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Observed tropical cyclone wind flow characteristics

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Abstract. Since 1998, several institutions have deployed mobile instrumented towers to collect research-grade meteorological data from landfalling tropical cyclones. This study examines the wind flow characteristics from seven landfalling tropical cyclones using data collected from eight individual mobile tower deployments which occurred from 1998-2005. Gust factor, turbulence intensity, and integral scale statistics are inspected relative to changing surface roughness, mean wind speed and storm-relative position. Radar data, acquired from the National Weather Service (NWS) Weather Surveillance Radar - 1988 Doppler (WSR-88D) network, are examined to explore potential relationships with respect to radar reflectivity and precipitation structure (convective versus stratiform). The results indicate tropical cyclone wind flow characteristics are strongly influenced by the surrounding surface roughness (i.e., exposure) at each observation site, but some secondary storm dependencies are also documented.

Keywords: tropical cyclones; radar; tower measurements; wind; gust factors; integral scales; turbulence intensity; roughness lengths.

1. Introduction

Understanding the structure and evolution of the tropical cyclone wind field is essential to preparedness, response and recovery, in addition to contributing to a wealth of underlying engineering and scientific applications. While the need to document the near-surface wind field is great, the capability of the national meteorological observing network (e.g. the National Weather Service's Automated Surface Observation Stations) to make such observations in landfalling tropical cyclones is abysmal (Blessings and Masters 2005). Given the great need, but limited capability, various institutions have initiated field programs to deploy meteorological monitoring systems in the path of landfalling tropical cyclones. Historically, these efforts have largely been focused on placing instrumented towers near the coast prior to a storm's arrival. During the devastating 2004 and 2005 Atlantic Hurricane Seasons, these limited, but targeted, field efforts led to the acquisition of the highest measured over-land wind speeds for each landfalling tropical cyclone. These efforts have yielded a database of research-grade wind speed time histories from which inferences about the

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near-surface wind flow characteristics within weak to moderate tropical cyclones can be made.

The complexity of the tropical cyclone boundary layer cannot be understated. While the inherent generation and interaction of multiple scales of motion is daunting, the dependency of the near-surface wind flow on the underlying surface characteristics cannot be ignored (Paulsen and Schroeder 2005, Vickery and Skerlj 2005). Several studies have compared gust factors and/or turbulence intensities observed in tropical cyclone and extratropical winds while ensuring relatively uniform roughness characteristics across their data sets (Krayer and Marshall 1992, Sparks and Huang 2001, Schroeder and Smith 2003, Paulsen and Schroeder 2005, Vickery and Skerlj 2005, Yu, *et al*. 2009). While small differences in the mean gust factor values have been noted, the underlying cause for these differences has not been fully understood. Extreme wind gusts, and their associated gust factors, have been documented in Hurricanes Hugo (Powell, *et al*. 1991), Andrew and Bertha (Vickery and Skerlj 2005). These significant gusts have largely been attributed to convective scale motions (e.g., Powell, *et al*. 1996, Sparks and Huang 2001) or even downbursts (Fujita 1985) transporting higher momentum to the surface. However, based on historical research, the occurrence of such large gusts appears to be rare (Vickery and Skerjl 2005, Sparks and Huang 2001) and their importance likely decreases with increasing wind speed (Bradbury, *et al*. 1994) and in the eyewall region (Sparks and Huang 2001). These results suggest that overall impact on structural damage may be minimal. However, questions remain.

Given the inherent limitations of most wind speed data sets, which typically only provide mean and gust values at set reporting times (e.g., every 10-minutes), only a small amount of research has been completed on evaluating the spatial gust scales present in the tropical cyclone wind field (Schroeder, *et al*. 1998, Schroeder and Smith 2003). Longitudinal power spectral density (PSD) estimates based on the evaluation of a few specific research-grade records (Powell, *et al*. 1996, Schroeder and Smith 2003, Lorsolo, *et al*. 2008, Yu, *et al*. 2008) have contained additional low-frequency energy relative to that expected for neutral surface layer flow (Kaimal, *et al*. 1972). This increase in low-frequency energy has historically been attributed to the "storm" environment such as the passage of rainbands or boundary layer rolls and/or streaks (Powell, *et al*. 1996, Lorsolo, *et al*. 2008).

This study examines tropical cyclone wind flow characteristics determined using research-grade wind speed records. Specifically, gust factors, turbulence intensities and longitudinal integral scales are evaluated using data collected from seven landfalling tropical cyclones which occurred from 1998-2005. Given the well-known dependence of the near-surface wind structure on nearby and distant terrain features (e.g., Deaves 1981), the resulting wind flow characteristics are stratified to account for varying exposures. Once this primary stratification is complete, a search for secondary influences is conducted. Specifically, changes in wind flow characteristics relative to varying mean wind speeds and storm-relative position of the deployment sites are explored. Given the historical discussion concerning the potential for convectively induced extreme gusts, available radar reflectivity data were acquired and evaluated to assess the precipitation structure. The radar reflectivity data was then coupled with the determined wind flow characteristics to evaluate if relationships could be established between precipitation intensity and structure and the near-surface wind flow.

2. Instrumentation and data

2.1. Wind speed and direction time histories

Texas Tech University (TTU) has deployed various instruments into the paths of landfalling tropical cyclones since 1998. Two ruggedized mobile instrumented tower systems, termed WEMITE

I/II (Schroeder and Smith 2003), have been deployed since 1998 and 1999, respectively. WEMITE I/II acquire common atmospheric state variables with relatively high (5-10 Hz) sampling rates including wind speed and direction measurements acquired from multiple levels within the lowest 10/15 m of the atmosphere. Additional non-ruggedized towers have also been deployed by TTU since 2000. These systems also observe the common atmospheric state variables, including wind information from the 10 m level, and employ sampling rates ranging from 1-10 Hz (depending on the data acquisition system). The instrument used to collect wind speed and direction data in this study was an R. M. Young Wind Monitor Model 05106. The instrument is a propeller vane–type anemometer that yields measurements of both wind speed and direction. The propeller has a distance constant of 2.7 m for 63% recovery. Additional platform information, including instrument response characteristics, has been previously presented by Schroeder and Smith (2003).

The tropical cyclone wind speed and direction time histories leveraged for this study were obtained from field campaigns conducted during the 1998-2005 Atlantic Hurricane Seasons. Only wind data acquired from the 10 m observation level were included in this study. Data from eight individual deployments that occurred within seven landfalling tropical cyclones, as documented in Table 1, are used to generate the resulting statistics. Each record includes data acquired during the passage of a tropical cyclone's eyewall over the deployment site. Several of the records also indicate the relative calm associated with eye, such as the Hurricane Isabel record shown in Fig. 1. Hurricane Isabel (2003) traversed from southeast to northwest across coastal North Carolina allowing the WEMITE tower to measure both the northwest and southeast eyewalls. A sharp change in wind direction occurred as the center of circulation passes just east of the deployment site. The instrument deadband is apparent in the wind direction time history illustrated in Fig. 1, with some resultant scatter in the raw (10 Hz) wind direction time history following the wind shift.

2.1.1. Quality control and data validation

Each year, prior to the deployment of the observational platforms in a tropical cyclone

Table 1 Tropical cyclone and deployment information for wind records used to generate bulk wind flow statistics. Comparisons to the National Hurricane Center best track intensities and the Hurricane Research Division H*Wind analyses are provided.

Tropical cyclone (Year)	Deployment Location	Observed Peak One-Minute Wind Speed (m/s)*	Standardized Peak One-Minute Wind Speed (m/s)**	HRD H*Wind Predicted Maximum at Site (m/s)	NHC Best Track Intensity (m/s)
Bonnie (1998)	Wilmington, NC	27	29	35	49
Floyd (1999)	Southport, NC	25	33	38	46
Isabel (2003)	Atlantic, NC	24	34	28	46
Frances (2004)	Ft. Pierce, FL	34	36	36	49
Frances (2004)	Vero Beach, FL	30	33	34	49
Ivan (2004)	Gulf Shore, AL	36	43	42	54
Katrina (2005)	Stennis, MS	30	40	43	54
Rita (2005)	Port Arthur, TX	42	42	28	51

*Winds are not standardized to represent a particular exposure.
** Winds are standardized to represent open exposure (Z_o = 0.03 m).

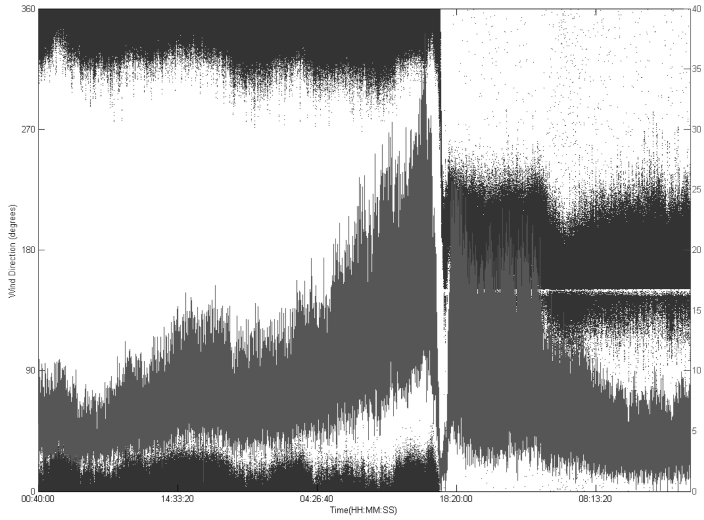

Fig. 1 Research-grade wind speed and direction time histories recorded at Atlantic, North Carolina during the passage of Isabel (2003)

environment, the associated instrumentation and data acquisition (DAQ) systems were calibrated and independently verified. Each instrument was calibrated individually, and known voltages were input into the DAQ system and verified. A final validation of the whole observational platform (instrumentation and DAQ systems) was made by deploying the systems adjacent to other independent observation platforms. Data were collected by both systems for an extended period of time and then quantitatively and qualitatively compared to ensure system functionally.

