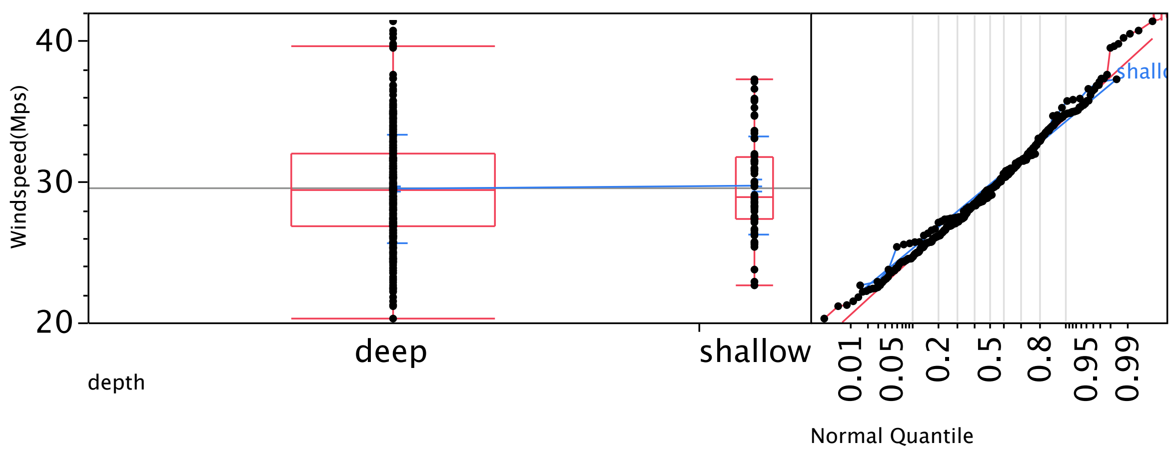


Fig. 9 a) Oneway analysis of wind speed at the 25 m height bin across water depth (left). b) Normal quantile plot for the shallow and deep water samples.

For this particular case, despite having a relatively flat distribution, the shallow water data pass the goodness of fit test for normality but the deep water do not. The oneway analysis box plots show that mean wind speeds and standard deviations are very similar for both groups, but the shallow water mean wind is slightly stronger than the deep water mean. The normal quantile plots show much of the data following along a straight line (indicative of a normal distribution) except at the tails. This tail characteristic was typical of nearly every height bin. The shallow data show smaller slope (indicative of smaller variance) and fewer observations in the tails than the deep data (due to the difference in sample size).

**t Test**

shallow-deep

Assuming unequal variances

| | | | |
|---|---|---|---|
| Difference | 0.2152 | t Ratio | 0.445279 |
| Std Err Dif | 0.4832 | DF | 93.29926 |
| Upper CL Dif | 1.1747 | Prob > \|t\| | 0.6571 |
| Lower CL Dif | -0.7444 | Prob > t | 0.3286 |
| Confidence | 0.95 | Prob < t | 0.6714 |


Fig. 10  t test for shallow vs deep water mean wind differences.  H0: Zero Difference

The t test assuming unequal variance computes the t ratio as the standard error of the estimate of the mean difference (0.48) divided by the difference between sample means (29.71-29.49 = 0.215), and results in a value of 0.445 (indicated by the vertical red line on the plot).  If the group means were truly the same in the population, the t value would be zero. In order to be significant, the probability of a t ratio value as high as that observed  when in the population, there is no difference in the means of each water depth category, would need to be less than 0.05.   In this case all the p values are well above 0.05 so there is no evidence to reject the null hypothesis that there are no differences between the shallow and deep water mean wind speeds  at this height and for this MBL group.   The non parametric tests also indicate no significant differences between shallow and deep water mean wind speeds at any individual height bin.

