11C.1 PROBABILITY DISTRIBUTIONS OF GUST FACTORS IN LAND-FALLING HURRICANES

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1.0 INTRODUCTION

In 2004, hurricanes Frances (25 August - 8 September) and Jeanne (13 - 28 September) passed close enough to Cape Canaveral Air Force Station (CCAFS) and the John F. Kennedy Space Center (KSC) to cause several hours each of sustained tropical storm force winds. These two storms provided a unique opportunity to study the horizontal and vertical distribution of various aspects of the wind field under tropical storm conditions since the wind towers and their associated data acquisition systems remained largely operational during the two events. The variation of the mean winds with height and location is being investigated elsewhere (John Schroeder, Texas Tech University, private communication). This study is limited to an examination of the properties of the gust factor.

Knowledge of both mean and peak winds is important to protection of high value assets and personnel at a spaceport like CCAFS/KSC (Lambert *et al.*, 2008). Forecast models and official predictions provide quantitative and generally reliable guidance about what the expected mean winds will be near the surface. Often, however, peak wind forecasts tend to be both less precise and less reliable (*ibid*). This study was undertaken to enable forecasters at the 45th Weather Squadron (45WS) to apply quantitative gust factors to the reliable forecasts of mean winds to assess the probability that peak wind constraints for operational assets at CCAFS/KSC will be violated during tropical storm events.

Ultimately it is hoped that the complete probability distribution of the gust factor can be modeled as a function of mean windspeed and height. That is a more ambitious undertaking than the one reported here. This report is limited to modeling the variation of the average value and standard deviation of the gust factor. It does not suffice to define the complete probability distribution unless the distribution is of a type, such as the Gaussian, that is fully defined by these two parameters. Unfortunately, the data do not appear to be distributed in such a convenient manner. Section 5.3 addresses future work to be undertaken to more completely specify the distribution.

Section 2 describes the data used in the study. Section 3 describes the analysis methodology, including the determination that certain data should be eliminated from the analysis because their behavior was inconsistent with all of the other available data. Section 4 presents the models developed from the analysis. The paper concludes with a discussion in section 5.

2.0 THE DATA

This study defines the Gust Factor (GF) as the ratio of the peak 1-second windspeed in a 5-minute period to the average windspeed over that period. The definition is used at each height for which tower data was available. This differs from the definition in Federal Coordinator for Meteorological Services and Supporting Research (2005) (hereafter FMH1) which is used operationally by the Air Force (William Roeder, private communication). FMH1 defines "gust factor" based on a 10-minute averaging period and only at the standard surface observing height of 10 meters. The professional literature relating to gust factors in tropical storms contains a much broader range of averaging periods and observation heights as may be seen from the papers cited elsewhere in this report. The operational constraints for which peak winds are significant occur at a variety of heights, most of which are not 10m. Limiting the definition of GF to observations at 10 m would defeat the purpose of the analysis. The data base of Eastern Range wind data contains both 5 and 10-minute averages, but using the 10-minute averaging period would cut the sample size in half. The sample sizes were smaller than desired for assessment of third and fourth moments or extreme values in the distribution of the GF even with the 5-minute averages, and it was not acceptable to reduce them by another factor of two.

2.1 The Measurements

Wind measurements were obtained from the KSC archive (http://trmm.ksc.nasa.gov) of Eastern Range wind towers at CCAFS/KSC. The tower network is described in detail in the Eastern Range Instrumentation Handbook (Computer Sciences Raytheon, 2006). Each tower is instrumented at one or more levels with commercial R.M. Young propeller/vane anemometers. Towers designated "launch and safety critical" are equipped with model 05305-18, which was specially modified for use on the Eastern Range. The remaining towers have model 05103 in its standard commercial version. Both models have a wind speed accuracy of 0.3 ms^{-1} or about 0.6 kt. The distance constant for model 05305-18 is listed as ≤ 5.2 m while that for model 05103 is given as 2.7 m. At the wind speeds involved in this report, both distance constants correspond to effective response times of less than 0.3 seconds. The wind direction accuracy for both models is 3 degrees with a delay distance of 1.3 m which is equivalent to a delay time of less than 0.1 second under the conditions of this study.