Each of the acquired tropical cyclone wind speed and direction data sets were also qualitatively and quantitatively reviewed. In some cases, data were acquired by another research group (such as the Florida Coastal Monitoring Program) at the same or nearby location and was available for comparison. In these cases, the data collected by each group was standardized to a common exposure and compared (e.g., Hurricane Katrina). The datasets included in this study represent complete, unaltered, validated time histories.

TTU has historically aimed to deploy the majority of its observational assets in open exposure (often at airports). This effort was made to build a database with relatively consistent terrain conditions from which to study storm-scale interaction with the near-surface wind flow. While this was the intention, some variation in exposure is unavoidable, as even airports are non-uniform. Differences in upstream exposure can result in substantial discrepancies between observed wind speeds from two nearby sites (e.g., Powell, *et al*. 1996). Even two records collected from different locations at the same airport can vary significantly due to changes in exposure. Exposure differences are also partly responsible for the dramatic differences between the observed peak one-minute wind speeds by land-based research towers and the estimated maximum sustained wind speeds reported by the National Hurricane Center (NHC) at landfall (Table 1). The one-minute wind estimates reported by NHC are practically assumed to have occurred over water (Powell and Reinhold 2007) and represent the absolute maximum one-minute mean wind speed expected within the entire tropical cyclone circulation. In most cases, even though the eyewall was sampled by a research tower, measured wind speeds rarely exceeded hurricane force as defined by the peak one-minute average wind speed at 10 m. Even with a decade of field efforts, the database is still short of providing information about mean winds of major hurricane strength, with the maximum one-minute wind speed measured by TTU's fleet of research towers being 42 m/s measured during Hurricane Rita's passage (2005).

A more reasonable comparison to the collected data is made through examination of H*Wind operational and post-storm analyses (Powell, *et al*. 1998), as developed by the National Oceanic and Atmospheric Administration's Hurricane Research Division (HRD). These analyses composite available data sources, provide quality control, and standardize the diverse data to a common framework for height (10 m), exposure (marine or open) and averaging time (one-minute mean). Hence, direct comparisons to H*Wind over-land analyses are possible following standardization of the acquired wind speeds to an equivalent open exposure. In this case, the one-minute peak wind speed from each storm was determined using a moving average, while the associated roughness length was estimated based on the measured turbulence intensity (Beljaars 1987) using a 10-minute window centered on the one-minute peak value. The comparisons of the peak observed and H*Wind predicted wind speeds, as shown in Table 1, reveal good agreement in most cases, especially during the prolific 2004 and 2005 Atlantic Hurricane Seasons, with the exception of Hurricane Rita. Excluding the Hurricane Rita comparison, the average H*Wind bias was an over prediction of the peak wind speeds by 1.1 m/s at each deployment site.

2.2. WSR-88D radar data

Wind measurements taken with the TTU portable towers were coupled with reflectivity data acquired with the National Weather Service (NWS) WSR-88D network. The NWS employs S-band (10 cm wavelength) Doppler radars (Klazura and Imy 1993) to provide operational weather radar coverage over the majority of the United States. The employed scanning strategies and the resultant spatial resolution of these operational radars are not conducive to studying detailed motions within the boundary layer. However, they are resistant to attenuation, making them beneficial for documenting large-scale precipitation patterns within the tropical cyclone's circulation. For this study, WSR-88D radar data were obtained for each event from nearest operational radar to each tower location. The radar's mode of operation yields a complete volume of information at a temporal revisit times of approximately five minutes.

3. Methodology

The radar scanning strategy allows the construction of composite reflectivity time histories which are evaluated over each deployment site. Multiple tilts of the radar reflectivity can also be combined into pseudo range height indicators (i.e., vertical cross-sections) allowing one to examine the structure of precipitation and qualitatively identify the presence of convective and stratiform precipitation over a given location.

Given the temporal resolution of the radar data, the wind flow statistics reported in this study were computed using five-minute fully segmented data windows using the same techniques followed in Schroeder and Smith (2003). In summary, gust factors were defined as the ratio between the maximum two-second wind gust and the average five-minute wind speed. The maximum two-second wind gust was found by applying a moving average through each five-minute data segment. The longitudinal turbulence intensity was defined as the ratio of the standard deviation of the longitudinal velocity component to the mean longitudinal wind speed. Longitudinal integral scales were determined by calculating the autocorrelation function (ACF) for each five-minute data segment of instantaneous longitudinal wind speed, and then fitting an exponential curve to the data to the point where the derivative of the ACF is zero (i.e., the correlation starts to increase with longer lag duration). Once the exponential curve is fit, it is integrated from zero to infinity to obtain the time integral scale. The time integral scale is then multiplied by the mean longitudinal wind speed over the same five-minute data segment to obtain the longitudinal integral scale. More details concerning the incorporated methodologies are available in Schroeder and Smith (2003).

While the complete wind speed time histories are inherently non-stationary due to the storm passage, the five-minute data segments used to evaluate the wind flow characteristics are assumed to be stationary. This assumption is not valid for cases where the wind speed rapidly increases or decreases over a short time period. These rapid changes are especially evident in a few records when the inner edge of the eyewall passes over the deployment site and higher wind speeds quickly transition to the relative calm of the eye. Employing the nonparametric run test with a 95% significance level, less than 10% of the five-minute data segments were identified as non-stationary. Other complications, including transitional flow regimes due to internal boundary layer development, are inherent to the dataset and subsequent analysis.

4. Characterstics of tropical cyclone wind flow

4.1. The influence of varying surface roughness/exposure

The roughness length (Z_o) can be determined using a variety of methods (Beljaars 1987) and has been estimated in this study using two techniques. The first method, termed "TI roughness" in this paper, quantitatively estimates the roughness length based on the measured turbulence intensity using the assumption of a logarithmic vertical profile and that the ratio of the standard deviation of the wind record to the friction velocity is 2.5. This technique results in a significant restriction on the data since the determined roughness length is dependent on the turbulence intensity, which is inherently linked to the gust factor through the wind speed distribution. The second method, termed "qualitative roughness" in this paper, is based on the subjective assessment of the immediate exposure surrounding each site using available aerial photography. For this method, eight 45° sectors were overlaid onto aerial photographs of the deployment sites. Roughness lengths were then qualitatively estimated for each sector by various faculty and students based on the surrounding obstacles (Weiringa 1992) and then averaged together to arrive at a final assigned roughness length value. This qualitative approach can result in errors when a significant change in roughness occurs within a 45° wind direction sector. In the few cases where this issue occurred, additional work was performed to further segregate the data into roughness regimes classified by the true upstream conditions instead of using one uniform value across the entire 45° sector. While this method provides an independent assessment of the roughness lengths without use of the collected data, it is also well recognized that the qualitative assessment of roughness is a difficult endeavor and can contain large errors (Powell, *et al*. 1996).

Without accounting for the effects of roughness characteristics, further analysis would be futile. Previous research (e.g., Vickery and Skerlj 2005, Paulsen and Schroeder 2005) has suggested that the prominent effect of mechanical mixing on the character of the near-surface wind field is readily apparent in tropical cyclones. This sensitivity of the wind flow characteristics to the surrounding exposure underscores the importance of accounting for even small changes in upstream roughness. To mitigate inherent differences in the resulting statistics due to changing exposures, this study stratifies the analysis results into four specified roughness regimes as documented in Table 2.

The two methodologies employed to assign roughness length values result in differences in the roughness regime assignment for many five-minute data segments. For a given mean wind direction and deployment site, the qualitative roughness will not change as it is only based on the subjective interpretation of the upstream exposure in each direction; however, the TI roughness estimate will vary even if the wind direction remains constant as it is based on the measured turbulence intensity within each five-minute data segment. The qualitative roughness assessment methodology did not yield any roughness lengths characteristic of a smooth exposure ($0.005\ \text{m} \le Z_o \le 0.0199\ \text{m}$), while the TI roughness estimate yielded 222 data segments which met this criteria. The smallest roughness length determined using the qualitative assessment methodology was 0.02 m. The resulting statistics suggested a general rough bias in the qualitative assessment relative to the TI roughness estimate.

Increasing upstream roughness leads to a reduction in mean wind speed due to increased friction, and a relative increase in turbulent fluctuations resulting in higher gust factors as illustrated in Fig. 2. The

Table 2 The four different roughness regimes used in this study and their associated range of roughness length (Z_o) values.