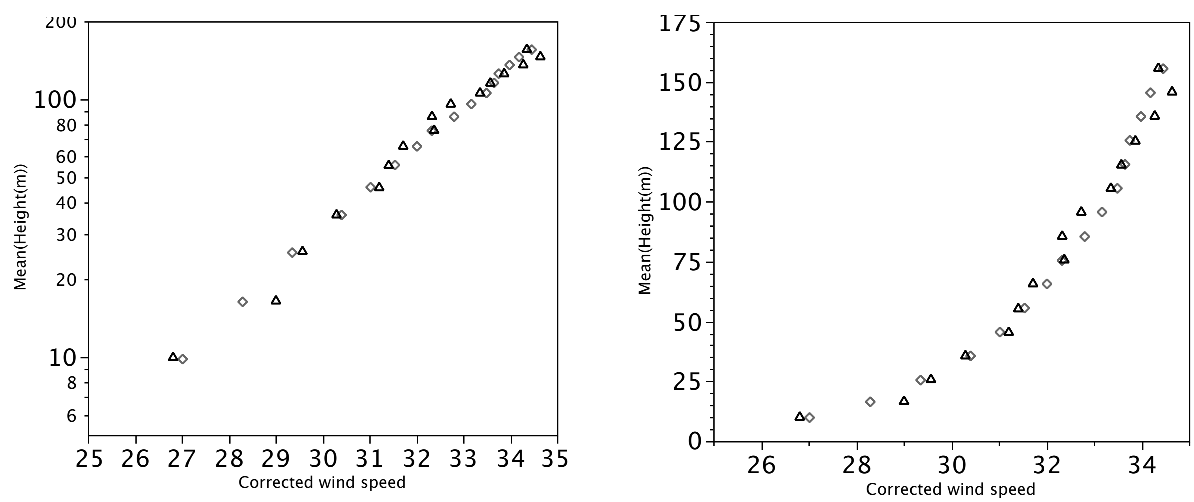


Fig. 11 Mean vertical wind profile for 30-39 m/s group a) linear scale, b) log scale.  Values represent height bin averages for deep (diamonds) and shallow (triangles) water.

The mean profiles in Fig.11 on the linear scale show that the deep water mean profile has less scatter than the shallow water profiles, likely due to the larger sample size (e.g. at 25 m, the shallow water group has only 64 samples compared to 350 for the deep water group). Surface layer roughness, friction velocity and drag coefficient were computed with and without the lowest two level height bins since these bins have fewer samples and are more likely to be affected by waves and higher signal to noise ratios associated with turbulence and satellite switching.

Even though the statistical tests suggest no significant differences in the means, even slight differences, if tending in the same direction, can have a big influence on the slope of the wind profile.

*Table 3. Surface layer quantities for the 30-39 m/s MBL group for shallow and deep water. U10 is the 10 m level neutral stability wind speed computed from the log law using the values of Ustar, and Zo in the table.*

| Water Depth | Height Range | Zo (mm) | Cd x $10^3$ | Ustar | U10 |
|---|---|---|---|---|---|
| Shallow | 10-160 | 0.47 | 1.61 | 1.08 | 26.96 |
| Deep | 10-160 | 0.5 | 1.63 | 1.09 | 26.95 |
| Shallow | 20-160 | 0.92 | 1.85 | 1.15 | 26.6 |
| Deep | 20-160 | 0.66 | 1.72 | 1.11 | 26.8 |

For the 30-39 m/s MBL group, the shallow and deep water profiles are remarkably similar for the 10-160 m surface layer height range. The 20-160 m range suggests that the shallow water profiles are associated with slightly higher roughness of 0.9 mm compared to 0.6, but the error bars for the shallow water estimates with a 20-160 m surface layer are very high with a 95% confidence limit range of about 0.35 to 2.5 mm, while the deep water range is much smaller at 0.5 to 0.9 mm.

*b. 20-29 m/s MBL group*

The number of shallow water profiles in the 20-29 MBL group is less than half that of the shallow water sondes in the 30-39 MBL group (19 compared to 42). The deep water samples in the 20-29 MBL group (from 224 profiles) show close placement to the diagonal straight line indicative of a normal distribution (Fig. x) everywhere but the last 5% of upper wind speed tail, however, none have high enough p values to accept the null hypothesis that the data come from a normal distribution (at the 5% level). The 20-29 MBL shallow water group shows a larger de

