**Near surface wind longitudinal velocity positively skews
with increasing aerodynamic roughness length**

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Abstract

Analysis of anemometric observations collected during the 1999-2016 Atlantic hurricane seasons and boundary layer wind tunnel (BLWT) measurements indicate that the near surface wind behavior deviates from Gaussian as surface roughness increases. Quadrant analysis of the Reynolds stress clearly demonstrates the linkage between the longitudinal skewness and downward transfers of momentum (sweep events) in strong winds, which previous studies have also observed. Modern wind load provisioning and BLWT similarity requirements do not explicitly account for this effect, although the experimental configuration of typical wind tunnel development sections may correctly simulate the phenomena. Here we quantify how the observed positive skewness affects the terrain exposure coefficient profile for ASCE 7. The results demonstrate the need to update peak factor calculations to accurately predict extreme winds acting on low-rise buildings in built-up terrain.

1. Introduction

The findings of this paper refute the dominant assumption in wind engineering that the surface (< 25 m) wind field exhibits Gaussian behavior over all terrain types. Results from 17 years of anemometric observations in tropical cyclones and recent boundary layer wind tunnel (BLWT) experiments indicate that the skewness (γ_{3u}) of the longitudinal velocity component increases with aerodynamic roughness length (z_0)—a phenomena not currently addressed by exposure conversion factors in wind load provisioning nor in standards to commission facilities for BLWT modeling, e.g. ASCE/SEI 49-12 and AWES-QAM-1-2001.

The cause is attributed to the prevalence of sweeps, i.e. downward and forward departures from the mean longitudinal flow, that positively skew the velocity. This mechanism, in part, also explains why field studies (e.g., Baldocchi and Hutchison 1987; Baldocchi and Meyers, 1988; Maitani and Shaw, 1990) have observed variations in high order moments near the canopy of suburban regions. Our observations strongly corroborate with previous findings originating from field measurements (e.g., Chen, 1990; Rotach, 1995; Rotach et al., 2005; Shaw et al., 1983) and the BLWT (e.g., Finnigan, 2000; Zhu et al., 2007; Raupach, 1981; Böhm et al., 2013), which have documented the dominance of large coherent structures within and just above the canopy of the turbulent boundary layer, and the correlation of these structures to the third moment of the longitudinal and vertical velocity components.

The study extends the work of Balderrama et al. (2012), expanding its dataset to include targeted field measurements in suburban terrain and ultrasonic anemometer measurements at five levels spanning 5 to 15 m. It also incorporates new approach flow data collected in a novel BLWT that can rapidly reconfigure the roughness element grid to achieve a user-specified z_0 for a user-specified geometric scale. The results suggest the standards should be conservatively updated to incorporate a linear change in γ_3 from [0.46, 0.0] over [4.4, 24.6] m, holding $\gamma_3 = 0.46$ below this extent. Applying the non-Gaussian up-crossing rate defined in Kareem and Zhou (1994) to the wind speed (pressure) conversion described in Masters et. al. (2010), we find up to a 14% increase in the pressure loading on suburban low-rise structures (ASCE 7-10, 2010).

2. Methodology

2.1. Field experiments in landfalling tropical cyclones

The study's field data originate from near-surface wind field observations collected during 1999-2016 Atlantic tropical cyclones through the Florida Coastal Monitoring Program (FCMP), a multi-institution consortium that includes the University of Florida, Clemson University, Florida International University, and the Institute for Business & Home Safety. Balderrama et al. (2011, 2012) describe the program in detail.

The dataset includes records from 86 deployments of portable weather stations in 25 named storms. The current study incorporates 13 new field experiments that deployed upgraded 15 m portable weather stations (see Table 1), with suburban terrain being the primary study target. The original 10 m