Roughness Regime	Z_o (m)
Smooth	$0.005 \le Z_o \le 0.0199$
Open	$0.02 \le Z_o \le 0.0499$
Roughly Open	$0.05 \le Z_o \le 0.0899$
Rough	$0.09 \le Z_o \le 0.1899$

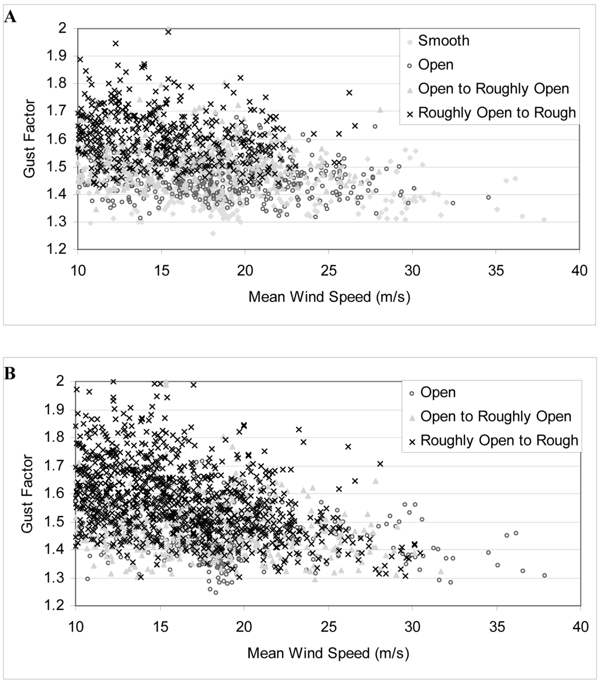

Fig. 2 Scatter plot of gust factor (two-second/five-minute.) versus mean wind following segregation into four different roughness regimes. Roughness regimes were assigned employing the TI assigned roughness (A) and the qualitative assigned roughness (B)

layered appearance in Fig. 2 results from the overall tropical cyclone gust factor dataset being stratified into the four identified roughness regimes as determined using the two applied techniques. The highest mean wind speeds occurred during periods classified as smooth and open. This result is partially due to the reduced frictional effects within those regimes, but is also related to platform location within each storm. For instance, the highest winds in the database were recorded during Hurricane Rita when the deployment location was in a region surrounded by relatively smooth and open exposures.

Turbulence intensities are expected to increase with increasing surface roughness, while integral scales are expected to decrease. These trends are easily verified through examination of Table 3. The results underscore the importance of accounting for exposure. The mean gust factor, turbulence intensity and longitudinal integral scale vary by 16%, 57%, and 39% respectively across the considered roughness regimes. In order to facilitate further analysis or make reasonable comparisons to prior research, the prominent effects of roughness must be considered.

Table 3 Wind flow statistics stratified into the various roughness regimes

Gust Factors - Tl Roughness				
	Smooth	Open	Roughly Open	Rough
Mean	1.40	1.46	1.53	1.62
Maximum	1.56	1.70	2.00	1.99
Minimum	1.26	1.31	1.33	1.41
Standard Deviation	0.06	0.07	0.08	0.10
Sample Size	222	505	469	553
Gust Factors - Qualitative Roughness				
	Smooth	Open	Roughly Open	Rough
Mean	NA	1.44	1.50	1.62
Maximum	NA	1.71	2.00	2.92
Minimum	NA	1.25	1.26	1.30
Standard Deviation	NA	0.08	0.10	0.17
Sample Size	0	312	535	1239
Longitudinal Turbulence Intensity - Tl Roughness				
	Smooth	Open	Roughly Open	Rough
Mean	0.152	0.178	0.204	0.238
Maximum	0.251	0.204	0.265	0.574
Minimum	0.133	0.158	0.185	0.210
Standard Deviation	0.010	0.009	0.009	0.020
Sample Size	222	505	469	553
Longitudinal Turbulence Intensity - Qualitative Roughness				
	Smooth	Open	Roughly Open	Rough
Mean	NA	0.168	0.189	0.238
Maximum	NA	0.265	0.574	0.566
Minimum	NA	0.115	0.117	0.140
Standard Deviation	NA	0.024	0.031	0.049
Sample Size	0	312	535	1239

Table 3 Continued

Longitudinal Integral Scale (m) - Tl Roughness				
	Smooth	Open	Roughly Open	Rough
Mean	92	93	94	79
Maximum	228	308	340	342
Minimum	18	15	17	8
Standard Deviation	43	43	54	50
Sample Size	222	505	469	553
Longitudinal Integral Scale (m) - Qualitative Roughness				
	Smooth	Open	Roughly Open	Rough
Mean	NA	117	103	72
Maximum	NA	308	342	334
Minimum	NA	19	26	8
Standard Deviation	NA	54	49	38
Sample Size	0	312	535	1239

4.2. Mean wind speed

An increase from moderate to high wind speeds is thought to have little effect on the wind flow characteristics given all other conditions remain constant (e.g., exposure). While gust factors, turbulence intensities, and integral scales are thought to be relatively constant as the wind speed increases, Ashcroft (1994) did find a slight reduction in median gust factor values at higher wind speeds through examination of extratropical data recorded at 14 sites in the United Kingdom. Vickery and Skerjl (2005) also found a slight decrease in the mean over-land gust factor with increasing mean wind speed using data collected from 12 tropical cyclones. A previous study completed using wind speed data collected by TTU from weak tropical cyclones suggested there is little dependence of gust factors on the mean wind speed (Paulsen and Schroeder 2005).

The current study includes a significant amount of additional data from higher mean wind speed regimes collected from recent more significant tropical cyclones (e.g., Ivan – 2004, Katrina and Rita – 2005). The results indicate there is a reduction in the two-second to five-minute gust factors as mean wind speeds increase as shown in Fig. 2 and documented in Tables 4A-D. Following segregation into mean wind speed regimes (5 m/s wind speed ranges), Fig. 3A indicates the mean gust factors tend to decrease approximately 5-6% as five-minute mean wind speeds increase from 10 m/s to 30+ m/s, with a slightly larger decrease found for rough and roughly open regimes relative to the smooth and open regimes. A similar examination can be conducted for the longitudinal turbulence intensities and integral scales. In summary, longitudinal turbulence intensities are also shown to decrease with increasing mean wind speed, while integral scales trended larger. It should be noted that very few records exist with five-minute mean wind speeds greater than 30 m/s as revealed in Tables 4A-D. Peak gust factor values found within each wind speed regime also tended to decrease with increasing wind speed. The highest peak gust factor values typically occurred when mean wind speeds were below 20 m/s.

Table 4 Wind flow statistics for the smooth (A), open (B), roughly open (C) and rough (D) exposures stratified by mean five-minute wind speed (m/s) regimes

A						
Gust Factors - Tl Roughness ($0.005m \le Z_o \le 0.0199m$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	1.41	1.39	1.41	1.40	1.41	1.37
Maximum	1.55	1.54	1.55	1.56	1.56	1.46
Minimum	1.29	1.26	1.32	1.31	1.32	1.31
Standard Deviation	0.06	0.05	0.07	0.07	0.07	0.07
Sample Size	31	97	32	34	11	5
Longitudinal Turbulence Intensity - Tl Roughness ($0.005m \le Z_o \le 0.0199m$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	0.152	0.150	0.157	0.152	0.148	0.147
Maximum	0.168	0.179	0.251	0.164	0.161	0.159
Minimum	0.139	0.133	0.142	0.137	0.139	0.133
Standard Deviation	0.008	0.008	0.018	0.008	0.007	0.010
Sample Size	31	97	32	34	11	5
Longitudinal Integral Scale (m) - Tl Roughness ($0.005m \le Z_o \le 0.0199m$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	64	86	86	123	155	186
Maximum	125	171	174	225	228	224
Minimum	39	39	19	57	93	125
Standard Deviation	18	33	35	40	41	39
Sample Size	31	97	32	34	11	5
B						
Gust Factors - Tl Roughness ($0.02m \le Z_o \le 0.0499m$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	1.47	1.47	1.46	1.44	1.39	NA
Maximum	1.70	1.69	1.65	1.65	1.42	NA
Minimum	1.31	1.35	1.32	1.33	1.37	NA
Standard Deviation	0.07	0.07	0.07	0.06	0.03	NA
Sample Size	95	201	122	39	3	0
Gust Factors - Qualitative Roughness ($0.02m \le Z_o \le 0.0499m$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	1.46	1.43	1.47	1.45	1.39	1.37
Maximum	1.62	1.71	1.65	1.56	1.56	1.46
Minimum	1.29	1.25	1.32	1.35	1.28	1.31
Standard Deviation	0.07	0.09	0.08	0.06	0.08	0.07
Sample Size	46	159	53	26	12	5

Table 4 Continued-1

Longitudinal Turbulence Intensity - Tl Roughness ($0.02m \le Z_o \le 0.0499m$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	0.179	0.177	0.178	0.175	0.166	NA
Maximum	0.202	0.193	0.204	0.190	0.167	NA
Minimum	0.158	0.162	0.162	0.162	0.164	NA
Standard Deviation	0.009	0.008	0.009	0.008	0.002	NA
Sample Size	95	201	122	39	3	0
Longitudinal Turbulence Intensity - Qualitative Roughness ($0.02m \le Z_o \le 0.0499m$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	0.180	0.165	0.176	0.165	0.145	0.147
Maximum	0.229	0.265	0.251	0.197	0.167	0.159
Minimum	0.130	0.120	0.124	0.144	0.115	0.133
Standard Deviation	0.022	0.026	0.020	0.014	0.017	0.010
Sample Size	46	159	53	26	12	5
Longitudinal Integral Scale (m) - Tl Roughness ($0.02m \le Z_o \le 0.0499m$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	78	94	109	126	160	NA
Maximum	164	308	243	289	201	NA
Minimum	23	33	24	61	99	NA
Standard Deviation	32	38	42	53	54	NA
Sample Size	95	201	122	39	3	0
Longitudinal Integral Scale (m) - Qualitative Roughness ($0.02m \le Z_o \le 0.0499m$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	98	111	129	156	156	186
Maximum	191	308	246	288	228	224
Minimum	27	37	19	64	69	125
Standard Deviation	38	52	48	63	47	39
Sample Size	46	159	53	26	12	5
C						
Gust Factors - Tl Roughness ($0.05m \le Z_o \le 0.0899m$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	1.53	1.54	1.50	1.48	NA	NA
Maximum	1.74	2.00	1.62	1.70	NA	NA
Minimum	1.34	1.38	1.36	1.43	NA	NA
Standard Deviation	0.08	0.09	0.06	0.07	NA	NA
Sample Size	138	160	79	12	0	0

