Thunderstorm characteristics of importance to wind engineering Part II: Profiles, gust factors and other observations

Franklin T. Lombardo[a*], Douglas A. Smith[b], John L. Schroeder[b], Kishor C. Mehta[b]

[a] *National Institute of Standards and Technology, Gaithersburg, Maryland 20899, MS 8611*

[b] *Wind Science and Engineering Research Center, Texas Tech University, Lubbock, Texas 79414*

Abstract

The idea that "wind is wind" allows statistics for wind and pressure collected in wind tunnels to be used in wind load standards. Statistics collected in wind tunnels are based on inherently stationary data and verified with field data that is stationary in the boundary layer (SBL). Some of the most extreme and important events for wind loading (e.g. thunderstorms) display non-stationary wind and pressure characteristics. Thunderstorms are therefore assumed to have the same properties as the SBL, although previous studies have shown differences. Wind data from thunderstorms, some of which displayed rapid wind speed increases (i.e. "ramp-up") were collected at Texas Tech University and from field campaigns. General characteristics of the ramp-up events are detailed. Vertical wind components and profiles, gust factors and variability of thunderstorms are compared with SBL data. Vertical ramp-up profiles show evolutionary behavior while maximum gust profiles suggest differences from the SBL. Gust factors for ramp-up events show that the Durst curve should not be used for averaging times greater than 60 s and can be fit to a cubic polynomial. Thunderstorm events also display considerable variability, which may affect wind load standards.

Keywords: **Thunderstorm; Non-Stationary; Gust Factor; Variability; Wind Profile**

1. Introduction

The engineering properties of wind, no matter the source, are homogenous. This is the fundamental assumption of current wind engineering practice. The idea that "wind is wind" allows statistics for wind and wind-induced pressure currently collected in wind tunnels to be used in wind load standards. Statistics collected in wind tunnels are based on data that inherently display steady mean and variance, known as *stationary* data. Wind tunnel results are validated with full-scale data that is stationary within the boundary layer (SBL) and over durations associated with the spectral gap (10 min to 120 min, Stull, 1988). Contrarily,

[*] Corresponding Author: Tel: (301) 975-5983
E-Mail Addresses: franklin.lombardo@nist.gov (FT Lombardo), doug.smith@ttu.edu (DA Smith), john.schroeder@ttu.edu (JL Schroeder), kishor.mehta@ttu.edu (KC Mehta)

thunderstorms, one of the most extreme and hence important events for wind loading, typically display wind and wind-induced pressure of unsteady mean and variance, and occur over shorter time scales associated with the spectral gap. These events are referred to as *non-stationary*. Non-stationary events such as thunderstorms are therefore assumed to have the same statistical and physical properties as stationary events in wind load standards. These assumptions have been shown to be questionable in some cases (Fujita, 1985; Kim and Hangan, 2007; Holmes et al., 2008). As a result, Orwig and Schroeder (2007) as well as Choi and Hidayat (2002) state that the wind load standard is not adequately suited for thunderstorm events. Figure 1 shows an example of a stationary wind speed record and a non-stationary wind speed record generated by a thunderstorm.

Thunderstorm wind and pressure data have long been challenging to the wind engineering community due to their transient (i.e., non-stationary, short temporal scale) characteristics. These characteristics render traditional correlation, spectral analysis and statistical techniques inappropriate. This is especially true in “ramp-up” thunderstorm events lasting over short time periods as shown in Figure 1. Calculation of wind engineering statistics (e.g., turbulence intensity, gust factor, integral scale) used in wind load standards are based on stationary wind data with longer temporal scales than most ramp-up events. Due to these transient characteristics and lack of available field data (Kwon and Kareem, 2009), meaningful comparisons with non-stationary events are unwieldy.

In addition to its transient characteristics, thunderstorm flow shows physical differences from the SBL that may affect wind characteristics and wind-induced pressures. The thunderstorm boundary layer profile, based on wind tunnel and limited full-scale data, in some cases, shows a substantial difference to that of the logarithmic profile of SBL winds. Due to strong downward velocities striking the ground surface and spreading out (Fujita, 1985), maximum horizontal wind velocities are expected to occur at heights 100 m (300 ft) or lower (Kim and Hangan, 2007). Differences in profile may cause different wind loading on structures than that of the SBL. As the mechanics associated with convective gusts differ significantly from traditional turbulence in both its kinematics and dynamics (Kwon and Kareem, 2009), rapid changes in wind speed and direction may cause rapid spatiotemporal pressure fluctuations on a structure (Kareem, 2008). Murgai et al.

(2006) used computer simulation and found that there are moderate effects of non-stationary gusts on surface pressures, concluding that there were lower peak suction pressures than produced by a constant flow. An increase in vertical wind speeds has been shown at thunderstorm onset (Lombardo 2009a). The vertical component of the wind has been shown to affect suction pressures on buildings (Wu, 2001, Letchford and Marwood, 1997). Due to the difference in generation mechanisms, the non-linear dependence on certain meteorological parameters (Wakimoto, 2001), and the lack of quality data, thunderstorm properties also are expected to display greater variability than the SBL, as has been noticed in other work (Choi, 2000; Choi and Hidayat, 2002; Lombardo, 2009a).

Full-scale thunderstorm wind data was collected at Texas Tech University and from field campaigns from 2003 to 2010. A listing of ramp-up events that were collected is found in Table 1. Due to the difficult nature of thunderstorm charactersitics, a number of studies (Holmes et al., 2008; Chen and Letchford, 2005) have assumed that instead of a constant mean wind speed over the course of the record, non-stationary data has a time varying mean wind speed. This time-varying mean wind speed at some averaging time is then compared with the constant mean wind speed of the stationary data in the computation of wind engineering parameters. The respective means are then subtracted from the original record to generate "residual turbulence". The values of both time-varying mean and residual turbulence will be used throughout this paper to compare thunderstorm wind data to that of the SBL. The averaging times used in the computation of time-varying means are shown in Table 2.

The data was collected to greatly increase the number of available thunderstorm data sets for research purposes. The time-varying mean and residual turbulence quantities of the thunderstorm wind data were used to make sound comparisions with SBL wind data. These comparisons enabled further information on the statistical and physical differences from the SBL, and subsequent identification of thunderstorm characteristics of potential importance to wind engineering. Vertical wind components and profiles, gust factors and variability are the characteristics discussed in this paper.

In the companion paper (Lombardo et al., in review) a segmentation algorithm using the averaging times in Table 2 identified temporal scales and turbulence for use in wind engineering parameterization. It was determined that averaging times 15 s – 60 s were acceptable for use in comparison with SBL wind data, and time scales of 60 s – 240 s were associated with ramp-up thunderstorm events. These temporal properties will be discussed throughout this second portion of the research. Data collection, instrumentation and identification are also discussed in the companion paper.

2. Thunderstorm/Ramp-Up Wind Characteristics

2.1 Thunderstorm Vertical Profiles

Generally, higher mean wind speeds are observed closer to the surface within the outflow environment, which indicates are more vertical, or uniform alignment of the profile (Orwig and Schroeder, 2007). This "uniform" profile has been observed in previous wind engineering studies. Using the maximum time-varying mean and maximum gust speeds, Holmes et al. (2008) found more of a uniform profile up to a height of 15 m (50 ft). Duranona et al. (2007) found although roughness dominated close to the ground, profiles of extreme events were near uniform above 20 m (66 ft). A thunderstorm event produced a nearly constant vertical profile up to the height of the tower (Ponte and Riera, 2007). Choi (2004) discovered peak wind speeds at a height of 100-200 m (656 ft). In addition, the vertical profile of the gust-front is time variant, but more reliable information is needed in the field to model thunderstorm profiles, as evolutionary profiles are currently not considered in wind engineering (Wang and Kareem, 2005; Kwon and Kareem, 2009). The maximum mean wind speed at some height may also be treated as a gust profile as used in the boundary layer wind case (Kwon and Kareem, 2009).

Following the suggestions and findings of the studies listed above, 7 ramp-up cases (Table 1) where wind speed was measured at more than one height were studied.