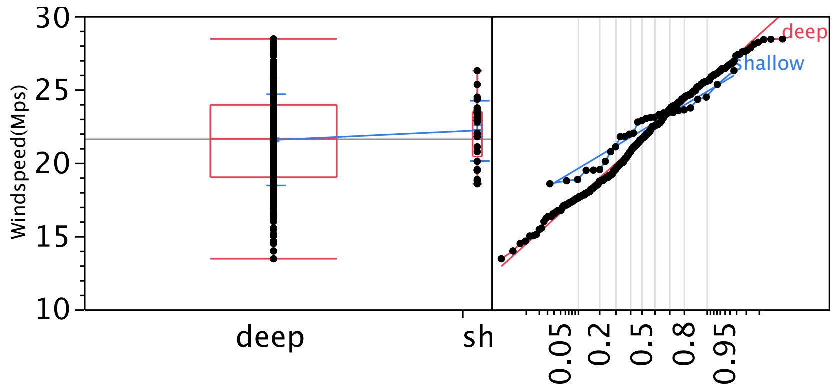


Fig. 12 Normal quantile plot for 20-29 MBL wind speed onshore /open ocean flow for the 25 m height bin. Blue line represents shallow water points, red diagonal line represents normal distribution.

parture from a normal distribution in the Normal Quantile plots. For example, the Normal Quantile plot for the 25 m bin shown above is typical. None of the individual bin shallow water data look normal or pass normal goodness of fit tests.

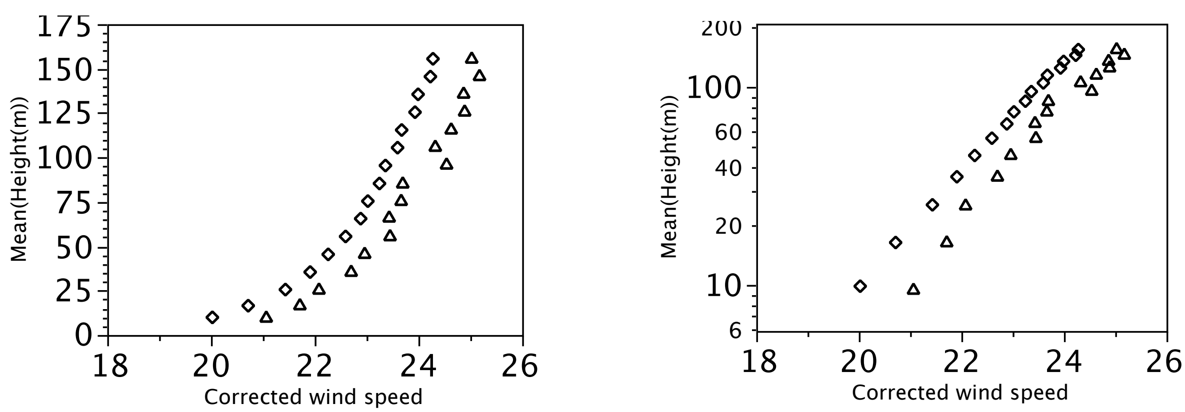


Fig. 13 As in Fig. 11 but for 20-29 MBL group.

All shallow water height bins in the 20-29 MBL group show larger mean wind speed values (corrected for shear bias) than their deep water counterparts (Fig. 13). However the Wilcoxon / Kruskal-Wallis test (a robust test that does not require samples from a normal distribution) shows significant differences in the bin means at the 95m, 125m, 145m levels. Many of the other bins show low (but not significant) p values. Given that the standard error of the mean for the shallow water samples is about three times larger than that for the deep water, a larger sample size would help strengthen our statistical analysis.

Table 4 indicates that the shallow water profiles have smaller roughness if the lowest two bins are included, but higher roughness and drag if the lowest two bins are excluded. The later (20 - 160 m surface layer) is preferred due to larger samples and smaller errors. Differences between shallow and deep water are not very large in these cases, accounting for about 0.4 m/s difference in the neutral stability 10 m wind speed computed by the log law. Similar to the 30-39 m/s group, using the 20-160 m surface layer, the shallow water sonde profile indicates higher roughness and drag coefficient in shallow water. However, the scatter in the shallow water observations is evident in Fig. z and the large 95 % confidence limits result in a range of from range in roughness from .02 to .4 mm for shallow water compared to 0.02 to 0.06 mm in deep water. For Cd, the range in shallow water is 0.95 to 1.57, while for deep water the range is much smaller (0.93 to 1.10).