FCMP weather stations are equipped with anemometers at 5, and 10 m. Two custom arrays of three fixed axis anemometers (RM Young Model Number 27106R) collect wind velocity observations (3D wind speed and direction) at the 5 and 10 m levels. Dynamic characteristics of the anemometer's four-blade polypropylene helicoid propellers (Model Number 08234) include a 2.7 m, 63% recovery distance constant and a damped natural wavelength of 7.4 m. A wind monitor (RM Young Model Number 05103V) installed at the 10 m level serves as a redundant anemometer system to monitor the horizontal component of the wind. The wind monitor 50% recovery vane delay distance is 1.3 m and it is rated for a 100 m/s gust survival. In 2010, two weather stations were upgraded with high-resolution ultrasonic anemometers (WindMaster Pro Model 1561-PK-020) installed at 5, 7.5, 10, 12.5, and 15 m above ground level. The units have a wind speed range of 0-65 m/s with a resolution of 0.01 m/s, and measure instantaneous u , v , and w wind components with a maximum sampling rate of 32 Hz. In this study, data were sampled at or resampled to 10 Hz.

Table 1. FCMP datasets included in this study in addition to those analyzed in Balderrama et al. (2012).

Year	Tropical Cyclone	Station ID	Latitude	Longitude	Town	Anemometry
2016	Matthew	T1	+28.1947	-80.5944	Satellite Beach, FL	3-Axis Propeller
2016	Matthew	T2	+32.7141	-79.9664	Charleston, SC	Ultrasonic
2016	Matthew	T2	+27.1889	-80.2411	Stuart, FL	Ultrasonic
2016	Matthew	T3	+32.7902	-79.9881	Charleston, SC	Ultrasonic
2016	Matthew	T3	+28.1937	-89.6056	Satellite Beach, FL	Ultrasonic
2016	Matthew	T5	+27.1802	-80.2295	Stuart, FL	3-Axis Propeller
2016	Hermine	T2	+29.6735	-83.3746	Steinhatchee, FL	Ultrasonic
2016	Hermine	T3	+29.6731	-83.3798	Steinhatchee, FL	Ultrasonic
2016	Hermine	T5	+29.6728	-83.3703	Steinhatchee, FL	3-Axis Propeller
2014	Arthur	T2	+35.2322	-75.6215	Hatteras, NC	Ultrasonic
2012	Sandy	T3	+39.3208	-74.5953	Linwood, NJ	Ultrasonic
2012	Isaac	T3	+29.6487	-90.6940	Houma, LA	Ultrasonic
2012	Isaac	T2	+29.5385	-89.7751	Bohemia, LA	Ultrasonic

2.2. Data processing

Data were segmented into continuous non-overlapping 15-min time histories. Quality control included comparing the propeller measurements at an elevation of 10 m to the redundant wind monitor measurements at the same elevation to detect anomalies. Data segments with mean wind velocities

below 5 m/s were removed to eliminate any effects from convection. The tower tilt correction described in Foken and Nappo (2008) was performed to align the anemometer coordinate system into the streamlines and towards the mean flow coordinate system. Negligible mean vertical and lateral wind components were verified to satisfy the requirements of an eddy-covariance method of analysis. Linear trend removal methods were performed on all 15-min records to remove first order non-stationarities.

Shear (friction) velocities for each data segment were calculated directly from the three measured orthogonal velocity components following Weber (1999):

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

The logarithmic mean velocity profile was then used to estimate the roughness length z_0 :

$$z_0 = (z - d) \exp \left[\frac{U(z)\kappa}{u_*} \right] \quad (2)$$

where $U(z)$ is the mean wind speed at elevation z , $\kappa = 0.4$ is von Karman's constant., and d is the zero-plane displacement height. Measurements were obtained at 2-5 levels, preventing direct estimation of d .

$$d = \overline{H} - 2.5z_0 \quad (3)$$

Thus the heuristic method of Jackson (1981) was applied:

where $\overline{H}$ is the average roughness element height, [nominally assumed to be 5 m, which is representative of locations surrounded by clusters of single family dwellings](#). Displacement height was assumed to be effectively zero for records with $z_0 < 0.15$ m.

For quality assurance, an independent procedure was performed to calculate z_0 . A bounded nonlinear function minimization was applied to satisfy the logarithmic formulation of the mean velocity profile and the modified [Harris and Deaves \(1980\)](#) variance model described in Vickery and Skerjl (2005). Percent differences between the two procedures were in the range of 2-6% for records corresponding to suburban terrain ($0.15 \text{ m} > z_0 \geq 0.7 \text{ m}$).