2.1.1 Evolutionary Profiles

Examples of evolutionary profiles are illustrated for three cases in Figure 1. Shown for the June 19, 2003 case, all five levels of the 50 m (160 ft) tower were operational and used in the analysis. For the other cases, the 200 m (656 ft) tower was used. All three cases shown in Figure 1 illustrate the gust (3 s) profile at T = 0 s, all of which resemble the SBL. Figure 1 also shows the rapid increase in wind speed over a short period of time, as gust wind speeds at 10 m (33 ft) and below increased approximately 13 m/s to 18 m/s (30 mph - 40 mph) in 30 s or less. The peak 3 s gust seems to work its way downward with time, illustrating momentum transferred downward toward the surface over a short period. The maximum 3 s gust wind speed from all working heights appear to be close to a uniform or possibly an impinging jet profile as noted in many publications such as (Holmes, 2001; Ponte and Riera, 2007; Holmes et al., 2008). The maximum gust profiles will be discussed further in the next section. All heights below the wind maximum approach the SBL "log" profile, which was also noticed in wind tunnel simulations by Mason et al. (2005), and in the hurricane environment below a distinct wind speed maximum (Giammanco et al., 2008).

Another way to illustrate these evolutionary profiles and their downward momentum transfer is to "track" the peak wind speed from its origins at higher levels to its destination near the surface. Heights were normalized by the maximum measuring height and times were from the earliest occurrence of a peak 3 s gust at any height. Of the seven ramp-up events, four show a very coherent vertical peak gust structure over the time period of the record, which ranges from approximately 10 s to 40 s once the earliest peak wind speed is reached depending on the tower height (Figure 2). Two show weak coherency between the higher levels and the near surface but show strong coherency in the near surface peaks. One record, which has high coherency in the near surface, looks to be relatively uncorrelated with the higher levels. This lack of correlation however simply could be due to other strong wind gusts that did not make it to the surface, or more localized near surface effects (e.g. turbulence).

2.1.2 Maximum Gust Profiles

As stated in the previous section the maximum 3 s gust at all heights resembled more of a uniform or impinging jet profile. ASCE (2010) uses a modified power law gust profile where the power law exponent is decreased. This decrease in exponent does create more of a uniform profile, but it is largely unknown whether thunderstorms or other non-stationary events follow a similar gust profile. Evidence from evolutionary profiles in Figure 1 is certainly compelling and is looked at in this section.

Maximum profiles from five different averaging times (3 s, 8 s, 34 s, 68 s, and 136 s) were analyzed to further determine the use of a specific averaging time(s) for non-stationary wind speeds and illustrate again the time scales associated with some ramp-up events. Also, these profiles show the “peak” wind speeds at a given averaging time regardless of gust coherency.

Figure 3 shows an illustration of the maximum wind speed profiles at a number of different averaging times for the March 8, 2010 and the August 12, 2009 cases. The March 8, 2010 case was produced from high-based virga and no ramp-up characteristics were examined at the near suface so therefore has not been included in the ramp-up events (Table 1). This March 8, 2010 event still shows the differences in vertical profile from convectively generated events. Note at averaging times greater than 68 s typically, the impinging jet or uniform feature in the profile is completely averaged out. This “smoothing” of important information due to the use of large time scales further stresses the need for a shorter time scale in thunderstorm prone areas. The “log” SBL profile is again noticed beneath the maximum wind speed for the maximum gust profiles. The peaks shown in Figure 3 occur around heights from 40 m – 80 m (150 ft - 250 ft), which are approximate hub heights for most current wind energy installations.

While the profiles shown in Figures 1 and 3 certainly exhibit differences from the SBL mean profile, the maximum 3 s gust wind speeds from the SBL were also calculated to see the differences, if any, between the gust profiles of thunderstorms and the SBL. Approximately 80% of the 642 SBL profiles studied exhibited a maximum 3 s gust at the maximum measuring height at 50 m (160 ft), while 18% occurred at 21 m (70 ft) and the other 2% at 10 m (33 ft). This percentage is a reduction from the mean 15 min profiles, in which 100% of profiles exhibited a maximum wind speed at maximum measuring height. Figure 4 shows the average maximum 3 s gust profile from the WERFL SBL normalized by the 10 m (33 ft) measuring height.

The gust profiles in ASCE (2010) give a 75 %, 46 % and 28 % reduction in power law exponent from those of the mean profiles in Exposures B, C and D respectively with Exposure C shown in Figure 4. This was verified from the WERFL SBL data with a 54 % reduction in the averaged power law exponent over all heights (Figure 2), generally considered to be in Exposure C (Levitan and Mehta, 1992). These occurrences shows some SBL similarities to ramp-up events in gust properties even though the ramp-up profiles develop over time scales of around 30 s - 200 s and the SBL profiles were over 15 min.

Examples of SBL profiles other than those in which the maximum wind speed occurs at the maximum measuring height are also shown. Figure 4 does show that maximum 3 s gust profiles in the SBL have some variation in height of the maximum wind speed. Normalizing the height of the maximum wind speed, z, by the maximum measuring height, z_{max}, yields a $z/z_{max}$of 0.88 when considering SBL gust profiles and a z_{max} of 50 m (160 ft). When performing the same analysis on the ramp-up profiles (Figures 3, 5), z/z_{max} yielded approximately 0.50, a considerable difference from that of the SBL, however the average $z_{max}$was approximately 170 m (~ 560 ft). The z/z_{max} values for the ramp-up events approached the 0.88 value associated with the SBL at an averaging time of somewhere between the 68 s and 136 s averaging times (not shown). Although the normalization scheme is not ideal due to the use of multiple z_{max} values, the scheme still shows that on average the height of the peak wind speed in ramp-up events is lower than that of the SBL when it is expected that the maximum gust will occur at the heighest measuring (i.e. a log profile) height.

As stated previous a large number (~80%) of the 642 SBL maximum 3 s gust profiles followed a typical “log” profile. In the 7 ramp-up events, all three types of profiles that have been discussed in this section (log, uniform and impinging jet) were exhibited. The impinging jet profiles were shown in Figure 2 and the uniform and log profiles are shown in Figure 5. The log profile was produced by a bow echo/supercell thunderstorm. This storm produced the highest wind speeds at any height of all the ramp-up events and caused some structural damage. However peak winds at the near surface were similar to all the other events, which had characteristics representative of non-supercell thunderstorms. In addition, this bow echo/supercell storm, although it displayed ramp-up characteristics, produced the longest duration of winds (Table 1) defined in the segmentation algorithm. This type of convective event is a more organized windstorm producing high winds over larger spatial extent (Wakimoto, 2001). And although in general the production of strong winds organized windstorms is likely similar to a non-supercell thunderstorm (Wakimoto, 2001), organized windstorms are longer lived and have methods of augmenting the near surface wind field that may be altogether different such as the rear-inflow jet and mesovortices (Wakimoto, 2001). The discrimination of thunderstorm wind-producing types in wind engineering is an area that requires further study, and can be accomplished with the advent of high resolution instrumentation such as surface and radar (Schroeder et al., 2009) platforms.

The profile information presented in this section requires a word of interpretation. Some higher levels were not functioning and fairly large gaps of approximately 30 m (100 ft) still existed when all levels were functioning properly, so the profiles may take on a different shape. This is especially true at higher levels where the observation density is lower. Additional tower measurements and remote sensed measurements as mentioned earlier could also help with this issue.

2.2 Vertical Velocity/Angle of Attack

The vertical velocity component of the wind is important in thunderstorm environments (Orwig and Schroeder, 2007) and may be important for the design of special structures, such as light roofs (Ponte and Riera, 2007). Vertical wind speeds have been shown to increase upon thunderstorm onset, possibly modifying vertical angle of attack (Lombardo, 2009a). An example showing vertical angle of attack, denoted by β is shown in Figure 6, where w is the vertical velocity and V is the total horizontal wind speed. In addition, wind tunnel tests (Letchford and Marwood, 1997) and field studies (Wu, 2001) on buildings have shown that a positive (upward) vertical angle of attack causes higher suction pressures on the roof. Positive excursions of vertical angle of attack typically last over periods < 1 s (Wu, 2001). Therefore it is imperative to analyze high resolution information on vertical and horizontal winds.

Given the information above, information from 12 non ramp-up thunderstorm events that had high resolution sonic anemometery were compared with 22 SBL runs. This comparison was performed to determine differences, if any, in the distributions of maximum vertical angle of attack and the vertical angle of attack variance at a height of 10 m (33 ft). Hypothesis testing was done using the non-parametric Wilcoxon Rank-Sum Test (Milton and Arnold, 2003) with a significance level at 0.05. When testing, both p-values were found to be greater than 0.05, meaning the research hypotheses of equality between variables could not be rejected.