*Table 4 Surface layer quantities for the 20-29 m/s MBL group for shallow and deep water.*

| Water Depth | Height Range | Zo (mm) | Cd x $10^3$ | Ustar | U10 |
|---|---|---|---|---|---|
| Shallow | 10-160 | 0.015 | 0.889 | 0.62 | 20.78 |
| Deep | 10-160 | 0.026 | 0.965 | 0.62 | 19.96 |
| Shallow | 20-160 | 0.096 | 1.20 | 0.70 | 20.31 |
| Deep | 20-160 | 0.035 | 1.01 | 0.63 | 19.88 |

*c. 40-49 m/s MBL Group*

For the 40-49 m/s MBL group 19 shallow water profiles were available compared to 307 in deep water. Testing for normality (Fig. 14) shows that a few deep water height bins (45 m, 55 m, 75 m, and 85 m) and shallow water bins (115 m, 125 m, 135 m, and 155 m) that pass significance tests for the normal distribution. At 25 m (Fig. 15) the means of the shallow and deep samples are nearly the same but the normal quantile plot (Fig. 14) shows that only the deep water samples tend towards a normal distribution. Wilcoxon tests show that no height bins with low enough p values to reject the null hypothesis that the means of the shallow and deep water groups are the same.

For the 40-49 MBL group, the deep water wind speeds are typically greater than those from shallow water. The shallow water profiles are associated primarily with landfalling storms, and exhibit stronger inflow, larger radial velocities, and tend to be found at larger radial distances from the storm center than the deep water profiles (possibly associated with a tendency for storms to expand while decaying near landfall.

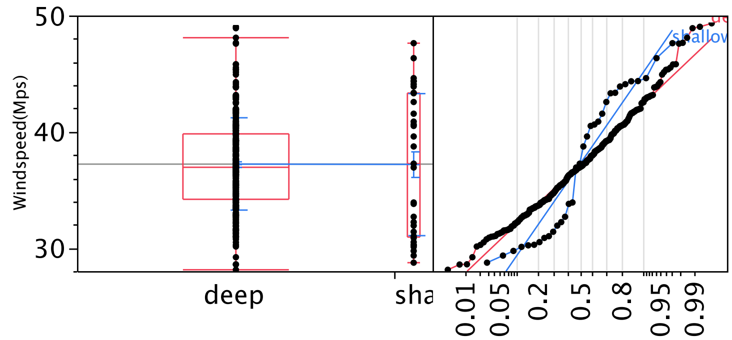


Fig. 14 Normal quantile plot for 40-49 MBL wind speed onshore /open ocean flow for the 25 m height bin. Blue line represents shallow water points, red diagonal line represents deep water fit to data. Normal distribution is indicated by points falling along the line.

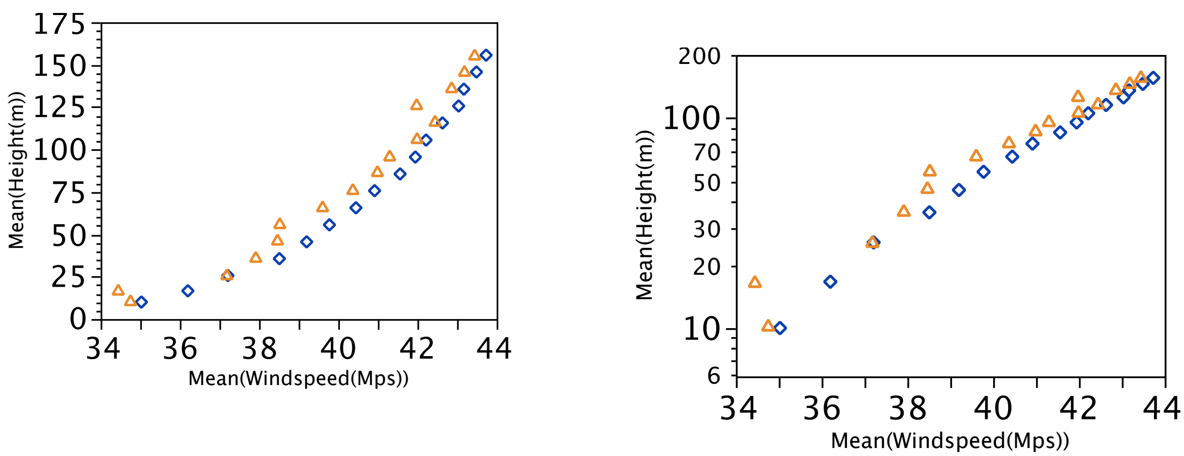


Fig. 15 As in Fig. 12 but for the 40-49 m s$^{-1}$ MBL group.