Data records were stratified by surface roughness (exposure) categories defined in ASCE 7-10 (2010), i.e. B (suburban), C (open), and D (marine). Table 2 lists the number of 15-min records stratified by surface roughness and the mean wind speed at 10 m. Table 3 lists the corresponding mean roughness length estimates, which were obtained from Eq. (2) for $U(z = 10 \text{ m})$.

Table 2. Total number of 15-min records ($z = 10$ m) stratified into mean wind speed and roughness length based on ASCE 7-10 exposure categories.

Terrain Type	ASCE 7-10 Exposure	Roughness Length Regimes	No. of 15-min data segments			
			$5 \leq U < 15$	$15 \leq U < 25$	$U \geq 25$	Total
Suburban	B	$0.15 \text{ m} > z_0 \geq 0.7 \text{ m}$	507	233	105	845
Open country	C	$0.01 \text{ m} > z_0 \geq 0.15 \text{ m}$	483	350	760	1593
Very smooth	D	$z_0 < 0.01 \text{ m}$	73	129	499	701
Total			1063	712	1364	3139

Table 3. Mean roughness lengths stratified into mean wind speed and roughness length ($z = 10$ m) based on ASCE 7-10 exposure categories.

Terrain Type	ASCE 7-10 Exposure	Roughness Length Regimes	Mean Roughness Length, z_0 (m)		
			$5 \leq U < 15$	$15 \leq U < 25$	$U \geq 25$
Suburban	B	$0.15 \text{ m} > z_0 \geq 0.7 \text{ m}$	0.499	0.536	0.423
Open country	C	$0.01 \text{ m} > z_0 \geq 0.15 \text{ m}$	0.119	0.095	0.064
Very smooth	D	$z_0 < 0.01 \text{ m}$	0.005	0.004	0.004

2.3. Conditional analysis of the Reynolds stress

Conditional (also known as quadrant) analysis of the Reynolds stress is useful to quantify the turbulent mechanisms of organized structures in the inertial sublayer and the roughness sublayer (RS), i.e. the region below the inertial sublayer affected by the coherent motions spawned by buildings, trees, etc. upwind (Lu et al., 1973). It applies conditional statistical averaging to partition the contribution of the mean Reynold stress into four quadrants based on the sign of the (mean-removed) longitudinal (u') and vertical (w') wind velocity components as shown in Table 4. Sweep and ejection events (quadrants two and four) make positive contributions to the Reynolds stress, with the former associated with downward motion and forward velocity greater than the mean. Quadrants one and three correspond to inward and outward interaction events and contribute negatively to the shear stress.

Table 4. Quadrants of events contributing to the total mean Reynold stress.

Quadrant (<i>i</i>)	u'	w'	Event
1	≥ 0	≥ 0	Outward interactions
2	≤ 0	≥ 0	Ejections
3	≤ 0	≤ 0	Inward interactions
4	≥ 0	≤ 0	Sweeps

The contribution of the total Reynolds stress from quadrant i is

$$\langle u'w' \rangle_{i,H} = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T u'(t)w'(t)I_{i,H}[u'(t), w'(t)] dt \quad (4)$$

where T is the averaging time and $I_{i,H}$ is the indicator function. $I_{i,H}$ takes a value of one if $|u'w'| \geq H|\overline{u'w'}|$, otherwise, $I_{i,H} = 0$. Increasing the hyperbolic “hole size” H allows examination of large-scale and sparse structures (i.e., coherent motions) by eliminating small and frequent contributions. The fraction of the shear stress transported is obtained from normalizing Eq. (4) by the mean Reynolds stress $\overline{u'w'}$.