Due to the common increase in wind speed associated with thunderstorm flow, the magnitude of wind speed at the time of the maximum β was also checked to determine whether or not the largest β had a higher wind speed magnitude and therefore potentially larger suction pressures. The thunderstorm wind speeds were found to be in the range of SBL wind speeds at maximum β.

Ramp-up events were also looked at to determine properties of vertical angle of attack in the near surface environment (i.e. 4 m (13 ft) or 10 m (33 ft)). However, since only uvw anemometery was available, high resoultion information < ~ 1 s is not reliable (Miller, 2007) so 1 s measurements were used. The near surface w perturbations ($w - \overline{w}$) were used to remove any potential bias. The information from uvw anemometers can be important because it may reveal the existence of a more prolonged positive (or negative) vertical angle of attack. Prolonged (mean) positive vertical angles of attack were shown to cause higher suction pressures (Letchford and Marwood, 1997), however positive, turbulent w fluctuations were found to cause no discernible higher suction. Therefore both 1 s and 60 s vertical angle of attack measurements were looked at to determine a “turbulent” and “mean” vertical angle of attack.

Analyses of the ramp-up events revealed peak or “turbulent” β values in all ramp-up events were no greater than 15 degrees in the vicinity ($\pm$15 sec) of peak winds. These values of β, and greater, have been observed on very short time scales in both the SBL (Wu, 2001) and thunderstorm events as shown here. The "mean" 60 s values ranged from -3.1 to +2.0 with an average value for 7 ramp-up events of -0.32. The hypothesis of median equal to zero could not be rejected on the basis of the sign-rank test. An example of vertical angle of attack information for a ramp-up event is shown in Figure 7. This information largely suggests that the vertical components of the wind in thunderstorms do not adversely affect pressures on low-rise buildings less than 18 m (60 ft), and shows some similarities to SBL vertical wind components and angle of attack. In other words, the vertical wind speeds do increase of thunderstorm onset, however so does the horizontal wind component, offsetting any effects from the vertical. To perform accurate vertical angle of attack analysis would require fairly constant horizontal angle of attack over relatively long time periods to make any definitive judgments on whether the vertical component has significant effects on full-scale structures.

Although no significant differences were shown in thunderstorm or ramp-up environments at the surface, the effect of vertical velocity/angle of attack may be more significant higher in the boundary layer in thunderstorm environments or throughout the boundary layer in a tornadic wind field. Significant upward and downward motion was noted in all ramp-up events, especially in the higher levels of the tower in ramp-up events (Lombardo, 2009a).

The ratio between the tangential wind speed and the mean vertical wind speed in tornadoes has been shown to be around 2-6:1 in both field and wind tunnel studies (Lee and Wurman, 2005; Haan et al., 2010). This ratio gives vertical angle of attack values around 10-30 deg. Again, these values have been observed on very short time scales in both the SBL (Wu, 2001) and in some of the thunderstorm events as shown here. A positive vertical angle of attack over a longer time scale or other tornadic vortex structures could influence suction pressures and may make vertical angle of attack an important parameter to consider.

2.3 Thunderstorm Gust Factors

Convective scale motions as shown throughout this paper associated with ramp-up thunderstorms may significantly alter the gust structure of wind data, and subsequently affect structural design. There is an ongoing debate on the validity of both the Durst curve (ASCE, 2010) and other curves for extreme wind events such as hurricanes (Krayer and Marshall, 1992; Paulsen and Schroeder, 2005). Wieringa (1973) noted that since gusts from thunderstorms are more dependent on convective elements other the surface roughness, that the traditional gust factor definition does not apply. Kwon and Kareem (2009) state that the mechanics of gusts associated with convective gust fronts differs significantly from traditional turbulence in both its kinematics and dynamics. Therefore, there is a need to critically assess the impact of abrupt changes in wind field magnitudes due to possible modifications in aerodynamics of structures (Kwon and Kareem, 2009).

As in other wind engineering parameters, studies on gust factors in thunderstorm environments have taken on a number of different definitions. Gust factors were found to be generally higher for thunderstorms without modification to the wind record (Choi, 2000; Choi and Hidayat, 2002) and using shorter (i.e. 2 min) segments without a time-varying mean (Orwig and Schroeder 2007). Holmes et al. (2008) and Chay et al. (2008) both used the largest value of the time-varying mean wind speed with respect to the overall peak to calculate gust factors. As shown with other parameters, magnitude of the peak/gust factor depends on the chosen period for the moving average (Chay et al. 2008). Chay et al. (2008) and Lombardo (2009a) also used a "local" gust factor definition where the time-varying mean at the exact time of the peak wind speed was used.

Gust information was looked at for the near-surface (i.e. 10 m (33 ft) if available) unless otherwise noted. In this case the gust factor (GF) definition is the maximum peak wind speed (~1 s) compared to the maximum time-varying mean wind speed in the record at a specific averaging time, *t*, regardless of its position with respect to the peak wind speed (i.e. "non-local" GF) as done in (Holmes et al., 2008; Chay et al., 2008) and shown in Equation 10. The "non-local" WERFL mean was remarkably close to the Durst curve (Lombardo, 2009a) shown in ASCE (2010), suggesting comparable results when using a time-varying mean wind speed.

$$GF = \frac{\hat{\mathrm{U}}}{\tilde{\mathrm{U}}_{\mathrm{t}}} \qquad (10)$$

The information in Figure 8 shows all ramp-up GFs compared to the range of SBL GFs at the WERFL site for 693 SBL 15 min runs. From information in Figure 8, it is apparent that all ramp-up GFs fall within the bounds of the SBL at averaging times < ~ 100 s. One ramp-up event straddles the maximum bound of most averaging times less than ~100 s. This event, represented in Figure 8, exhibits very extreme convective motions over a short time scale as briefly discussed in Section 3.4.3. These types of extreme events require further study. At averaging times greater than approximately 100 s, some ramp-up GFs begin to exceed the bounds of the SBL GF's and by averaging times around 300 s, nearly all ramp-up events exceed the bounds of the SBL. This implies the difference in time scales between ramp-up and SBL events and is shown further when compared to GF values used in ASCE (2010) in Figure 9. The GF values used in ASCE (2010) should not be used for any thunderstorm records at averaging times 100 s and greater and likely not for averaging times greater than 30 s - 60 s. Similar "gustiness" at averaging times/time scales < ~30 s is displayed in Figure 1 although there is some considerable variability in the ramp-up GF's at these time scales. Additional data will be needed to make any definitive statements regarding the gust structure of thunderstorm or ramp-up events at shorter averaging times. The 10^{th} and 90^{th} percentiles of the SBL GFs were also shown to illustrate the variability of the ramp-up events versus those of the SBL. Differences in behavior highlight the need to consider gust occurrence in non-stationary downburst differently than in conventionally used stationary techniques (Chay et al., 2008).

The only event that doesn't exceed the bounds at averaging times > 300 s is, perhaps not surprisingly, the bow echo/supercell event, which displayed the longest temporal scale of any ramp-up event and the highest sustained winds. This difference in gust structures again indicates the differences between thunderstorm types. Even including this event, the increase in GFs with respect to averaging time seems to resemble a cubic polynomial. Fitting a cubic polynomial the mean ramp-up GF value at all averaging times revealed an R^2 value to be over 0.99 out to an averaging time of 1500 s (Lombardo, 2009a). Cubic polynomials were also fit to $\pm$1 standard deviation of the mean values shown in Figure 8 to generate a GF "envelope" and extrapolated to 3600 s as shown in Figure 9. The equation for the ramp-up GF's is shown in Figure 9 is given in Equation 11.

$$GF = 0.011\ln(T)^3 - 0.072\ln(T)^2 + 0.23\ln(T) + 0.85 \quad (11)$$

where T is the averaging time/moving average in seconds.

In addition to the data collected at the WERFL site, GFs from thunderstorm events were collected from the West Texas Mesonet (Schroeder et al., 2005) (WTM) and are shown in Figure 9. The WTM is a high resolution observing network currently employing over 60 stations throughout West Texas and New Mexico. The WTM stations are well sited and are mostly in open terrain (Vega, 2008). They record a wind speed value every 3 s and over a 5 min period the maximum wind speed recorded on those 3 s intervals is kept as a 'peak' wind speed. The mean wind speed over that 5 min period is therefore the average of each 3 s value within that 5 min period. A peak wind speed threshold of 31 m/s (70 mph) was set for two reasons. One to ensure that only 'extreme' events were used, and secondly to remove non-thunderstorm data automatically as it has shown to be somewhat of a limiting value for non-thunderstorm data in the West Texas region (Vega, 2008; Lombardo, 2009b). There were a few non-thunderstorm and tornadic data points above this threshold, and these points were removed manually. A total of 83 thunderstorm events were used for analysis. If more than one wind speed exceeded the threshold for a particular event at a particular station, the highest of the peak wind speeds was used for the gust factor analysis. The 5, 10, 15, 30 and 60 min mean wind speeds were compared with the peak wind speed from the WTM stations. The 10, 15, 30 and 60 min mean wind speeds were calculated using the minimum consecutive mean of the 5 min values (e.g. 2 for 10 min, 3 for 15 min, etc…) that contained the peak wind speed for a conservative representation of GF.