**d.** *50-59 m s⁻¹ Group*

Only nine wind profiles were available for the 50-59 m $s^{-1}$ group so the sample size was insufficient to conduct difference testing. The mean profiles suggest that shallow water profiles above the 35 m bin have higher winds than deep but at levels at or below 25 m, the deep water profiles show stronger winds. Further analysis of the 50-59 m $s^{-1}$ group will await accumulation of a larger shallow water sample size.

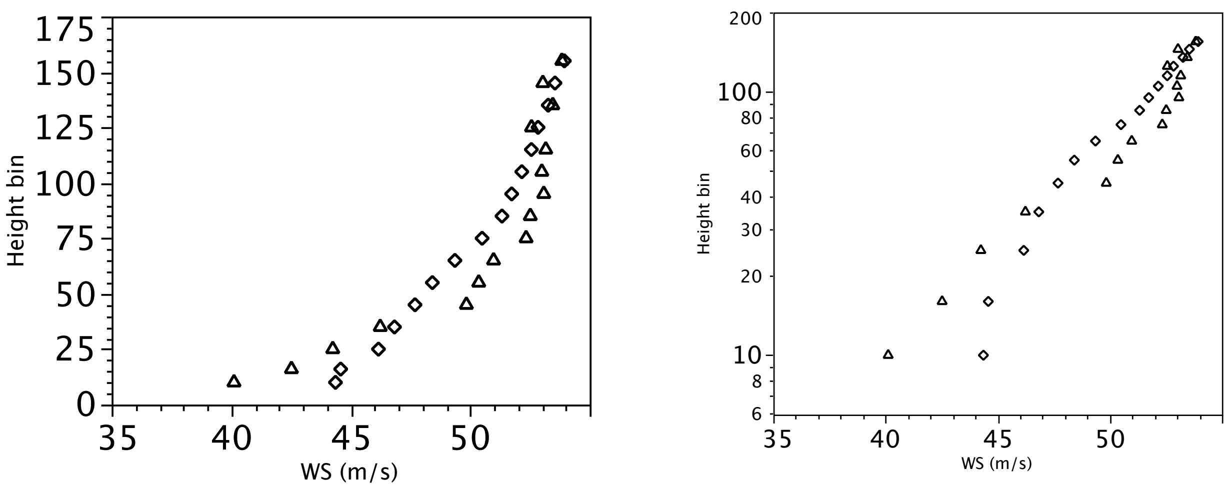


Fig. 16 As in Fig. 12 but for the 50-59 m $s^{-1}$ MBL group.

**e.** *Drag coefficient and surface layer quantities*

Profile method computations of roughness length, drag coefficient, and friction velocity were tabulated for the shallow (Table 5) and deep (Table 6) water profiles within each MBL group for the 20-160 m surface layer. For a given MBL wind range, the roughness values for shallow water tend to be larger than those for deep water, with larger drag coefficients, respectively. The error bars on the CD and Zo estimates are relatively large however. When shallow and deep water quantities (Figs. 17-19) are plotted on the same graph, it is difficult to see meaningful differences, and indeed, none of the differences were statistically significant. In figs. 17-19, we included values for the 50-59 m $s^{-1}$ MBL group. This group showed the largest differences, with higher roughness and Cd suggested for shallow water. However, the sample size for shallow water is too small to draw any meaningful conclusion.