$$S_{i,H} = \frac{\langle u'w' \rangle_{i,H}}{\overline{u'w'}} \quad (5)$$

The difference in stress fraction between quadrants two and four

$$\Delta S_H = S_{4,H} - S_{2,H} \quad (6)$$

expresses the imbalance of sweep and ejection events (> 0 = sweep dominance). Raupach (1981) established a relation between $\Delta S_{H=0}$ and the third moments (skewness) of the fluctuations in the velocity components u' and w' , which can be derived by a cumulant-discard method (Antonia and Atkinson, 1973; Nakagawa and Nezu, 1977). For $H = 0$, the theoretical difference in all stress contributions in the sweep and ejection quadrants ΔS_0 ($\Delta S_0 = S_{4,0} - S_{2,0}$) can be expressed as

$$\Delta S_0 = \frac{1 + \rho}{\rho\sqrt{2\pi}} \left[\frac{2C_1}{(1 + \rho)^2} + \frac{C_2}{1 + \rho} \right] \quad (7)$$

where,

$$C_1 = (1 + \rho) \left[\frac{1}{6} (M_{03} - M_{30}) + \frac{1}{2} (M_{21} - M_{12}) \right] \quad (8)$$

$$C_2 = - \left[\frac{1}{6} (2 - \rho) (M_{03} - M_{30}) + \frac{1}{2} (M_{21} - M_{12}) \right] \quad (9)$$

In Eqs. (8) and (9), $\rho = \overline{u'w'}/\sigma_u\sigma_w$ is the correlation coefficient and M represent the third moments

($M_{03} = \overline{w'w'w'}$, $M_{30} = \overline{u'u'u'}$, $M_{12} = \overline{u'w'w'}$, $M_{21} = \overline{u'u'w'}$).

2.4. Boundary layer wind tunnel measurements

FCMP field observations were compared against flow measurements in the University of Florida's BLWT, which is a low-speed open circuit tunnel with dimensions of 6 m W x 3 m H x 38 m L. Comparison of field and wind tunnel observations was conducted during a validation study of the Terraformer, which is an automated roughness element grid that rapidly reconfigures the height and orientation of 1116 roughness elements in a 62 X 18 grid to achieve desired upwind terrain conditions. The grid extends nominally 18.3 m along the length of the tunnel (see Figure 1). Dimensions of the elements are 5 cm by 10 cm, and they are spaced 30 cm apart in a staggered pattern. Height and orientation can be varied from 0-160 mm and 0-360 degrees, respectively. Two orientations were applied. The narrow and wide edge cases refer to the 5 cm and 10 cm face perpendicular to the flow, respectively.

Figure 1. Plan view of the BLWT at the University of Florida, illustrating the two element orientations considered for this study, namely wide and narrow edge windward.

Spatially averaged semi-logarithmic mean velocity profiles are shown in Figures 2. The profiles were measured over the last row of the roughness elements closest to the test section, at location $x = 29.5$ m (see Figure 1), using an automated gantry system instrumented with four Turbulent Flow Instrumentation Cobra pressure probes that measure u , v , and w velocity components and static pressure within a $\pm 45^\circ$ acceptance cone. Response characteristics include a maximum frequency response of 2 kHz and a 2-100 m/s sensing range. Three vertical traverses were taken across the width of the tunnel—at the centerline and ± 500 mm off the centerline of the tunnel. Aerodynamic parameters z_0 and u_* values (Table 5) were estimated from a non-linear least squares fit of the log law to the mean velocity profile in the inertial-sublayer (ISL) region ($z \sim 150$ -900 mm), following the curve-fitting method in Karimpour et al. (2012). Zero-plane displacement height estimates were based on the geometric arrangement of the roughness array following MacDonald et al. (1998):

$$\frac{d}{h} = 1 + A^{-\lambda}(\lambda - 1) \quad (10)$$

where λ is the plan area index defined as the ratio of the lot area to the plan area of the roughness element, and A is a constant taken as 4.43—the recommended value for a staggered array. The reference mean wind velocity U_{ref} was measured at a height $z_{ref} = 1.48$ m.

Figure 2. Spatially averaged mean velocity profiles of six independent BLWT simulations measured at location $x = 29.5$ m.

Table 5. Equivalent full-scale roughness lengths obtained from suburban terrain BLWT simulation.