The GF's as calcuated from the WTM data are in fairly good agreement with the hypothetical curve shown in Figure 9. The mean GF values for the WTM fall within the bounds of the hypothetical curve for all averaging times. This behavior is noted although the GF's were calculated using block averaging for the WTM data, while the ramp-up GF data from the WERFL was calculated using moving averages. Also in Figure 9 are GF's from ramp-up events taken from other publications. In a premliminary detailed analysis of the data it was noted that different storm types may have different GFs. For example highly organized severe windstorms may have lower GFs than non-supercell thunderstorms. Further research on this specific topic is ongoing.

Although there is no physical meaning likely attributed to the curve in Figure 9, it could aid wind engineering practitioners when looking at average wind speed values over some period of time in conjunction with a ramp-up thunderstorm event. Intensity of thunderstorm procuding wind types is likely to be a function of environmental parameters as well (i.e. dewpoint depressions, downdraft strength, storm dynamics, etc..). This information should be further studied from an engineering standpoint.

2.4 Thunderstorm Variability

In a structural reliability framework, which is taken into account in some form when considering an overall wind load on a structure (Ellingwood and Tekie, 1999; ASCE, 2010), the variability that a particular parameter exhibits is of importance (Yu and Chowdury, 2009). Therefore, the variability displayed in thunderstorm wind properties is also of interest and is significant due to their physical and statistical differences (Ponte and Riera, 2010). Reduction of the time scale alone, assuming physical and statistical characteristics are the same, will increase the amount of variability in wind engineering parameters. Shown in Figure 10 are two examples of this variability. One example, from hurricane wind data in Schroeder (1999), shows the increase in variability by the reduction of time segment suggested in Section 3.3.3 with no time-varying mean values applied. The second example from stationary wind data at the WERFL site shows the difference in 100 s and 900 s time segements with the time-varying mean (averaging time) applied to SBL data.

Strong variability in physical thunderstorm characteristics such as vertical profiles of the horizontal wind and turbulence intensity (Choi, 2000; Choi and Hidayat, 2002) has also exacerbated the problem with codification of thunderstorm winds. Vertical profiles, and other thunderstorm characteristics (i.e. temporal scale), as shown in this document and in Lombardo et al. (in review) do display considerable variability, although due to the lack of data, the differences in probability distributions, if any, are difficult to determine. Regardless, In ASCE (2010), the differences would present themselves mainly in the gust-effect factor, a factor which accounts for wind turbulence-structure interaction in the along-wind direction. The gust-effect factor has also been analyzed for potential modification or addition due to the properties of thunderstorms or non-stationary events in Kwon and Kareem (2009). The gust effect factor, or G, in ASCE (2010) can be taken as 0.85 for rigid structures or as follows:

$$G = 0.925\left(\frac{1+1.7g_Q I_z Q}{1+1.7g_v I_z}\right) \qquad (12)$$

where g_Q and g_v are peak factors for background and wind response respectively, which are set equal to 3.4, I_z is turbulence intensity and Q accounts for background response. The wind engineering parameters GF, TI and longitudinal integral scale (L_{ux}) are all used in the computation of G. It has been suggested that peak and gust factor behavior should be considered using a different duration or time scale for thunderstorms (Chay et al., 2008).

The equations for turbulence intensity and background response can be found in ASCE (2010). The G values determined using Equation 12, were performed with three methods using the dimensions of the WERFL building (Levitan and Mehta, 1992) scaled up to a standard height of 10 m (33 ft) and a width of 23 m (~ 75 ft). To illustrate the variability of thunderstorm parameters, a simple example was constructed where wind engineering parameters using 34 s and approximately 5 min moving averages for both SBL and thunderstorm data were used in the computation of G. For the 5 min times, WTM GF and TI were also used in conjuction with SBL L_{ux} values from the WERFL site. Exposure C was the assumed terrain regime. The three methods:

1) Actual values using stationary wind data (642 events total)
2) Simulated values (N = 642) using the kernel density empirical cumulative distribution functions of thunderstorm and SBL wind data from WERFL using the inverse transform method (Rubinstein and Kroese, 2008) (42 events total)
3) Simulated values (N = 642) using the kernel density empirical cumulative distribution functions of thunderstorm and SBL wind data from WTM using the inverse transform method (83 events total)

The background response variable g_Q was kept constant at 3.4. As this analysis applies to only rigid structures, dynamically sensitive structures are also designed with respect to the vertical wind profile. The profiles differ significantly in some ramp-up events (Section 3.5) and consideration should be taken in future work.

Although the mean values are near equivalent for the 5 min averaging time, the increased variability is readily apparent for thunderstorm data using both WERFL and WTM data as shown in Figure 11 (left). This is likely due to the inherent non-stationarity at this averaging time. The variability is less apparent when a 34 s time-varying mean is applied to the data (Figure 11, left). In fact, the 5 min stationary and the 34 s thunderstorm data closely resemble each other with the exception of a slight right shift and heavier tail in the thunderstorm data. The distribution of the stationary data subjected to the 34 s averaging time is more peaked than the 273 s (~ 5 min) values, likely demonstrating the removal of inherent non-stationarities in the "stationary" data. In other studies, thunderstorm peak factors were found to most statistically similar to a 30 s stationary process (Chay et al., 2008). Distributions of ramp-up events were not modeled due to the small number of data points, so all thunderstorm events were used. This may mask differences in some thunderstorm events compared to stationary/non-thunderstorm data.

3. Conclusions

For wind engineering purposes, thunderstorms have traditionally been difficult to analyze and therefore have been prohibitive for comparisons with wind tunnel and SBL data. Due to this difficulty, a number of thunderstorm/ramp-up events were collected, described and analyzed in this paper. The objective of the work was to gain valuable insight on their characteristics and subsequent importance in wind engineering.

Evolutionary profiles in ramp-up events noted a transition from a "log" SBL profile to a uniform, or impinging jet profile. Momentum in evolutionary profiles seems to work downward over very short time scales (e.g. 30 s) This downward momentum shows coherency over a 10 s - 40 s period in some cases when considering the maximum peak wind speed at each measuring height. Impinging jet profiles were noted in cases when using a 68 s averaging time and below. Using higher averaging times would like "smooth" the profile, causing important information to be missed. Normalizing height of the maximum wind speed by the maximum measuring height revealed that ramp-up events, on average, occur at a lower height than in the

SBL, in which the maximum wind speed should be at the maximum measuring height. Regardless, different types of profiles were exhibited for ramp-up events and may encourage further discrimination by thunderstorm type.

Distributions of maximum vertical angle of attack and vertical angle of attack variance for thunderstorm events show no significant differences than that of the SBL. Turbulent components also show little difference and suggest the vertical component of the wind for thunderstorms will not affect low-rise buildings differently than the SBL. Further study should be devoted to heights corresponding to high-rise buildings and the tornadic boundary layer.

Most ramp-up gust factors exceed the bounds of the SBL at averaging times of 100 s, and all ramp-up gust factors exceed the bounds at 300 s. This further signifies the difference in time scales of two types of events and suggests the Durst curve should not be used for averaging times greater than a 100 s, and likely no greater than 60 s. Ramp-up gust factor behavior with averaging time using high resolution data resembles a cubic polyonomial. Lower resolution data fit fairly well to the polynomial at higher averaging times.

Thunderstorm parameters in this paper have illustrated their considerable variability, partly due to the lack of available data. A preliminary look at the gust effect factor suggests that the distributions between SBL and thunderstorm data may be different, and alternate defintions in standards of thunderstorm events, considering their variability, and other properties illustrated here, are likely warranted.