**Table 5 Surface layer quantities for shallow water**

| MBL Group (m/s) | Hurricanes | Profiles | Zo (mm) | Cd x $10^3$ | Ustr | U10 |
|---|---|---|---|---|---|---|
| 20-29 | 8 | 19 | 0.096 | 1.19 | 0.7 | 20.3 |
| 30-39 | 9 | 42 | 0.92 | 1.85 | 1.15 | 26.6 |
| 40-49 | 5 | 19 | 1.46 | 2.05 | 1.50 | 33.0 |
| 50-59 | 5 | 9 | 8.7 | 3.22 | 2.25 | 39.6 |

**Table 6 Surface layer (20-160 m) for deep water profiles.**

| MBL Group (m/s) | Profiles | Zo (mm) | Cd x $10^3$ | Ustr | U10 |
|---|---|---|---|---|---|
| 20-29 | 224 | 0.035 | 1.01 | 0.63 | 19.9 |
| 30-39 | 252 | 0.66 | 1.72 | 1.11 | 26.8 |
| 40-49 | 307 | 1.17 | 1.95 | 1.48 | 33.5 |
| 50-59 | 187 | 2.28 | 2.27 | 1.94 | 40.6 |

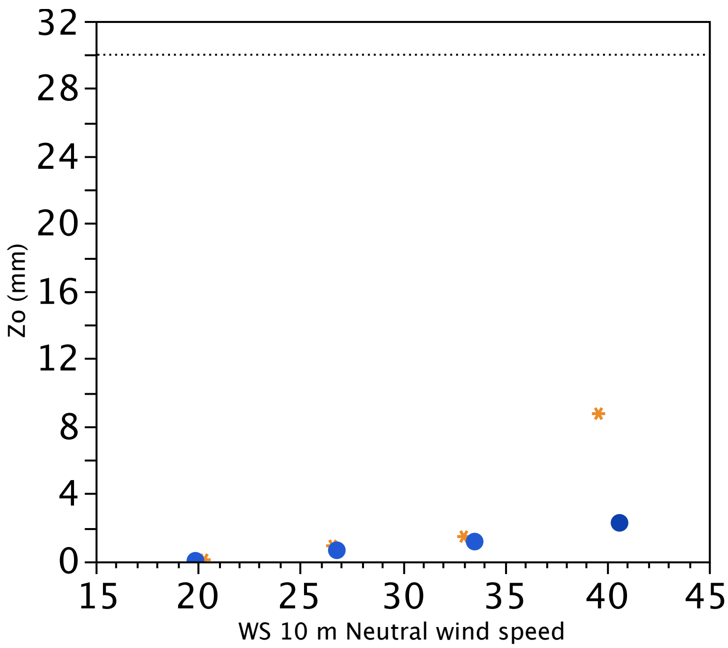


Fig. 17 Variation of shallow and deep water roughness (x) as a function of 10 m neutral stability wind speed. Brown stars squares represent shallow water values while blue circles represent deep (> 50 m) values. Dashed line represents open terrain roughness.

The variation of surface layer quantities with wind speed is similar to that shown in Powell et al., 2003, 2007. The decrease of roughness and $C_D$ with wind speed is not shown in Fig. 17 and 18 because the decrease is not apparent until we include the 60-69 m $s^{-1}$ MBL group. There were insufficient shallow water profiles to include in our analysis for MBL groups exceeding 60 m $s^{-1}$, so this characteristic is not apparent in Figs. 17-19. The open terrain roughness value of 30.0 mm is indicated by the dashed line in Fig. 17. Open terrain roughness is defined by the American Society of Civil Engineers (ASCE) wind load standard as “Exposure C” and is the specified wind exposure for hurricane conditions regardless of whether the upstream fetch is from the land or ocean. As seen in Fig. 17, the shallow and deep water roughness values are an order of magnitude smaller than the open terrain value. Roughness determines the $C_D$ hence an open terrain roughness corresponds to a $C_D$ of 4.75 x $10^{-3}$, which is a factor of 2-4 larger than the shallow or deep water $C_D$.