Table 4 Continued-2

Gust Factors - Qualitative Roughness ($0.05m \le Z_o \le 0.0899m$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	1.51	1.50	1.48	1.42	1.36	NA
Maximum	1.74	2.00	1.71	1.65	1.39	NA
Minimum	1.30	1.31	1.30	1.31	1.32	NA
Standard Deviation	0.10	0.10	0.09	0.07	0.05	NA
Sample Size	143	193	95	32	2	0
Longitudinal Turbulence Intensity - Tl Roughness ($0.05m \le Z_o \le 0.0899m$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	0.205	0.203	0.202	0.197	NA	NA
Maximum	0.223	0.265	0.220	0.205	NA	NA
Minimum	0.188	0.188	0.185	0.188	NA	NA
Standard Deviation	0.009	0.009	0.008	0.005	NA	NA
Sample Size	138	160	79	12	0	0
Longitudinal Turbulence Intensity - Qualitative Roughness ($0.05m \le Z_o \le 0.0899m$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	0.192	0.189	0.184	0.164	0.147	NA
Maximum	0.247	0.574	0.243	0.203	0.155	NA
Minimum	0.121	0.124	0.117	0.123	0.139	NA
Standard Deviation	0.028	0.036	0.024	0.021	0.011	NA
Sample Size	143	193	95	32	2	0
Longitudinal Integral Scale (m) - Tl Roughness ($0.05m \le Z_o \le 0.0899m$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	80	108	120	152	NA	NA
Maximum	340	286	334	288	NA	NA
Minimum	30	32	30	73	NA	NA
Standard Deviation	46	50	58	79	NA	NA
Sample Size	138	160	79	12	0	0
Longitudinal Integral Scale (m) - Qualitative Roughness ($0.05m \le Z_o \le 0.0899m$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	95	109	112	126	158	NA
Maximum	340	342	243	289	161	NA
Minimum	39	39	45	61	155	NA
Standard Deviation	45	53	43	47	4	NA
Sample Size	143	193	95	32	2	0

Table 4 Continued-3

D						
Gust Factors - Tl Roughness ($0.09m \le Z_o \le 0.1899m$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	1.63	1.60	1.57	1.61	NA	NA
Maximum	1.94	1.99	1.75	1.77	NA	NA
Minimum	1.43	1.44	1.44	1.51	NA	NA
Standard Deviation	0.10	0.09	0.08	0.10	NA	NA
Sample Size	213	142	53	5	0	0
Gust Factors - Qualitative Roughness ($0.09m \le Z_o \le 0.1899m$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	1.64	1.57	1.51	1.44	1.41	NA
Maximum	2.92	2.24	1.84	1.77	1.42	NA
Minimum	1.30	1.30	1.32	1.31	1.39	NA
Standard Deviation	0.16	0.13	0.10	0.11	0.02	NA
Sample Size	421	320	152	34	3	0
Longitudinal Turbulence Intensity - Tl Roughness ($0.09m \le Z_o \le 0.1899m$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	0.238	0.238	0.232	0.237	NA	NA
Maximum	0.301	0.574	0.259	0.248	NA	NA
Minimum	0.210	0.213	0.216	0.219	NA	NA
Standard Deviation	0.014	0.032	0.009	0.012	NA	NA
Sample Size	213	142	53	5	0	0
Longitudinal Turbulence Intensity - Qualitative Roughness ($0.09m \le Z_o \le 0.1899m$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	0.248	0.226	0.211	0.184	0.150	NA
Maximum	0.566	0.385	0.337	0.248	0.164	NA
Minimum	0.142	0.141	0.152	0.141	0.140	NA
Standard Deviation	0.047	0.043	0.035	0.028	0.013	NA
Sample Size	421	320	152	34	3	0
Longitudinal Integral Scale (m) - Tl Roughness ($0.09m \le Z_o \le 0.1899m$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	77	108	75	96	NA	NA
Maximum	241	342	171	122	NA	NA
Minimum	21	25	30	44	NA	NA
Standard Deviation	36	72	39	31	NA	NA
Sample Size	213	142	53	5	0	0

Table 4 Continued-4

Longitudinal Integral Scale (m) - Qualitative Roughness ($0.09\text{m} \le Z_o \le 0.1899\text{m}$)						
	$10 \le WS \le 15$	$15 \le WS \le 20$	$20 \le WS \le 25$	$25 \le WS \le 30$	$30 \le WS \le 35$	$WS \ge 35$
Mean	69	83	87	102	96	NA
Maximum	249	328	334	191	99	NA
Minimum	21	25	24	44	93	NA
Standard Deviation	32	44	44	33	3	NA
Sample Size	421	320	152	34	3	0

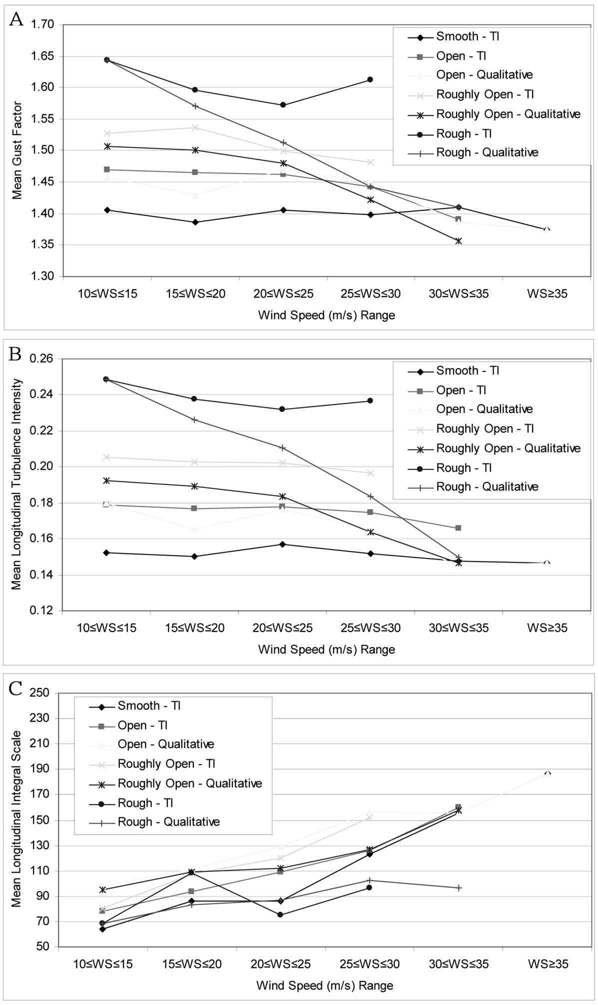

Fig. 3 A plot of mean gust factors (A), longitudinal turbulence intensities (B) and longitudinal integral scales (C) for various ranges of five-minute mean wind speeds

4.3. Storm-relative radial position

Given the previously identified relationships with wind speed, and the fact that the highest mean wind speeds are typically found in the eyewall region of a hurricane, it was hypothesized that the wind flow characteristics may vary by radial distance from the storm center. The vertical structure of the boundary layer is also expected to change with radial distance from the storm center (e.g., Rosenthal 1962), with its depth reaching a minimum in the eyewall and increasing radially outward. Hence, there are several factors which may influence the storm-relative wind flow characteristics.

To investigate this hypothesis, storm positions were extracted from available reconnaissance data. The storm positions were then linearly interpolated between each center fix to provide a storm location at each five-minute time interval. A radial distance between each deployment site and storm location could then be calculated and associated with each parameter. An attempt was made to accommodate cyclone structural changes by normalizing the calculated radial distance with the radius of maximum winds (also based on available reconnaissance data). The resulting plots for open exposure based on TI (Fig. 4A-C) and qualitative (Fig. 5A-C) roughness methodologies indicate modest decreases in gust factor and turbulence intensities with decreasing normalized radius, while longitudinal integral scales increase slightly with decreasing normalized radius. These results are expected given the previous identified trends with mean wind speed. While modest trends are presented in each plot, significant scatter is apparent. Some of this scatter is likely due to differences in storm structure and intensity. For instance, the peak five-minute mean wind speeds measured at the radius of maximum winds in Hurricane Rita was significantly different than those measured in Floyd.

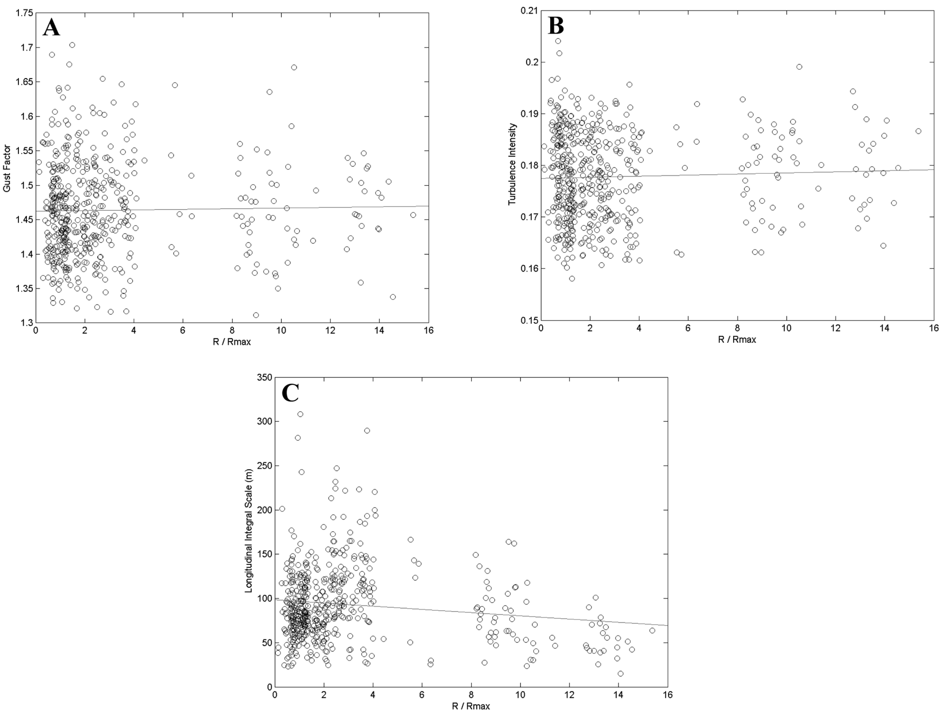

Fig. 4 Scatterplot of two-second to five-minute gust factor (A), longitudinal turbulence intensity (B) and longitudinal integral scale (C) versus normalized radial position. All data were classified as open exposure based on TI based roughness estimates