Acknowledegments

Jeff Livingston, Glenn Allen, Brad Coffman and George Riddick are acknowledged for their service at the Texas Tech University field site. Dr. Chris Weiss, Brian Hirth, Wesley Burgett, Pat Skinner and Jason McNeill asssited with some of the data acquistion. Thanks are extended to Kelsey Seger and Carol Ann Stanley of the Wind Science and Engineering department at Texas Tech for their logisitical and administrative support.

F.T. Lombardo finalized this work during his current tenure as a NIST/NRC Postdoctoral Research Associate. National Science Foundation (Grant No. 0221688) provided part of the funding for this research through support of F.T. Lombardo while a graduate student at Texas Tech University. Dr. Andy Swift of Texas Tech is also acknowledged for funding support provided through the Texas Wind Energy Institute.

References

Akyuz, F. (1994). "Thunderstorm peak gust estimation for structures", Ph.D. Dissertation, University of Missouri-Columbia, 84 pp.

American Society of Civil Engineers (ASCE). (2010). *Minimum design loads for buildings and other structures, ASCE/SEI 7-10,* Reston, VA.

Chay, M.T., Wilson, R., and Albermani, F. (2008). "Gust occurrence in simulated non-stationary winds", *J. Wind Eng. Ind. Aerodyn.,* **96**, 2161-2172

Chen, L., and Letchford, C.W. (2005). "Proper orthogonal decomposition of two vertical profiles of full-scale nonstationary downburst wind speeds", *J. Wind Eng. Ind. Aerodyn.*, **93**, 187-216

Choi, E.C.C. (2000). "Wind characteristics of tropical thunderstorms", *J. Wind Eng. Ind. Aerodyn.,* **84**, 215-226

Choi, E.C.C. (2004). "Field measurement and experimental study of wind speed profiles during thunderstorms", *J. Wind Eng. Ind. Aerodyn.,* **92**, 275-290

Choi, E.C.C., and Hidayat, F. A. (2002). "Gust factors for thunderstorm and non-thunderstorm winds", *J. Wind Eng. Ind. Aerodyn.,* **90**, 1683-1696

Duranona, V., Sterling, M., Baker, C.J. (2007). "An analysis of extreme non-synoptic winds", *J. Wind Eng. Ind. Aerodyn.,* **95**, 1007-1027

Ellingwood, B. and Tekie, P.B. (1999). "Wind load statistics for probability-based structural design", *J. Struct. Eng.*, **124**, 453-464

Fujita, T. (1985). *The Downburst*, SMRP 210, U. of Chicago Press

Giammanco, I.M., Schroeder, J.L., Powell, M.D., and Smith, D.A. (2008). "GPS dropwindsonde observations of tropical cyclone low-level wind maxima", Proc., 28^{th} Conference on Hurricanes and Tropical Meteorology

Haan, F.L., Balaramudu, V.K., Sarkar, P.P. (2010), "Tornado-Induced wind loads on a low-rise building", *J. Struct. Eng.,* **136**, 106-116

Holmes, J.D. (2001). *Wind Loading on Structures*. Spon Press, London-NY

Holmes, J.D., Hangan, H.M., Schroeder, J.L., Letchford, C.W., Orwig, K.D. (2008). "A forensic study of the Lubbock-Reese downdraft of 2002", *Wind and Structures*, **11**, 137-152

Kareem, A. (2008). "Numerical simulation of wind effects: A probabilistic perspective", *J. Wind Eng. Ind. Aerodyn*., **96**, 1472-1497

Kim, J. and Hangan, H. (2007). "Numerical simulations of impinging jets with application to downbursts", *J. Wind Eng. Ind. Aerodyn.,* **95**, 4, 279-298

Krayer, W.R., and Marshall, R.D. (1992). "Gust factors applied to hurricane winds", *Bull. Amer. Met. Soc.,* **73**, 613-618

Kwon, D. and Kareem, A. (2009). "Gust front factor: New framework for wind load effects on structures", *J. Struct. Eng.*, **135**, 6, 717-732

Lee, W.C., and Wurman, J. (2005). “The diagnosed structure of the Mulhall tornado”, *J. Atmos.Sci.*, **62**, 2373-2393

Letchford, C.W., and Marwood, R. (1997). “On the influence of v and w component turbulence on roof pressures beneath conical vortices”, *J. Wind Eng. Ind. Aerodyn.*, **69-71**, 567-577

Levitan, M. and Mehta, K.C. (1992). “Texas Tech field experiments for wind loads part II: meteorological instrumentation and terrain parameters”, *J. Wind Eng. Ind. Aerodyn.*, **41-44**, 1577-1588

Li, C.Q. (2000). "A stochastic model of severe thunderstorm for transmission line design", *Prob. Eng. Mech.*, **15**, 359-364

Lombardo, F.T. (2009a). *Analysis and Interpretation of Thunderstorm Wind Flow on a Bluff Body*, Ph.D. Dissertation, Texas Tech University, 259 pp.

Lombardo, F.T. (2009b). “Location and storm type effects in the estimation of extreme wind speeds”, *11th Americas Conference on Wind Engineering, San Juan, PR*, CD-ROM

Mason, M.S., Letchford, C.W., James, D.L. (2005). "Pulsed wall jet simulation of a stationary thunderstorm downburst, Part A: Physical structure and flow field visualization", *J. Wind Eng. Ind. Aerodyn.*, **93**, 557-580

Miller, C. (2007). “Defining the effective duration of a gust”, *Proc. 12th International Conf. on Wind Engineering*, Cairns, CD-ROM

Milton, J.S. and Arnold, J.C. (2003). *Introduction to Probability and Statistics: Principles and Applications for Engineering and the Computing Sciences*, McGraw-Hill, 798 pp.

Orwig, K.D. and Schroeder, J.L. (2007). “Near surface wind characteristics of extreme thunderstorm outflows”, *J. Wind Eng. Ind. Aerodyn.*, **95**, 565-58

Paulsen, B.M. and J.L. Schroeder, 2005: “An examination of tropical and extra-tropical gust factors and the underlying wind speed histograms”, *J. Applied Meteor.*, 44, 270-280.

Ponte, J. and Riera, J.D. (2007). "Wind velocity field during thunderstorms", *Wind and Structures*, **10**, 287-300

Ponte, J. and Riera, J.D. (2010). “Simulation of extreme wind series caused by thunderstorms in temperature latitudes”, *Struct. Safety*, **32**, 231-237

Rubenstein, R.Y and Kroese, D.P. (2008). *Simulation and the Monte Carlo method*, Wiley, 345 pp.

Schroeder, J.L. (1999). *Hurricane Bonnie wind flow characteristics*. Ph.D. Dissertation, Texas Tech University, 137 pp.

Schroeder, J.L, Burgett, W.S., Haynie, K.B., Sonmez, I., Skwira, G.D., Doggett, A.L. and Lipe, J.W. (2005). “The West Texas mesonet: A technical overview”, *J. Atmos. Ocean. Tech.*, **22**, 211-222

Schroeder, J.L., Weiss, C.C. and Guynes, J.G. (2009). “Innovative technologies to investigate fine scale atmospheric motions and their impact”, *Proc. 11th Americas Conference on Wind Engineering, San Juan, PR*, CD-ROM

Stull, R.B. (1988). *An Introduction to Boundary Layer Meteorology*, Kluwer, 666 pp.

Vega R. (2008). *Wind directionality: A reliability based approach*, Ph.D. Dissertation, Texas Tech University, 303 pp.

Wakimoto, R. (2001). “Convectively driven high wind events” *Severe Convective Storms*, Dowsell, C. ed.

Wang L. and Kareem, A. (2005). "Modeling and simulation of transient winds in downbursts/hurricanes" *Proc. 10th Americas Conf. on Wind Engineering*, Baton Rouge, LA

Wieringa, J. (1973). "Gust factors over open water and built up country", *Boundary Layer Met.*, **3**, 424-441

Wu, F. (2001). *Full-scale study of conical vortices and their effects on roof corners*, Ph.D. Dissertation, Texas Tech University, 198 pp.

Yu, B. and Chowdury, A.G. (2009). “Gust factors and turbulence intensities for the tropical cyclone environment”, *J. Appl. Met. Clim.*, **48**, 534-552

Tables

Table 1. Summary of ramp-up thunderstorm events.