BLWT Test No.	Terraformer Configuration		BLWT Aerodynamic Parameters			Equivalent Full-Scale Roughness Length	
	Roughness Element Orientation	Element Height, h (mm)	U_{ref}/u_*	d/h	z_0/h	Geometric Scale	z_{0FS} (m)
1	Wide	20	29.9	0.131	0.021	400	0.171
2	Wide	30	16.4	0.131	0.076	100	0.227
3	Narrow	40	19.7	0.131	0.017	300	0.208
4	Narrow	60	16.5	0.131	0.037	120	0.267
5	Narrow	80	14.2	0.131	0.066	70	0.371
6	Narrow	100	12.5	0.131	0.095	60	0.572

Plots of BLWT longitudinal turbulence spectra at a height $z = 610$ mm are shown in Figure 3 for the six corresponding mean velocity profiles. Measured data were compared with the power spectra model in ESDU 74030 and 74031 (1974), which was first derived by von Kármán (1948) for isotropic turbulence:

$$nS_{uu}(z, n)/\sigma_u^2 = 4f/(1 + 70.8f^2)^{5/6} \quad (11)$$

where $f = nL_u^x/U$. $S_{uu}(z, n)$ is the power spectral density function, where n is the frequency, U is the longitudinal mean velocity, and L_u^x is the longitudinal integral length scale of the turbulence. Measured spectra were calculated following Welch's method in Bendat and Piersol (2000). Time histories were segmented into eight contiguous blocks, and a Hanning tapering window with 50% overlap was applied to suppress side-lobe leakage. These plots are representative of measurements obtained between 320-860 mm, outside of the immediate influence of the individual roughness elements. In all cases in this range, similitude was achieved.

Figure 3. Longitudinal turbulence spectra of six independent BLWT simulations, measured at location $x = 29.5$ m ($z = 610$ mm).

3. Results

3.1. Higher order central moments

Figures 4 and 5 show semi-logarithmic whisker subplots of the mean longitudinal skewness (γ_{3u}) and kurtosis (γ_{4u}) at elevations of 5 m and 10 m for three mean wind speed ranges for data collected in the field. The whiskers bound the 25th and 75th quantiles, and the letters B, C and D inside the whisker box

indicate the exposure category. An increase in skewness with terrain roughness is evident for all wind speed ranges. Skewness values at 5 m are consistently larger than 10 m values for the three exposures. Records with mean wind speeds above 25 m/s in exposure B (suburban) show mean skewness values of 0.49 and 0.37 for elevations of 5 m and 10 m, respectively. Table 6 summarizes the statistics of all 5 m and 10 m 15-min records based on exposure category and mean wind speed. The table shows that for a given terrain exposure, the mean γ_{3u} may be assumed to be invariant to mean wind speed. Further, the non-Gaussianity is specific to the third central moment. No change in kurtosis was observed.

Figure 4. Observed mean (longitudinal) skewness values stratified into mean wind speed and terrain roughness.

Figure 5. Observed mean (longitudinal) kurtosis values stratified into mean wind speed and terrain roughness.

Table 6. Statistics of 15-min records stratified into mean wind speed and roughness length based on ASCE 7-10 exposure categories.

ASCE 7-10 Exposure	U Range (m/s)	U (m/s)		I_u		γ_{3u}		γ_{4u}	
		5-m	10-m	5-m	10-m	5-m	10-m	5-m	10-m
B	$5 \leq U < 15$	8.2	9.9	0.33	0.31	0.50	0.43	3.28	3.10
	$15 \leq U < 25$	17.8	20.8	0.31	0.30	0.55	0.47	3.28	3.05
	$U \geq 25$	28.6	32.8	0.29	0.28	0.53	0.41	3.24	2.97
C	$5 \leq U < 15$	9.3	10.5	0.25	0.23	0.36	0.30	3.06	2.97
	$15 \leq U < 25$	18.6	20.7	0.23	0.22	0.39	0.33	3.06	2.96
	$U \geq 25$	35.6	40.3	0.21	0.20	0.33	0.25	2.99	2.89
D	$5 \leq U < 15$	9.5	10.8	0.18	0.16	0.24	0.17	2.97	3.00
	$15 \leq U < 25$	18.2	20.5	0.19	0.17	0.28	0.24	2.99	2.99
	$U \geq 25$	37.7	42.6	0.17	0.15	0.21	0.17	2.93	2.90

3.2. Reynolds stress fractions

In Figure 6, the average Reynolds stress fractions $|S_{i,H}|$ are shown as a function of H for and exposure categories. Observations at 10 m (top three subplots) display a slight decrease in ejection contributions with increasing roughness. At $H = 0$, ejection contributions in higher winds ($U \geq 25$ m/s) account for ~60,