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Because of the tropical storm conditions, not every tower in the network was reporting data and some multiple level towers did not report every level. Some towers were available for both storms, and others for only one of the two storms. Some towers were eliminated from consideration because their measurements were too intermittent or only available at wind speeds well below tropical storm force. Table 1 presents the list of towers available for this study. Some were eliminated after reviewing their records. Figure 1 shows where they are located. Most have their four digit identification number in the figure. The first two digits correspond to the distance (n. mi.) west from the coastline. The last two digits correspond to the distance (n. mi.) north from Port Canaveral. In this study, some of the tower identification codes were modified slightly.

For each sensor on each tower, for each 5-minute period, the mean wind speed for the period, 1-second peak wind speed within the period, mean wind direction for the period and direction of the peak wind within the period were available as a function of time. Wind speeds were reported in integral knots and wind directions in integral degrees from true north. One knot equals 0.515 ms^{-1}. Knots are used as the primary unit of windspeed in this report because both the data base and the operational requirements are in that unit.

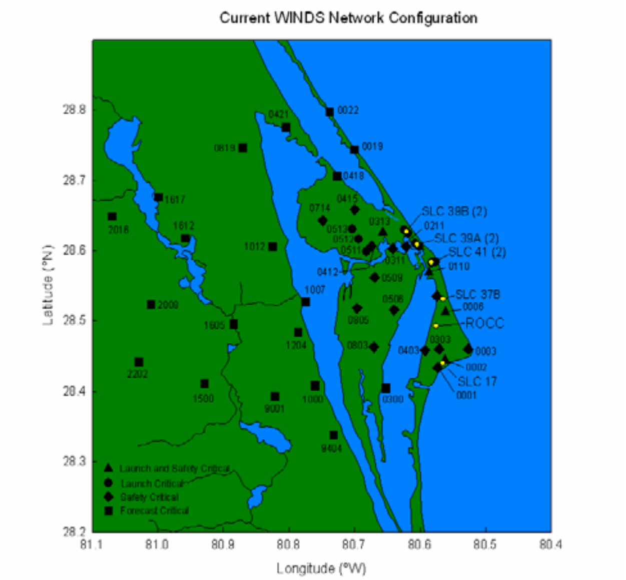

Figure 1. Location of the wind towers in the Eastern Range network. The figure is taken from Figure 1.1-1 of Computer Sciences Raytheon, 2006. The indicated location of the ROCC is incorrect, but has no bearing on this study. The actual location is just southwest of tower 0001.

2.2 The Storms

2.2.1 Frances

Hurricane Frances formed from a vigorous tropical wave that left the coast of Africa on 21 August. Details of its evolution and track may be found in a variety of sources including Beven (2004). It passed through the northern Bahamas on 2 - 4 September and crossed the Florida coast about 90 n. mi. (167 km) south of Cape Canaveral late on Saturday, 5 September. Its closest approach to the Cape was about 70 n. mi. (130 km) to the southwest Sunday morning, 6 September. The Eastern Range was subjected to sustained tropical storm force winds and rain squalls that produced numerous power outages and damaged homes and businesses throughout central Florida. Wind tower data to the KSC archive was lost, presumably due to loss of power, at about 8 AM local time (1200 UTC) on Saturday, well before the storm made landfall. Winds at the Eastern Range had reached gale force and were increasing rapidly at the time archiving ceased. The wind direction over the tower network remained within 30 degrees of 060 degrees (ENE) throughout period for which storm data were available.

2.2.2 Jeanne

Hurricane Jeanne formed from a tropical wave that left the coast of Africa on 7 September. Details of its evolution and track may be found in a variety of sources including Lawrence and Cobb (2005). It passed through the northern Bahamas on 25 September and crossed the Florida coast about 100 n. mi. (185 km) south of Cape Canaveral on Saturday afternoon, 25 September. Its closest approach to the Eastern Range was about 80 n mi (148 km) to the southwest early Sunday. The Range was again subjected to sustained tropical storm force winds and rain squalls that produced numerous power outages and damaged homes and businesses throughout central Florida. Both the track and the intensity were similar to Frances. Wind tower data to the KSC archive were not lost this time, however, and wind speeds peaked around 8 AM local time (1200 UTC) Sunday morning. The wind direction over the wind tower network varied nearly linearly with time beginning at 020 degrees (N) at 0000 UTC on the 26th, sweeping through the easterly semicircle, and ending at 170 (S) degrees at 0200 UTC on the 27th. There was no indication that the change in wind direction affected any of the measurements.