Date	Measured	Storm Type	Temporal Scale (s)	Peak Wind (mph)	Profile
June 19, 2003	160 ft Tower	Non-Supercell	100	~60	Yes
May 20, 2006	200 m Tower	Non-Supercell	200	~60	No
May 14, 2008	StickNet	Supercell	250	~80	No
May 21, 2008	200 m Tower	Non-Supercell	170	~70	Yes
June 19, 2008	200 m Tower	Non-Supercell	75	~60	Yes
August 14, 2008	200 m Tower	Non-Supercell	150	~60	Yes
June 4, 2009	200 m Tower	Bow Echo/Supercell	300	~80	Yes
August 12, 2009	200 m Tower	Non-Supercell	75	~60	Yes

Table 2. The averaging times, *t*, used in the computation of residual turbulence

Number	*t(s)*	*Number*	*t(s)*
1	1.1	11	34.1
2	1.6	12	51.2
3	2.1	13	68.3
4	3.2	14	102.4
5	4.3	15	136.5
6	6.4	16	204.8
7	8.5	17	273.1
8	12.8	18	409.6
9	17.1	19	546.1
10	25.6	20	723

Figure Captions

Fig. 1. Evolutionary profiles for three ramp-up cases

Fig. 2. “Tracking” of peak wind speeds at each measurment height.

Fig. 3. Maximum gust profiles for averaging times of 3 s, 8 s, 34 s, 68 s and 136 s. Maximum 3 s profile is on the far right and increasing averaging times continue to the left respectively. Note “impinging jet” profile for averaging times < 68 s for March 8, 2010 event and < 136 s for August 12, 2009 event.

Fig. 4. Various mean and gust profiles for the SBL and those prescribed in ASCE. “SBL Gust” refers to the mean 3 s maximum profile for 642 events, while “SBL Mean” is the mean 15 min profile for 642 events. “Low Max” refers to an individual profile that did not fit a log profile.

Fig. 5. Maximum gust profiles for averaging times of 3 s, 8 s, 34 s, 68 s and 136 s. Maximum 3 s profile is on the far right and increasing averaging times continue to the left respectively. Note “uniform” gust profile for May 21, 2008 event and a “log” gust profile for the June 4, 2009 event.

Fig. 6. Illustration showing measurement of vertical angle of attack.

Fig. 7. Vertical angle of attack (β) for March 8, 2010 event. Black solid lines and gray solid line indicates 1 s and 60 s “turbulent” and “mean” vertical angle attack and dotted, gray vertical line indicates the time of the peak wind speed.

Fig. 8. Ramp-up GFs compared to those of the WERFL SBL. The range and the 10^{th} and 90^{th} percentile of the SBL GF’s are denoted by black dashed lines. Black dots represent ramp-up GF’s at 10 m, while the light gray dot is taken at 2.25 m (7 ft) and the dark gray dot is at 17 m (55 ft). Residual turbulence plot showing event outside of bounds of 34 s averaging time shown top left.

Fig. 9. Hypothetical mean GF curve (gray, solid line). Dotted gray lines indicate ± 1 standard deviation of the ramp-up GF’s. Solid black line is the Durst Curve as shown in ASCE (2010). Other symbols are GFs from other studies (‘*’ Akyuz (1994), ‘x’, Choi (2002) and ‘+’ Holmes et al. 2008). Errorbars with ‘.’ marker indicate mean WTM GF’s and their respective standard deviations for given averaging times.

Fig. 10. Two examples of increased variability with shorter averaing time/moving average.

Fig. 11. Illustration on left shows the increased variability for thunderstorm data in the Gust Effect Factor, G, when using 273 s averaged wind engineering parameters. Image on right shows the reduction in variability when using a 34 s averaging time.

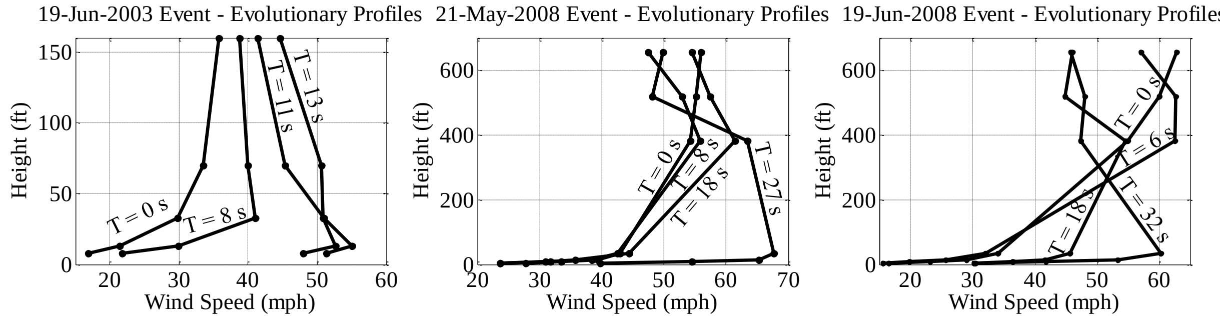
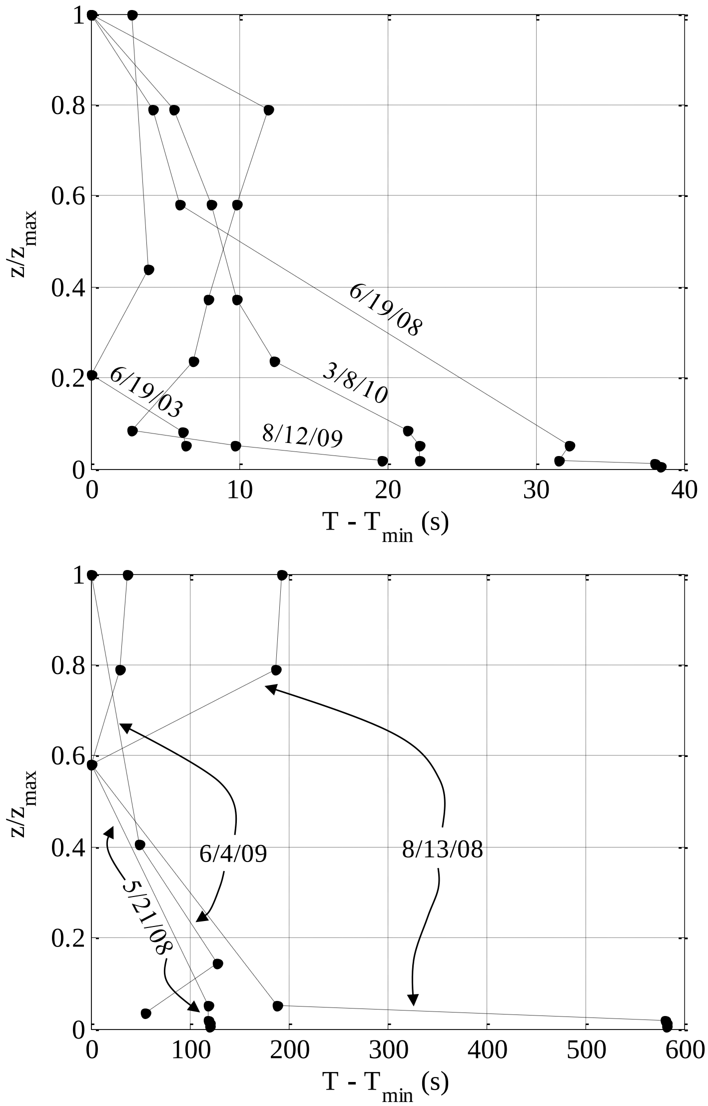

19-Jun-2003 Event - Evolutionary Profiles
Height (ft)
Wind Speed (mph)
T = 0 s
T = 8 s
T = 11 s
T = 13 s
0
50
100
150
20
30
40
50
60
21-May-2008 Event - Evolutionary Profiles
Height (ft)
Wind Speed (mph)
T = 0 s
T = 8 s
T = 18 s
T = 27 s
0
200
400
600
20
30
40
50
60
70
19-Jun-2008 Event - Evolutionary Profiles
Height (ft)
Wind Speed (mph)
T = 0 s
T = 6 s
T = 18 s
T = 32 s
0
200
400
600
20
30
40
50
60

Figure 1



1
0.8
0.6
0.4
0.2
0
z/z_max
0
10
20
30
40
T - T_min (s)
6/19/08
3/8/10
6/19/03
8/12/09
1
0.8
0.6
0.4
0.2
0
z/z_max
0
100
200
300
400
500
600
T - T_min (s)
6/4/09
8/13/08
5/21/08