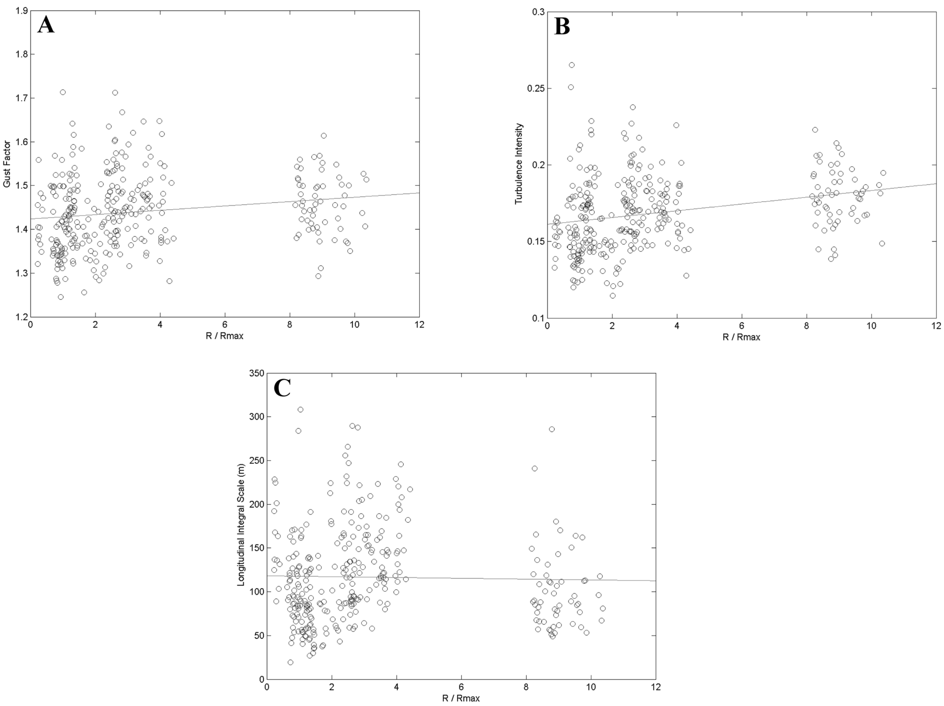

Fig. 5 Scatterplot of two-second to five-minute gust factor (A), longitudinal turbulence intensity (B) and longitudinal integral scale (C) versus normalized radial position. All data were classified as open exposure based on qualitatively determined roughness estimates

Although of interest, azimuthal storm-relative relationships were not explored, due to limitations in the employed database. As discussed previously, the storm center passed over or very close to each deployment site. This limitation results in very little azimuthal distribution of the data with the vast majority aligned along and just right the storm motion vector.

4.4. Radar patterns and precipitation structure

Whether or not slight differences exist between tropical and extra-tropical wind flow characteristics continues to be a topic of debate in the literature. Historical research on the subject (e.g., Sparks and Huang 2001, Schroeder and Smith 2003, Bradbury, *et al*. 1994, Paulsen and Schroeder 2005, Vickery and Skerlj 2005) has almost always mentioned the potential influence of convective gusts on the near-surface wind flow characteristics. Deep convection in a tropical cyclone is typically found in the outer rain-bands and eyewall regions, with the precipitation in the intermediate areas typically being stratiform in structure (Jorgensen 1984). Hence, one can hypothesize that the probability of observing a convective gust is likely higher in the eyewall and outer convective regions of the storm. However, convective gusts in the outer regions are likely of less concern since the mean wind speeds are far below design wind speeds. In the eyewall, where the mean wind speeds are already significant, these convective gusts may contribute to localized damage gradients.

Beyond the potential for convective gusts, the individual time histories qualitatively reveal some interesting trends in wind flow characteristics. Examination of the time histories presented in Fig. 6A-C

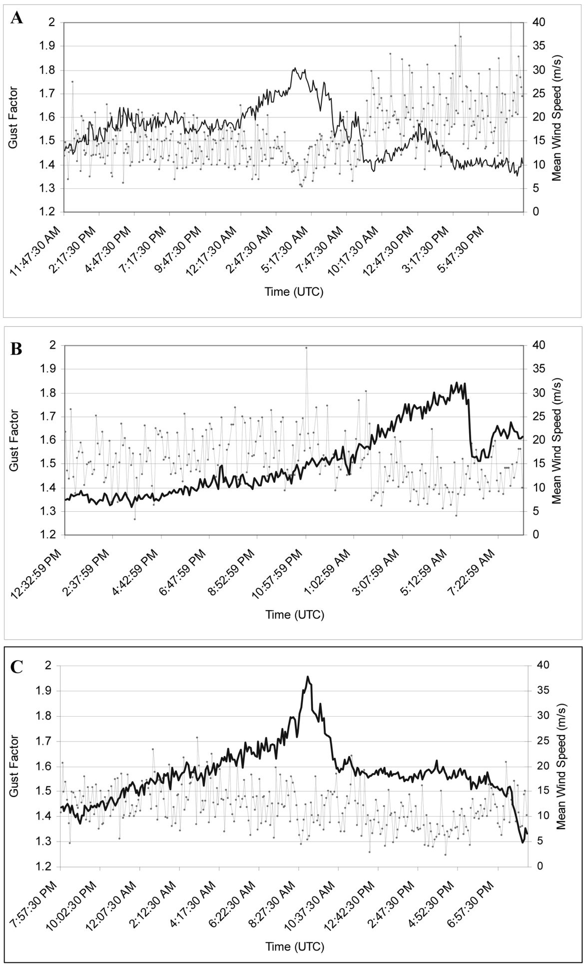

Fig. 6 Five-minute mean wind speed and two-second to five-minute gust factor time histories for Hurricanes Frances (A), Ivan (B) and Rita (C)

indicates a reduction in gust factor value through the eyewall region of three tropical cyclones. These reductions are not always associated with decreasing surface roughness as verified through review of the qualitatively derived roughness lengths, but are evident in many of the storms intercepted by TTU over the past decade. Longitudinal turbulence intensities, as shown in Fig. 7A-C, also tend to decrease locally through the eyewall region of many storms. Longitudinal integral scales present a more complex pattern as illustrated in Fig. 8A-C, but there are numerous cases where integral scale values seem to change mean value (e.g., Fig. 8B – just after 1:00 AM in the Hurricane Ivan time history), without the influence of changing upstream roughness. These repeated trends are, at a minimum, intriguing and form the basis for further examination.

4.4.1. Composite reflectivity

This study attempts to merge the tower and radar reflectivity data to explore more subtle

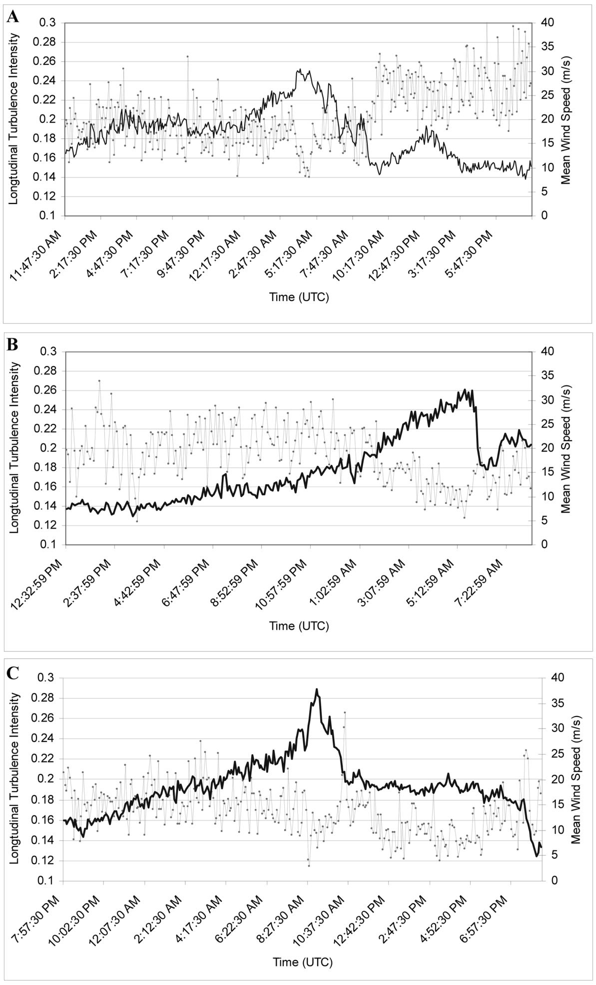

Fig. 7 Five-minute mean wind speed and longitudinal turbulence intensity time histories for Hurricanes Frances (A), Ivan (B) and Rita (C)

relationships between the wind flow characteristics and tropical cyclone structure. Radar reflectivity information was extracted from the WSR-88D archive for each storm. Time histories of composite radar reflectivity (the maximum reflectivity found within the column) were developed. The time histories are comprised of individual composite reflectivity values extracted from the radar field at locations that represent the deployment sites.