~70, and ~82% of the total mean stress for exposures B, C, and D, respectively. Sweep events appear to contribute equally for the three exposure categories at $z = 10$ m. The 10 m subplots in Figure 6 also suggest a minor reduction in the contribution of inward/outward interaction events in more built-up terrain. At 5 m, a significant increase in sweep contributions is observed for exposure B (suburban) in high winds ($U \geq 25$ m/s), comprising over 95% of the total mean stress for $H = 0$. Sweep contributions are still present for larger hole sizes. At $H = 20$, mean $|S_{i,H}|$ associated with sweeps account for ~18% ($U \geq 25$ m/s), while ejection events appear to vanish for $H \geq 18$. The two interaction events at 5 m display greater contributions to the Reynolds stress in rougher terrain for $U \geq 25$ m/s (bottom right subplot).

Figure 6. Mean Reynolds stress fractions $|S_{i,H}|$ for mean wind speed values stratified into mean wind speed and terrain roughness for the field observations.

Subplots of spatially averaged Reynolds stress fractions from BLWT simulation are shown in Figure 7. Two elevations (above the tunnel floor) z where normalized by the six roughness length estimates presented in Table 5. Large sweep contributions (greater than 90%) for $H = 0$ can be observed for element heights of 40, 60 and 100 mm, all oriented with the narrow edge perpendicular to the flow. For h

= 60 mm, a height of $z = 5$ m will result in a roughness length of 0.36 m ($z/z_0 = 14$), which would classify as Exposure B in ASCE 7-10. Additionally, sweep contributions are still present up to $H = 20$ for these three element configurations. For $h = 80$ mm, sweep contributions account for 80% of the Reynolds stress at $H = 0$. However, ejections at $H = 0$ are approximately 60%, which results in sweep dominance. Subplots for the two wide edge element orientations (top two subplots) show sweep contributions around 80% for $H = 0$. However, capturing the coherent structures in the roughness sublayer is more challenging as the element height approaches zero (i.e., flush tunnel floor)—i.e., the thickness of the “wake region” is zero for $h = 0$ mm.

Figure 7. Spatially averaged Reynolds stress fractions $|S_{i,H}|$ of six independent BLWT simulations measured at location $x = 29.5$ m.

3.3. Relation of stress fraction difference and skewness

Figure 8 plots the theoretical stress fraction difference ΔS_0 obtained from Eq. (7) against the measured ΔS_0 values—i.e., Eq. (6)—for three wind speed ranges. Observations at both 5 m and 10 m heights show good agreement of measured ΔS_0 with values found from Eq. (7). The bulk of records associated with exposure B (suburban) favor positive values of ΔS_0 , hence suggesting sweep dominance.

Figure 8. Theoretical and measured stress fraction difference ΔS_0 between sweep and ejection quadrants for mean wind speed values stratified into mean wind speed and terrain roughness. Suburban (Exposure B) measurements are denoted by black circular markers.

Figure 9 plots the longitudinal skewness values (γ_{3u}) against ΔS_0 values. The six scatter plots exhibit a positive linear trend between ΔS_0 and γ_{3u} . Proportionality coefficients obtained from linear regression analysis are included in the subplots. Slightly higher linear coefficient values are found at 5 m heights for all three wind speed regimes. This suggests greater sweep dominance at 5 m than over 10 m heights. Linear coefficient values for records with $U \leq 25 \text{ m/s}$ closely match proportionality values of γ_{3u} .

and ΔS_0 established in Raupach (1981). However, the coefficient decreases for $U \geq 25$ m/s, with values of 0.33 and 0.27 for 5 m and 10 m observations, respectively.

Figure 9. Measured stress fraction difference ΔS_0 versus longitudinal skewness for mean wind speed values stratified into mean wind speed and terrain roughness. Suburban (Exposure B) measurements are denoted by black circular markers.