Figure 2

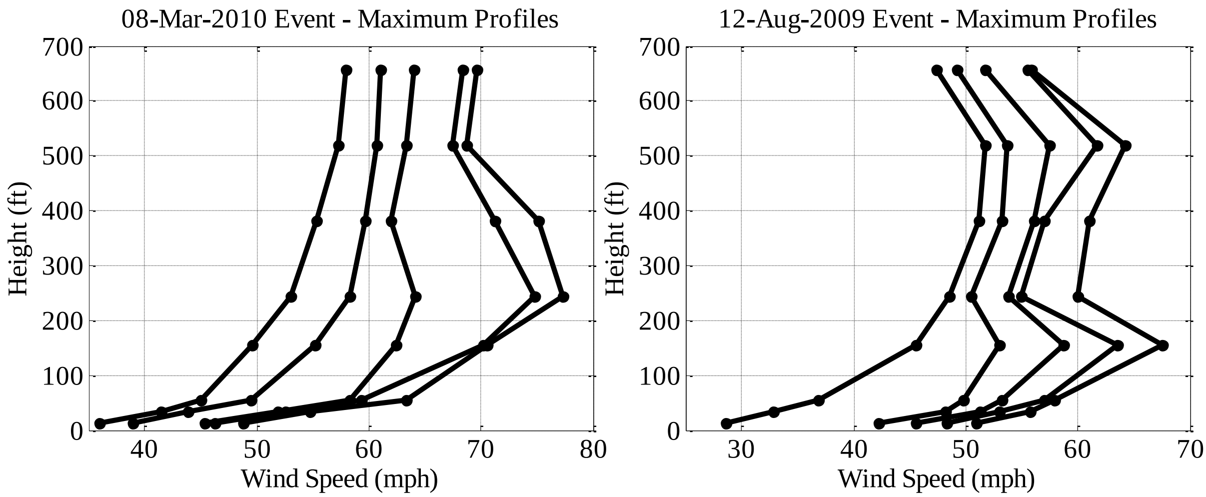
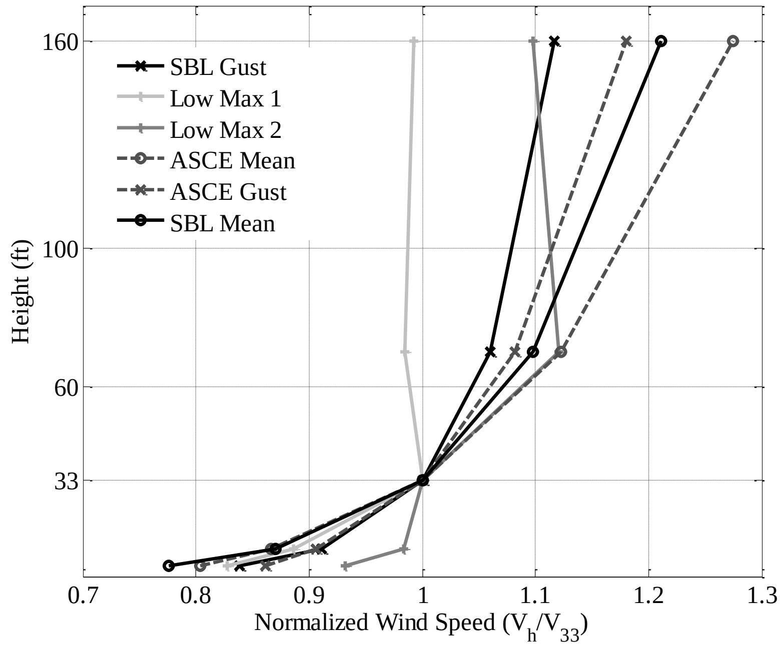

08-Mar-2010 Event - Maximum Profiles
Height (ft)
Wind Speed (mph)
0
100
200
300
400
500
600
700
40
50
60
70
80
12-Aug-2009 Event - Maximum Profiles
Height (ft)
Wind Speed (mph)
30
40
50
60
70

Figure 3



SBL Gust
Low Max 1
Low Max 2
ASCE Mean
ASCE Gust
SBL Mean
Height (ft)
160
100
60
33
0.7
0.8
0.9
1
1.1
1.2
1.3
Normalized Wind Speed (V_h/V_{33})

Figure 4

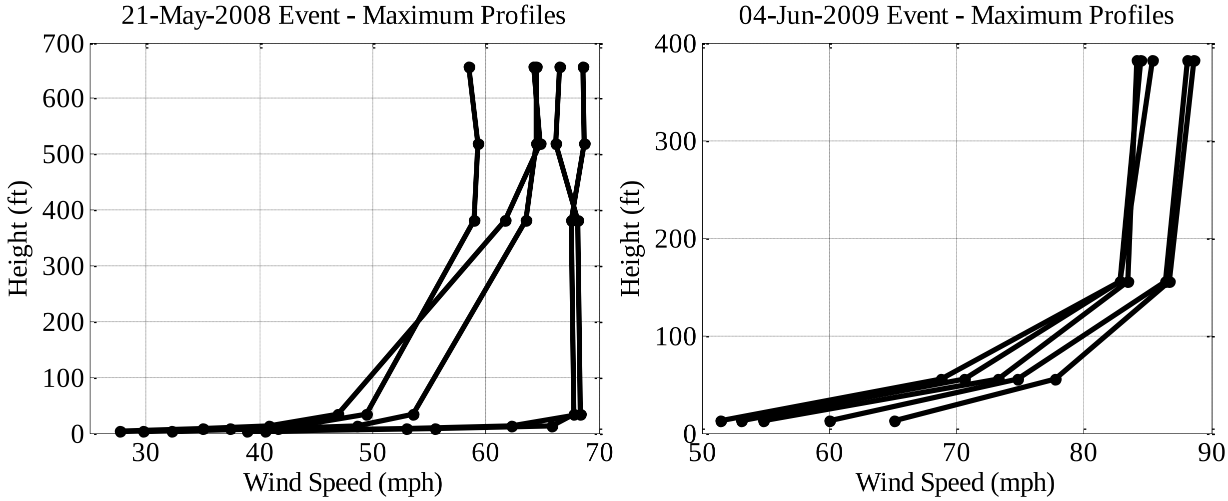

21-May-2008 Event - Maximum Profiles
Height (ft)
Wind Speed (mph)
0
100
200
300
400
500
600
700
30
40
50
60
70
04-Jun-2009 Event - Maximum Profiles
Height (ft)
Wind Speed (mph)
0
100
200
300
400
50
60
70
80
90

Figure 5

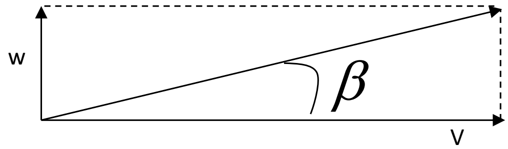
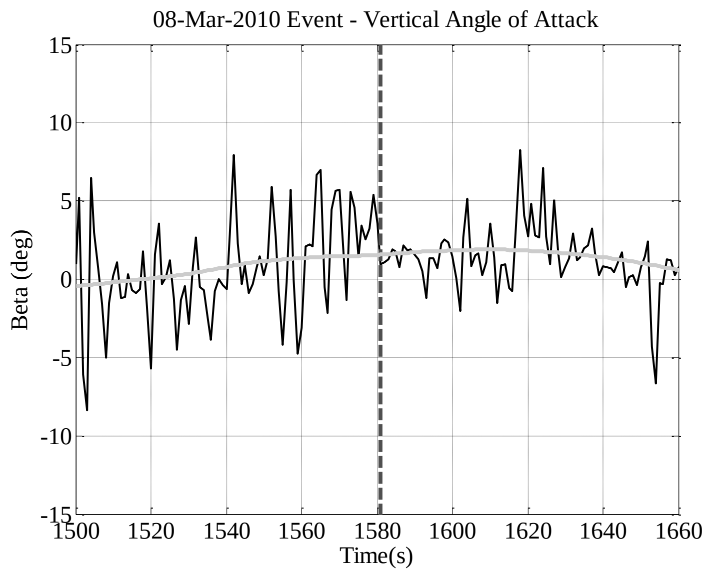
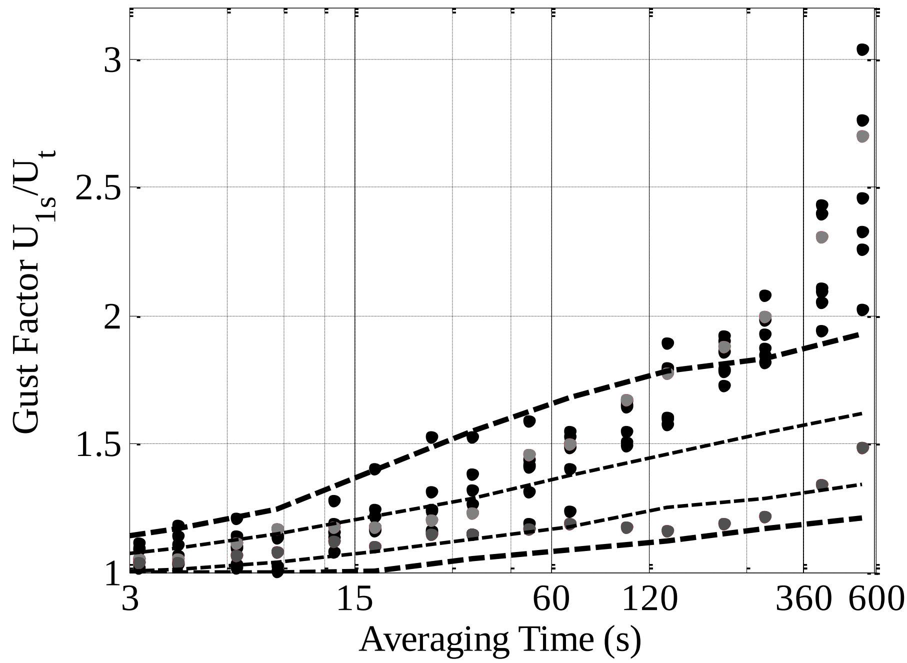