Stronger ‘convective’ gusts are sometimes assumed to be associated with localized cellular convection with higher reflectivity values. To investigate this hypothesis, direct comparisons of wind flow statistics were made to composite reflectivity values as summarized in Tables 5A-D and shown in Fig. 9A-C. It should also be noted that regardless of the roughness regime considered, the sample sizes for the highest composite reflectivity (REF) categories (REF $\geq$ 47.5 dBZ and 42.5 dBZ $\leq$ REF $\geq$ 47.5 dBZ) are relatively small for most roughness regimes and the variability of the resulting wind flow statistics significant. Focusing on the general trends which can be identified, gust factors and turbulence intensities appear to increase slightly with increasing composite

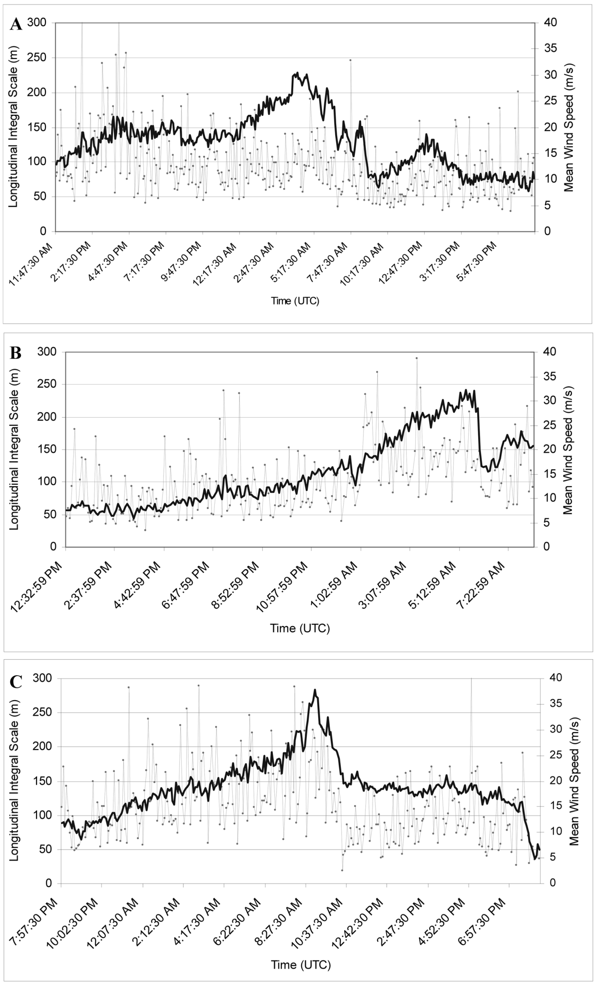

Fig. 8 Five-minute mean wind speed and longitudinal integral scale time histories for Hurricanes Frances (A), Ivan (B) and Rita (C)

reflectivity. However, these increases are relatively small (approximately 1-4% when comparing composite reflectivity regimes with significant sample sizes). Longitudinal integral scales show a more steady increase as composite reflectivities increase, with increases of 10-40% common across the various roughness classifications.

The influence of rare, but significant, convective gusts would likely be buried in the mean statistics, so the peak gust factor values were also examined. Regardless of the methodology employed to assign the roughness regime, the smooth and open exposures did not contain any two-second to five-minute gust factors larger than 1.71. The roughly open classification yielded gust factor values as high as 2.0, while the rough classification resulted in values as large as 2.92. The largest gust factor value found in the entire database occurred during Hurricane Katrina and was likely due to a “convective” gust. The 10-minute segment containing the large gust factor is shown in Fig. 10. The 10-minute mean wind speed across the segment is only 11.5 m/s, while the peak two-second wind gust reaches 33.6 m/s. Review of the radar data indicates an associated composite

Table 5 Wind flow statistics for the smooth (A), open (B), roughly open (C) and rough (D) exposures stratified by composite reflectivity (dBZ)

A

Gust Factors - Tl Roughness ($0.005m \leq Z_o \leq 0.0199m$)

	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	1.39	1.39	1.39	1.39	1.40	1.39	1.41	1.38
Maximum	1.53	1.50	1.56	1.54	1.55	1.55	1.54	NA
Minimum	1.31	1.32	1.26	1.29	1.30	1.30	1.34	NA
Standard Deviation	0.06	0.05	0.08	0.07	0.06	0.06	0.06	NA
Sample Size	62	24	16	18	35	50	14	1

Longitudinal Turbulence Intensity - TI Roughness ($0.005m \leq Z_o \leq 0.0199m$)

	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	0.149	0.155	0.152	0.150	0.152	0.153	0.155	0.148
Maximum	0.179	0.251	0.163	0.161	0.164	0.165	0.168	NA
Minimum	0.133	0.134	0.139	0.133	0.139	0.137	0.141	NA
Standard Deviation	0.009	0.022	0.008	0.007	0.007	0.007	0.008	NA
Sample Size	62	24	16	18	35	50	14	1

Longitudinal Integral Scale (m) - TI Roughness ($0.005m \leq Z_o \leq 0.0199m$)

	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	89	83	98	71	96	100	99	89
Maximum	171	157	228	151	224	208	187	NA
Minimum	26	19	35	18	36	42	39	NA
Standard Deviation	35	32	65	34	54	42	48	NA
Sample Size	62	24	16	18	35	50	14	1

Table 5 Continued-1

B

Gust Factors - Tl Roughness ($0.02m \leq Z_o \leq 0.0499m$)

	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	1.46	1.46	1.46	1.46	1.47	1.46	1.48	1.49
Maximum	1.59	1.64	1.58	1.68	1.70	1.65	1.67	1.57
Minimum	1.32	1.36	1.35	1.34	1.31	1.32	1.34	1.41
Standard Deviation	0.06	0.06	0.06	0.07	0.07	0.08	0.09	0.05
Sample Size	60	31	32	73	129	135	33	9

Gust Factors - Qualitative Roughness ($0.02m \leq Z_o \leq 0.0499m$)

	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	1.40	1.43	1.45	1.44	1.46	1.46	1.46	1.45
Maximum	1.62	1.64	1.71	1.59	1.61	1.71	1.60	1.50
Minimum	1.25	1.28	1.26	1.29	1.31	1.28	1.36	1.38
Standard Deviation	0.07	0.09	0.10	0.09	0.07	0.09	0.07	0.04
Sample Size	94	30	18	12	45	76	22	6

Longitudinal Turbulence Intensity - Tl Roughness ($0.02m \leq Z_o \leq 0.0499m$)

	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	0.176	0.179	0.180	0.177	0.178	0.178	0.176	0.183
Maximum	0.194	0.204	0.191	0.196	0.193	0.202	0.193	0.197
Minimum	0.162	0.162	0.161	0.161	0.158	0.162	0.163	0.173
Standard Deviation	0.008	0.009	0.007	0.009	0.008	0.009	0.009	0.008
Sample Size	60	31	32	73	129	135	33	9

Table 5 Continued-2

Longitudinal Turbulence Intensity - Qualitative Roughness ($0.02m \le Z_o \le 0.0499m$)

	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	0.157	0.165	0.172	0.174	0.176	0.174	0.174	0.176
Maximum	0.229	0.265	0.220	0.207	0.211	0.238	0.227	0.188
Minimum	0.122	0.120	0.139	0.133	0.139	0.115	0.145	0.148
Standard Deviation	0.021	0.034	0.026	0.021	0.019	0.023	0.019	0.015
Sample Size	94	30	18	12	45	76	22	6

Longitudinal Integral Scale (m) - Tl Roughness ($0.02m \le Z_o \le 0.0499m$)

	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	91	81	78	80	90	106	101	125
Maximum	308	170	201	155	281	289	184	247
Minimum	15	23	26	26	30	24	31	46
Standard Deviation	47	36	41	29	39	49	34	60
Sample Size	60	31	32	73	129	135	33	9

Longitudinal Integral Scale (m) - Qualitative Roughness ($0.02m \le Z_o \le 0.0499m$)

	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	97	91	118	90	114	143	134	167
Maximum	308	170	228	125	224	290	288	266
Minimum	27	19	35	53	49	56	67	89
Standard Deviation	47	40	62	25	48	54	53	72
Sample Size	94	30	18	12	45	76	22	6

Table 5 Continued-3

C								
Gust Factors - Tl Roughness ($0.05m \le Z_o \le 0.0899m$)								
	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	1.50	1.53	1.53	1.53	1.53	1.52	1.54	1.55
Maximum	1.64	1.67	1.74	1.70	2.00	1.73	1.80	1.61
Minimum	1.34	1.38	1.40	1.33	1.39	1.36	1.44	1.44
Standard Deviation	0.07	0.07	0.08	0.08	0.08	0.07	0.09	0.09
Sample Size	36	34	56	79	128	100	31	3
Gust Factors - Qualitative Roughness ($0.05m \le Z_o \le 0.0899m$)								
	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	1.48	1.46	1.50	1.50	1.50	1.50	1.51	1.54
Maximum	1.73	1.67	1.72	1.74	2.00	1.99	1.80	1.58
Minimum	1.34	1.32	1.37	1.32	1.26	1.30	1.34	1.49
Standard Deviation	0.08	0.09	0.07	0.10	0.11	0.11	0.11	0.05
Sample Size	56	34	38	91	141	131	41	3
Longitudinal Turbulence Intensity - Tl Roughness ($0.05m \le Z_o \le 0.0899m$)								
	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	0.202	0.204	0.204	0.206	0.203	0.205	0.204	0.195
Maximum	0.222	0.265	0.223	0.224	0.220	0.220	0.215	0.200
Minimum	0.192	0.192	0.185	0.189	0.187	0.188	0.193	0.188
Standard Deviation	0.008	0.014	0.009	0.009	0.008	0.008	0.007	0.006
Sample Size	36	34	56	79	128	100	31	3