Scatter subplots in Figure 10 show the relation of the vertical skewness (γ_{3w}) and ΔS_0 . An approximate negative linear relation between γ_{3w} and ΔS_0 is observed. Oikawa and Meng (1995) detected similar trends from field observations at heights above the ground near the suburban canopy region. In addition, vertical skewness values in Figure 10 compare well with calculated γ_{3w} values from Raupach et al. (1996), which ranged from -0.5 to -1.0 within a vegetated canopy layer. A robust multilinear regression was performed to the scattered data using iteratively re-weighted least squares with a bi-square weighting function. The linear coefficients are included in the subplots. No prior work was found for comparison of regression analysis coefficient for γ_{3w} . Nevertheless, it can be deduced from Figure 9 that sweep events in suburban regions are predominantly associated with negatively skewed distributions of the vertical wind component in strong winds.

Figure 10. Measured stress fraction difference ΔS_0 versus vertical skewness for mean wind speed ranges: (a) 5 m/s-15 m/s, (b) 15 m/s-25 m/s, and (c) greater than 25 m/s. Suburban (Exposure B) measurements are denoted by black circular markers.

Table 7 summarizes results presented in this section, which reveal the increasing trend of sweep dominance in rougher upwind terrain. Measured ΔS_0 values exceed 20% for the three wind speed ranges in Exposure B at $z = 5$ m. However, Exposures C and D show mean stress fraction differences in the range of 2%-12% for the same measurement height. Furthermore, negative ΔS_0 values—i.e., ejection dominance—are observed for two wind speed ranges collected at 10 m in Exposure D.

Table 7. Mean stress fraction difference ΔS_0 between sweep and ejection stratified into mean wind speed and roughness length based on ASCE 7-10 exposure categories.

ASCE 7-10 Exposure	U range (m/s)	γ_{3u}		Measured ΔS_0		Theoretical ΔS_0	
		5-m	10-m	5-m	10-m	5-m	10-m
B	$5 \leq U < 15$	0.48	0.41	0.202	0.153	0.192	0.146
	$15 \leq U < 25$	0.49	0.41	0.229	0.161	0.222	0.155
	$U \geq 25$	0.49	0.37	0.239	0.132	0.227	0.126
C	$5 \leq U < 15$	0.31	0.28	0.093	0.090	0.094	0.087
	$15 \leq U < 25$	0.36	0.31	0.120	0.091	0.114	0.088
	$U \geq 25$	0.31	0.24	0.090	0.058	0.088	0.058
D	$5 \leq U < 15$	0.24	0.17	0.004	-0.012	0.004	-0.003
	$15 \leq U < 25$	0.26	0.22	0.036	0.024	0.038	0.024
	$U \geq 25$	0.21	0.17	0.021	-0.005	0.026	0.000

4. Discussion

Effects of observed non-Gaussian trends within the roughness sublayer on suburban exposure coefficient values (K_z values in ASCE 7-10) are now examined. Figure 11 includes the proposed non-Gaussian exposure coefficient K_{zNG} profile for suburban exposure based on linearly varying γ_{3u} values with height above ground level—i.e., the skewness profile. The proposed non-Gaussian exposure coefficient is calculated from

$$K_{zNG} = \left(\frac{U_{gNG}(z)}{U_{g,ref}} \right)^2 \quad (12)$$

in which $U_{g,ref}$ is the 3 s gust velocity at 10 m in open terrain ($z_0 = 0.02$ m), $U_{gNG}(z)$ is the gust velocity profiles obtained from

$$U_{gNG}(z) = U(z)[1 + g_{NG}I_u] \quad (13)$$

where $U(z)$ is the mean velocity profile [Eq. (2)]. The shear velocity in Eq. (2) is determined for a given gradient wind speed U_g based on the relation between u_* and U_g described in Irwin (2006). The turbulent intensity I_u is computed from Harris and Deaves (1980) variance model.