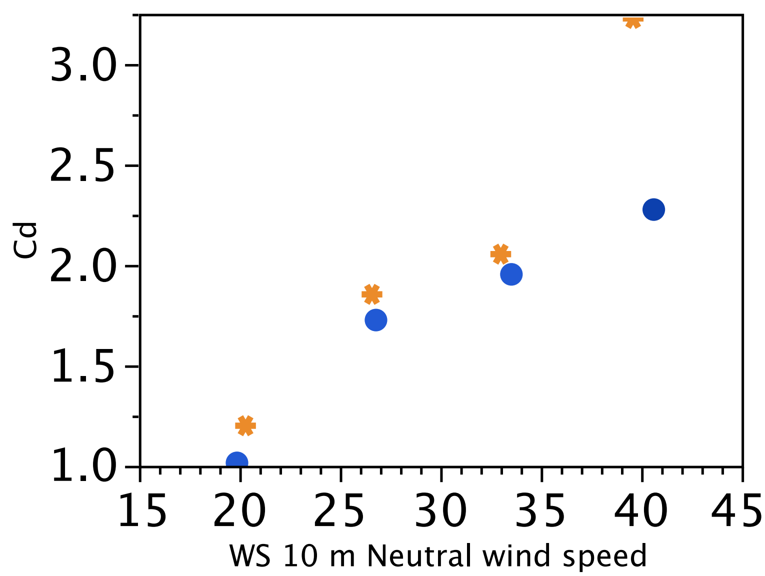


Fig. 18 As in Fig. 17 but for Drag coefficient (x $10^3$). Values for the 50-59 m $s^{-1}$ MBL group correspond to only nine shallow water profiles and large error bars at the wind speed of 40 m $s^{-1}$.

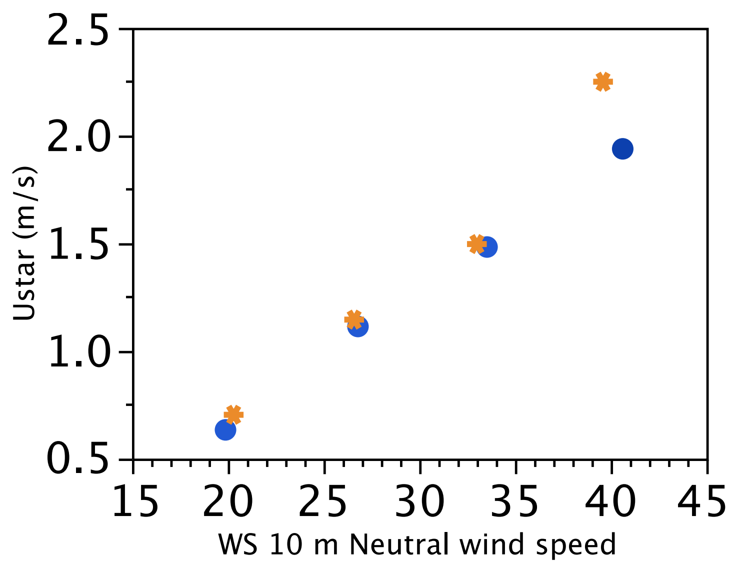


Fig. 19 As in Fig. 17 but for friction velocity. Values for the 50-59 m $s^{-1}$ MBL group correspond to only nine shallow water profiles and large error bars at the wind speed of ~40 m $s^{-1}$.

Our results indicate no need for water depth dependent roughness or CD parameterizations for surface layer modeling of tropical cyclones for surface winds up to hurricane force. Examination of higher surface wind speeds will await a larger sample of shallow water wind profiles in MBL winds > 50 m s-1. We recommend an enhancement to the AOML field program landfall experiments to acquire additional shallow water wind profiles and have also proposed to NOAA's Integrated Ocean Observing System Program for an adaptive observing system comprised of 2m and 10 m towers deployed by University partners, together with the NOAA P3 research aircraft.

In light of our findings, we also considered the meaning of "unobstructed flow", used in the definition of the maximum sustained wind speed (NWS 2006): " the highest one-minute average wind, $V_{MS}$, (at an elevation of 10 m with an unobstructed exposure) associated with that weather system at a particular point in time". Unfortunately no such definition exists with respect to surface roughness. Over land, open terrain would qualify as "unobstructed" but over water the marine roughness can be an order of magnitude smaller, with higher wind speeds. For example, for neutral atmospheric stability, assuming a 250 m level wind speed of 45 m $s^{-1}$, the wind at 10 m would be 29 m $s^{-1}$ for open terrain and 33 m $s^{-1}$ for a marine roughness of 1.5 mm. This ambiguity in the hurricane intensity definition leaves it to the user to try to interpret what "unobstructed flow" means, but it can make a 10% difference at hurricane threshold wind speeds and the difference will increase with stronger winds since the marine roughness decreases with extreme winds.

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