Table 5 Continued-4

Longitudinal Turbulence Intensity - Qualitative Roughness ($0.05m \le Z_o \le 0.0899m$)								
	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	0.184	0.182	0.189	0.186	0.192	0.191	0.187	0.185
Maximum	0.269	0.242	0.225	0.250	0.574	0.249	0.228	0.200
Minimum	0.136	0.123	0.143	0.121	0.117	0.124	0.144	0.175
Standard Deviation	0.026	0.028	0.018	0.026	0.043	0.028	0.021	0.013
Sample Size	56	34	38	91	141	131	41	3
Longitudinal Integral Scale (m) - Tl Roughness ($0.05m \le Z_o \le 0.0899m$)								
	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	99	85	91	91	93	94	106	137
Maximum	284	287	198	340	256	334	288	266
Minimum	17	28	24	24	27	29	34	53
Standard Deviation	61	53	47	54	48	58	60	113
Sample Size	36	34	56	79	128	100	31	3
Longitudinal Integral Scale (m) - Qualitative Roughness ($0.05m \le Z_o \le 0.0899m$)								
	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	98	94	110	100	100	107	109	98
Maximum	181	287	233	340	342	296	269	157
Minimum	39	35	40	26	31	40	39	46
Standard Deviation	39	47	52	51	52	48	43	56
Sample Size	56	34	38	91	141	131	41	3

Table 5 Continued-5

D								
Gust Factors - Tl Roughness ($0.09m \leq Z_o \leq 0.1899m$)								
	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	1.63	1.62	1.59	1.63	1.62	1.62	1.64	1.73
Maximum	1.95	1.83	1.94	1.94	1.90	1.99	1.87	1.89
Minimum	1.41	1.46	1.43	1.46	1.44	1.44	1.47	1.55
Standard Deviation	0.11	0.10	0.10	0.10	0.10	0.10	0.08	0.13
Sample Size	44	44	61	85	138	130	38	8
Gust Factors - Qualitative Roughness ($0.09m \leq Z_o \leq 0.1899m$)								
	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	1.64	1.62	1.59	1.59	1.60	1.59	1.73	1.79
Maximum	2.05	2.14	2.02	2.07	2.50	2.59	2.92	2.38
Minimum	1.32	1.36	1.30	1.34	1.30	1.31	1.36	1.41
Standard Deviation	0.14	0.14	0.14	0.13	0.15	0.17	0.24	0.19
Sample Size	95	106	137	184	316	257	96	42
Longitudinal Turbulence Intensity - Tl Roughness ($0.09m \leq Z_o \leq 0.1899m$)								
	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	0.237	0.239	0.236	0.240	0.238	0.236	0.240	0.243
Maximum	0.275	0.301	0.287	0.266	0.574	0.266	0.263	0.270
Minimum	0.217	0.210	0.213	0.213	0.214	0.213	0.217	0.224
Standard Deviation	0.016	0.017	0.015	0.015	0.031	0.013	0.013	0.016
Sample Size	44	44	61	85	138	130	38	8

Table 5 Continued-6

Longitudinal Turbulence Intensity - Qualitative Roughness ($0.09m \le Z_o \le 0.1899m$)

	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	0.246	0.239	0.233	0.230	0.231	0.230	0.271	0.295
Maximum	0.347	0.384	0.380	0.371	0.465	0.497	0.566	0.432
Minimum	0.164	0.161	0.142	0.154	0.140	0.141	0.141	0.187
Standard Deviation	0.042	0.039	0.040	0.038	0.045	0.051	0.068	0.059
Sample Size	95	106	137	184	316	257	96	42

Longitudinal Integral Scale (m) - Tl Roughness ($0.09m \le Z_o \le 0.1899m$)

	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	66	70	77	72	82	89	85	53
Maximum	191	169	328	266	342	296	269	70
Minimum	23	27	21	21	8	26	38	38
Standard Deviation	34	35	53	43	54	54	53	11
Sample Size	44	44	61	85	138	130	38	8

Longitudinal Integral Scale (m) - Qualitative Roughness ($0.09m \le Z_o \le 0.1899m$)

	0≤REF≤17.5	17.5≤REF≤22.5	22.5≤REF≤27.5	27.5≤REF≤32.5	32.5≤REF≤37.5	37.5≤REF≤42.5	42.5≤REF≤47.5	REF≥47.5
Mean	62	68	75	68	76	72	76	69
Maximum	167	191	328	175	256	334	201	127
Minimum	15	23	21	21	8	13	15	32
Standard Deviation	31	33	43	34	41	38	37	24
Sample Size	95	106	137	184	316	257	96	42

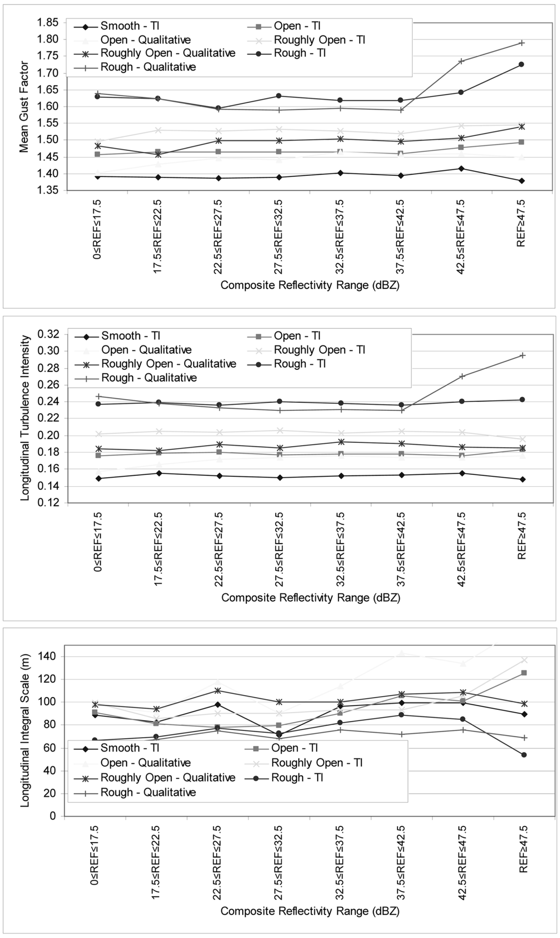

Fig. 9 A plot of mean gust factors (A), longitudinal turbulence intensities (B) and longitudinal integral scales (C) for various ranges of composite reflectivity

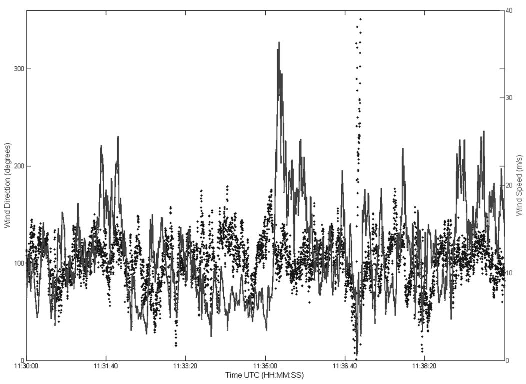

Fig. 10 Five-minute raw (10 Hz) wind speed and direction time history obtained during the passage of Hurricane Katrina. The data segment contains an example of an extreme gust which occurred on the inner edge of a curve reflectivity band which was exiting the area near the deployment site

reflectivity value of approximately 45 dBZ over the deployment site during this time period, but qualitative review of the radar reflectivity cross-sections indicates a higher reflectivity (~50 dBZ) curved element was moving northward at the time and exiting the area. Hence, the deployment site was located on the inner edge of this feature when the gust occurred. This yields evidence of a more complex relationship, as the kinematic and precipitation fields are not necessarily aligned in space or time.

Other large gust factor values were also investigated, but there were only a few occurrences of gust factors with a value near two when wind speeds were greater than 15 m/s. Most of these occurred in roughness conditions that were very rough ($Z_o \geq 0.19$ m) and hence they were not included in the database. During Hurricane Frances, a gust factor of 1.99 occurred with a mean wind speed of approximately 15 m/s. The qualitatively identified roughness length was 0.09 m. The large gust factor occurred at 15:32 UTC on 4 September 2004, when the outer portion of the stratiform precipitation field extended over the deployment site. There were no sharp reflectivity gradients and no cellular convection evident in the region via Melbourne WSR-88D radar reflectivity data at the time. Another large gust factor of 1.99 occurred in Hurricane Ivan as shown in Fig. 6B at 22:58 UTC on 15 September 2004. At this time the mean wind speeds were 15.4 m/s and the roughness length was qualitatively estimated at 0.07 m. Radar reflectivity data acquired from the WSR-88D in Mobile indicates largely stratiform precipitation in the region with some embedded shallow cellular precipitation cores of modest composite reflectivity.

These results are intriguing and suggest that precipitation, and/or the associated vertical motions, may influence the mean scale of the low-level wind field. At the same time, convectively induced extreme short duration gusts (and their associated large gust factors) appear to be exceedingly rare in the collected data, especially when mean wind speeds increase to 15 m/s or greater. Taken alone, composite radar reflectivity values are a good indication as to the intensity of the precipitation that is occurring at a particular location in space, but they do not give any indication of the precipitation structure (stratiform or convective).