Figure 6



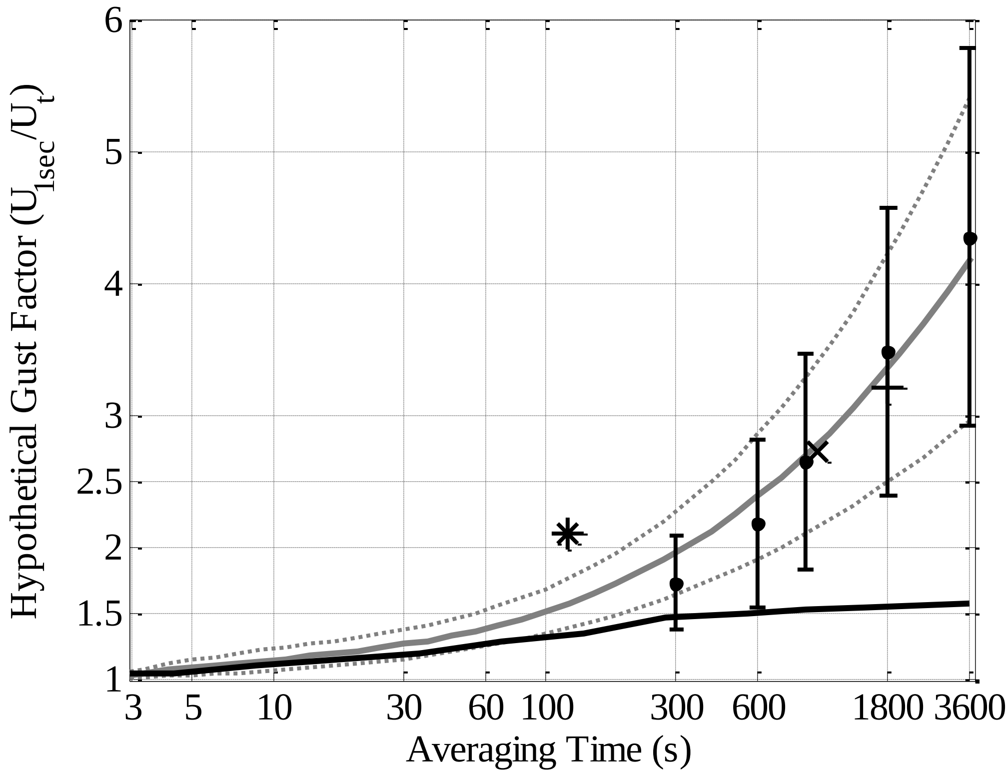
08-Mar-2010 Event - Vertical Angle of Attack
15
10
5
0
-5
-10
-15
Beta (deg)
1500
1520
1540
1560
1580
1600
1620
1640
1660
Time(s)

Figure 7



3
2.5
2
1.5
1
Gust Factor U_{1s}/U_t
3
15
60
120
360
600
Averaging Time (s)

Figure 8



Hypothetical Gust Factor (U_{1sec}/U_t)
6
5
4
3
2.5
2
1.5
1
3
5
10
30
60
100
300
600
1800
3600
Averaging Time (s)

Figure 9

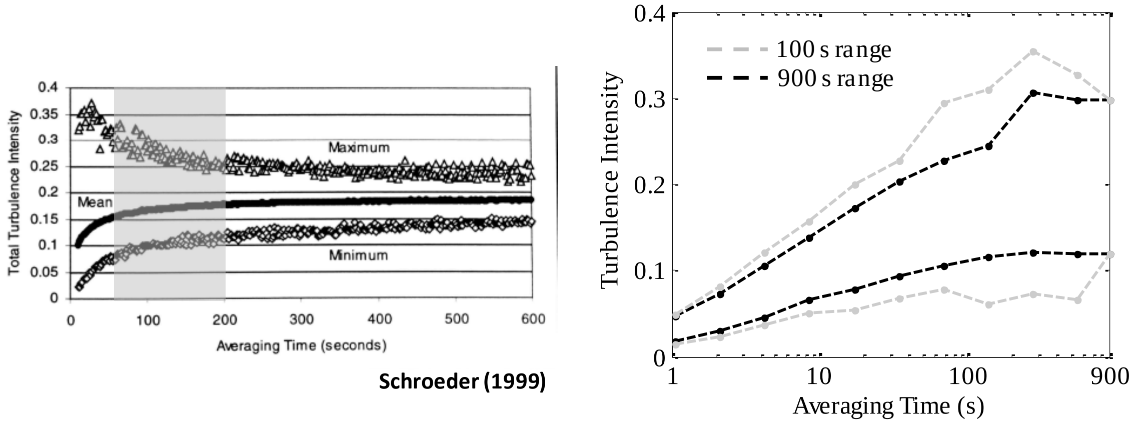
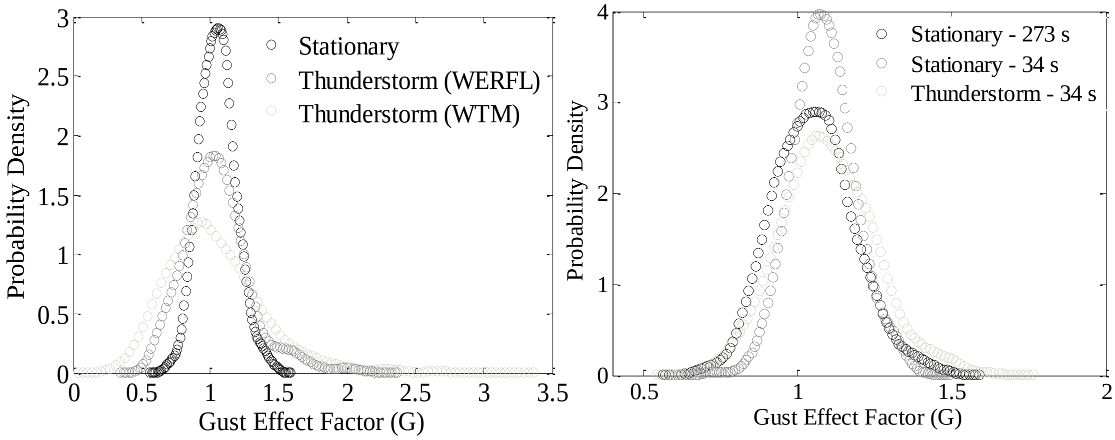

Total Turbulence Intensity
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Maximum
Mean
Minimum
0
100
200
300
400
500
600
Averaging Time (seconds)
Schroeder (1999)
Turbulence Intensity
0.4
0.3
0.2
0.1
0
100 s range
900 s range
1
10
100
900
Averaging Time (s)

Figure 10



Probability Density
Stationary
Thunderstorm (WERFL)
Thunderstorm (WTM)
Gust Effect Factor (G)
0
0.5
1
1.5
2
2.5
3
3.5
Probability Density
Stationary - 273 s
Stationary - 34 s
Thunderstorm - 34 s
Gust Effect Factor (G)
0.5
1
1.5
2
3
4

Figure 11