Balderrama et al. (2012) demonstrated that the non-Gaussian peak factor model in Kareem and Zhao (1994, henceforth KZ94) is more accurate than the Gaussian model defined in Davenport (1964,

$$g_{NG} = \alpha \left\{ \left(\beta + \frac{\gamma}{\beta} \right) + h_3(\beta^2 + 2\gamma - 1) + \dots \right\} \quad (14)$$

$$h_4 \left[\beta^3 + 3\beta(\gamma - 1) + \frac{3}{\beta} \left(\frac{\pi^2}{12} - \gamma + \frac{\gamma^2}{2} \right) \right]$$

henceforth D64). The non-Gaussian peak factor g_{NG} from KZ94 can be expressed as

where γ is Euler's constant, 0.5772, $\beta = \sqrt{2 \ln(vT)}$, v is the crossing rate, and T is the duration of the record. The parameters α , h_3 , and h_4 are dependent on the third (skewness) and fourth (kurtosis) moments (see KZ94). In the special case where $\gamma_{3u} = 0$ and $\gamma_{4u} = 3$, Eq. (14) takes the form of the Gaussian D64 peak factor model. A constant kurtosis value of $\gamma_{4u} = 3.0$ was selected in Eq. (14) to generate K_{zNG} values. A value of $z_0 = 0.15$ m was chosen for the proposed K_{zNG} profile. This roughness length corresponds to the lower limit value specified in ASCE 7-10 (2010) for suburban terrain.

The (linear) skewness profile shown in Figure 11 (left subplot) was constructed from mean γ_{3u} values of FCMP observations at 5 m, 7.5 m, 10 m, 12.5 m, and 15 m for suburban exposure ($z_0 = 0.15$ m-0.7 m). Full-scale γ_{3u} values in Figure 10 are limited to 15 min records collected from 2012-2016 using ultrasonic (US) anemometry—see Table 1. Only records satisfying $U \geq 10$ m/s were considered. Horizontal whiskers at the three FCMP elevations indicate the 25th and 75th quantiles. Below $z = 4.6$ m, skewness values are kept constant ($\gamma_{3u} = 0.46$).

Figure 11. Proposed non-Gaussian exposure coefficient K_z versus elevation above ground z .

BLWT skewness profiles from the six independent tests summarized in Table 5 are also shown in Figure 11 (left subplot). Most of the BLWT data show skewness values in the range of 0.20-0.5 up to 5 m full-scale elevation. Above 5 m, the BLWT data exhibit a noticeable decreasing trend towards zero skewness. Table 8 summarizes proposed skewness values and non-Gaussian K_{zNG} values for heights up to 24.4 m. The table shows a ~14% increase in suburban exposure coefficient values at $z = 10$ m from K_z values provided in ASCE 7-10 (2010).

Table 8. Proposed exposure coefficient values obtained from non-Gaussian peak factor model

Height above ground level, z		γ_{3u}	Peak factor, $g_{NG}(t = 3s)$	Suburban exposure coefficient, K_z		% Increase
ft	(m)			Proposed (K_{zNG})	ASCE 7-10 Exposure B	
15	4.6	0.46	3.48	0.63	0.57	+9.8
20	6.1	0.43	3.44	0.70	0.62	+12.3
25	7.6	0.39	3.40	0.75	0.66	+13.5
30	9.1	0.35	3.36	0.80	0.70	+14.0
40	12.2	0.27	3.28	0.86	0.76	+13.9
50	15.2	0.20	3.21	0.91	0.81	+13.0
60	18.3	0.12	3.13	0.95	0.85	+11.7
70	21.3	0.04	3.05	0.98	0.89	+10.2
80	24.4	0.00	3.01	1.01	0.93	+9.3

5. Conclusions

Analysis of anemometric observations collected during 1999-2016 Atlantic hurricane seasons, along with BLWT studies display non-Gaussian wind behavior in suburban terrain exposures within the suburban roughness sublayer. Observations in suburban terrain predominantly show positively skewed distributions of the along-wind component, thus increasing the probability of peak gust events. In addition, field data suggests a dependence of longitudinal skewness with height in rougher terrain. Positive skewness values appear to increase with decreasing elevation near the suburban canopy. BLWT studies for suburban terrain also seem to follow similar tendencies. Quadrant analysis reveals the linkage between positive values of the longitudinal skewness and downward transfers of momentum (sweep events). Most of these records are associated to rougher terrain conditions (suburban). However, sweep dominance appears to be less pronounced in higher winds. Positively skewed distributions measured within the roughness sublayer were incorporated into exposure coefficient calculations for suburban terrain through a non-Gaussian peak factor model. A non-trivial increase in suburban exposure coefficient values was found.

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