4.4.2. Stratiform versus convective precipitation events

To further examine any potential relationships between wind flow characteristics and precipitation event type, the data were stratified further into stratiform and convective precipitation events. For this study, a qualitative assessment of precipitation type was made using animations of 0.5° elevation plan position indicators coupled with pseudo range height indicators (vertical cross-sections). The radar reflectivity data were examined to locate horizontal reflectivity gradients and vertical reflectivity above the melting level (bright band), as both are indicative of convective precipitation (Houze 2007). If the interpretation of the radar reflectivity data was unclear or no rainfall was occurring (reflectivity = 0) at the deployment site then the precipitation event was classified as neither stratiform nor convective.

Based on the qualitative radar analysis, convective precipitation structures comprise approximately 15.7% of the defined precipitation events in the included database. This percentage is close to historical studies (Jorgensen 1984) indicating stratiform precipitation events outnumber convective precipitation events by an order of magnitude. Precipitation events associated with higher composite radar reflectivities (greater than ~40 dBZ) were more likely to be classified as convective, while stratiform events typically maintained lower reflectivity values on average. The majority of the convective events occurred in the eyewall and outer convective bands. As expected there was a dearth of convective precipitation events at moderate radii from the center. There was also considerable storm to storm variability in the percentage of convective events. Several of the tropical cyclones, including Floyd and Ivan, resulted in a significant amount of convective precipitation near the deployment sites, while Hurricane Bonnie resulted in almost exclusively stratiform precipitation over the Wilmington deployment site.

Tables 6 and 7 indicate the small sample sizes associated with the identified convective precipitation events relative to the stratiform events. After segregating the data into the identified roughness regimes, the sample sizes are reduced even further, and the results are variable. There is minimal change in the measured gust factor and turbulence intensity values, but a bit more variability in the longitudinal integral scale (typically noisy to estimate anyway). For the qualitatively assessed open exposure, the longitudinal integral scale difference is more substantial, reaching a 34% increase for convective relative to stratiform precipitation events. However, data acquired in exposures qualified as rough do not show the same relationship.

4.4.3. Eyewall samples

The eyewall is sometimes hypothesized as a location where efficient vertical transport of

Table 6 Wind flow statistics for the smooth, open, roughly open and rough exposures as determined using TI derived roughness lengths stratified by precipitation structure

	Longitudinal Integral Scale (m)	Gust Factor	Longitudinal Turbulence Intensity	Sample Size
Tl Smooth - Convective	79.5	1.39	0.152	21
Tl Smooth - Stratiform	92.4	1.40	0.151	120
Tl Open - Convective	99.2	1.49	0.179	56
Tl Open - Stratiform	89.9	1.46	0.178	287
Tl Roughly Open - Convective	106.2	1.53	0.205	51
Tl Roughly Open - Stratiform	94.0	1.53	0.204	273
Tl Rough - Convective	72.4	1.64	0.242	67
Tl Rough - Stratiform	86.2	1.62	0.235	306

Table 7 Wind flow statistics for the open, roughly open and rough exposures as determined using qualitatively derived roughness lengths stratified by precipitation structure

	Longitudinal Integral Scale (m)	Gust Factor	Longitudinal Turbulence Intensity	Sample Size
Qualitative Open - Convective	154.3	1.46	0.171	17
Qualitative Open - Stratiform	115.0	1.45	0.178	212
Qualitative Roughly Open - Convective	120.9	1.50	0.187	69
Qualitative Roughly Open - Stratiform	98.9	1.50	0.192	275
Qualitative Rough - Convective	72.9	1.64	0.243	141
Qualitative Rough - Stratiform	73.1	1.62	0.234	671

momentum may result in higher surface level wind speeds (Franklin, *et al*. 2003). Given this hypothesis, an additional qualitative assessment of the WSR-88D data provided an estimate of the portions of the collected wind records which occurred during the passage of an eyewall. For this study, the inner and outer edge of the eyewall was qualitatively estimated using vertical and horizontal reflectivity gradients. This task is complicated by several factors, including the presence of concentric eyewall structures in some storms. In this study, only inner eyewalls were considered, as the inner eyewalls always contained the highest wind speed values for each tropical cyclone with the exception of Hurricane Bonnie (1998) whose outer eyewall produced slightly higher winds at the Wilmington deployment site. Another complication is the often deteriorating structure of the rear semi-circle (the second eyewall passage over the same site) due to dry air intrusion. To mitigate this issue, only the first eyewall passage was considered. Another complication is that the reduction in wind speed at the inner edge of the eyewall typically occurs slightly inward of the reflectivity gradient (Jorgensen 1984). Hence this analysis includes data obtained from the inner edge of the eyewall when the reflectivity values may already be decreasing, but wind speeds remain high.

Based on the qualitative review of the available wind speed time histories, the compiled eyewall statistics indicate that eyewalls are regions with slightly lower mean gust factors (~2-5%) and longitudinal turbulence intensities (~1-14%), but larger mean longitudinal integral scales (~6-43%). These results are contrary to hypotheses that argue eyewalls are regions containing anomalously high near-surface wind gusts or increased turbulence. It should be noted again that the sample size

Table 8 Eyewall wind flow statistics for various roughness regimes as determined using TI derived (A) and qualitatively derived roughness lengths (B)

A				
TI Roughness	Smooth	Open	Roughly Open	Rough
Mean Gust Factor	1.40	1.46	1.54	1.61
Mean Long. Turbulence Intensity	0.152	0.179	0.203	0.253
Mean Long. Integral Scale (m)	109	114	98	102
Sample Size	25	27	23	23
Average Roughness Length of Sample (m)	0.013	0.035	0.067	0.127
% Relative to Mean Gust Factor	100%	100%	101%	99%
% Relative to Mean Long. Turbulence Intensity	100%	100%	99%	106%
% Relative to Mean Long. Integral Scale	118%	122%	105%	128%

B			
Qualitative Roughness	Open	Roughly Open	Rough
Mean Gust Factor	1.42	1.48	1.55
Mean Long. Turbulence Intensity	0.158	0.196	0.215
Mean Long. Integral Scale (m)	167	110	84
Sample Size	20	25	63
Average Roughness Length of Sample (m)	0.030	0.071	0.133
% Relative to Mean Gust Factor	99%	99%	96%
% Relative to Mean Long. Turbulence Intensity	94%	104%	90%
% Relative to Mean Long. Integral Scale	143%	107%	117%

in any given roughness regime is small. In fact, only 100 five-minute data segments were identified in the eyewall region for all of the storms considered. This small sample size underscores the need for continued observational field work in landfalling tropical cyclones. It should be noted that without the deployment efforts during the prolific 2004 and 2005 Atlantic Hurricane Seasons the eyewall statistics would have been reduced by well over 50%.

5. Conclusions

Using research grade wind speed and direction time histories, acquired from eight deployments in seven landfalling tropical cyclones, the wind flow characteristics were investigated. The analysis evaluated two-second to five-minute gust factors, as well as longitudinal turbulence intensity and integral scales. The results indicate the near-surface wind flow characteristics are relatively well behaved in tropical cyclones. Major changes in wind flow characteristics are normally accompanied by changing wind directions and upstream roughness/terrain conditions. Once stratified into different roughness regimes to account for the influences of exposure, mean gust factors and longitudinal turbulence intensities indicated a slight, but statistically significant (according to the T-test at a 0.05 significance level), decrease with increasing mean wind speed, while the mean integral scales were substantially larger in the higher wind regimes. These same trends were revealed when the data were examined using a storm-relative perspective. Slightly lower gust factors and turbulence intensities occurred near the eyewall (also the location of the highest wind speeds), while integral scales increased; but the scatter was substantial.

Comparisons with WSR-88D radar reflectivity data indicate a slight increase in gust factor and longitudinal turbulence intensity during periods of more intense precipitation (as revealed through examination of the composite reflectivity radar fields), while integral scales show a more substantial increase. Radar reflectivity data were examined further to diagnose the presence of convective precipitation events. However, substantial and consistent differences in wind flow statistics occurring during stratiform relative to convective precipitation were not noted. The statistics also indicate that eyewall passages tend to reduce the expected gust factor and turbulence values, while the integral scales tend to increase. This result offers strong evidence that, in general, the near surface wind field within the eyewall region is not more turbulent than that which occurs elsewhere in the hurricane.

Overall, the data indicate that longitudinal integral length scales may respond to the tropical cyclone environment and storm-scale changes more readily than gust factors and turbulence intensities. At least one "convective" gust was likely identified in Hurricane Katrina. However, significant "convective gusts" appear to be extremely rare based on the historical studies (Krayer and Marshall 1992, Sparks and Huang 2001, Schroeder and Smith 2003, Paulsen and Schroeder 2005, Vickery and Skerlj 2005). This study based on more recent data indicates their influence is seemingly minimal when the mean wind speeds reach modest values (> 15 m/s). It is not surprising that significantly higher gust factor values have been rarely documented in regions of higher wind speeds, including the eyewall. Hence, the importance of the embedded convective gust is likely minimal from an engineering design standpoint.

Even with a decade of field efforts, there are still numerous reasons to continue to document landfalling tropical cyclones and obtain research-grade data with mobile towers. Certainly, the collected data is useful from an operational standpoint, but there is also still a continuing need for research-grade wind speed and direction time histories. Fortunately for coastal residents of the

United States, after combining data from eight deployments comprising seven of the most significant events in the past decade, the database still does not include winds of major hurricane strength. Once the data is stratified by roughness regime and then reduced via another criterion (e.g., such as composite radar reflectivity or precipitation type) the sample sizes are still relatively small. Future research efforts focused on the collection of coupled tower and research radar datasets will provide further opportunities to better understand the wind flow found within landfalling tropical cyclones.

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