3.0 THE ANALYSIS METHODOLOGY

3.1 Data Stratification

A brief perusal of the technical literature showed that the gust factor is a function of averaging time (Durst, 1960) and roughness length (Schroeder *et al.*, 2002; Paulsen and Schroeder, 2005). There is also a suggestion that it is a decreasing function of mean wind speed (Vickery and Skerlj, 2005; Schroeder *et al.*, 2005). Given these dependencies, it seemed likely that it might also be a function of height above ground and stability. In

	Levels (feet AGL)											
TowerID	**12**	**30**	**54**	**60**	**90**	**145**	**162**	**204**	**295**	**394**	**492**	**Notes**
0001	X		X									
0003	X		X									
0019			X									
0020	X		X		X	X		X				Tower 0002 NW
0021	X		X		X	X		X				Tower 0002 SE
0022			X									
0036					X							
0061	X		X				X	X				Tower 0006 NW
0062	X		X				X	X				Tower 0006 SE
0108	X		X									
0211	X		X									
0300			X									
0303	X		X									
0311	X		X									
0397				X								39B NWCS
0403	X		X									
0412	X		X									
0415	X		X									
0418			X									
0509	X		X									
0511		X										SLF S
0512		X										SLF C
0513		X										SLF N
0714	X		X									
0803	X		X									
0819			X									
1007			X									
1012			X									
1101	X		X				X	X				Tower 0110 NW
1102	X		X				X	X				Tower 0110 SE
1204			X									
1500			X									
1605			X									
1612			X									
2008			X									
2016			X									
2202			X									
3131	X		X				X	X	X	X	X	Tower 0313 SW
3132	X		X				X	X	X	X	X	Tower 0313 NE
9001			X									
9404			X									

Table 1. Towers initially available for the gust factor analysis.

addition, the scatter (variance) in the gust factor as a function of windspeed appears to increase markedly at lower wind speeds (Vickery and Skerlj, 2005; Schroeder *et al.*, 2005).

For the reasons stated above, the data were stratified by storm, tower, height and mean wind speed for analysis. This provided statistically significant sample sizes ($N \geq 30$) without masking the expected variations. Although they may be significant variables, no attempt was made to determine either the stability or the site roughness lengths, and those dependencies are not part of this study.

The towers were divided into two groups by height for analysis. The first group contained all towers having levels above 54 ft (16.5 m). These were called "tall towers", and they were used to examine the variation of the gust factor with height as well as wind speed. The second group was the large number of towers with data only from a height of 54 ft and, in most cases, 12 ft(3.7 m). The 54 ft data from these towers provided a much larger statistical sample size for evaluating the variation of the gust factor with wind speed at a fixed height. It also facilitated a coarse evaluation of whether there were major geographical effects due to the differing locations of the towers. The 54 ft level from the tall towers was included in this set as well as in the tall towers set. The 12 ft data from the second set of towers was not used for this application because the variation with location at that height was expected to be dominated by site-specific effects like sheltering by nearby shrubbery. The 12 ft data from the tall towers was considered with caution in examining the variations with height.

Wind speeds were grouped into bins as shown in Table 2. Mean wind speeds less than 15 kt (7.7 ms^{-1}) were excluded because a quick visual examination of scatter plots showed that, consistent with the literature, the variability of the gust factor became too large for quantitative analysis below that speed.

Bin [Nominal Mean WS in Kt. (ms^{-1})]	**Minimum WS**	**Maximum WS**
20 (10.3)	15 (7.7)	24 (12.4)
30 (15.5)	25 (12.9)	34 (17.5)
40 (20.6)	35 (18.0)	44 (22.7)
50 (25.8)	45 (23.2)	N/A

Table 2. Wind speed bins and associated minimum and maximum mean wind speeds in kt (ms^{-1})

A separate analysis was done for each storm and for each tower. Several of the tall towers had instruments on two sides of the tower. In those cases, each side was processed separately as if it were an independent, co-located tower.

3.2 The Period of Record

For both storms, the period of record was limited to the period of time during which the influence of the storm was plainly visible in the time series of the mean and peak wind speed data. For Frances, the period began at 1200 UTC on 4 September and ended with loss of the archive at 1200 UTC on 5 September (24 hours). For Jeanne, there was no loss of power and the selected period of record was 1800 UTC on 25 September through 0700 UTC on 27 September (37 hours).

3.3 The Statistics

For each stratification of the data (specified storm, tower, height, and speed bin) the following statistics were computed for each of the following variables:

Variables
- Mean windspeed
- Peak windspeed
- Gust factor
- Mean wind direction
- Peak wind direction

Statistics
- Sample size (count)
- Minimum
- Median
- Maximum
- Variance
- Average
- Standard deviation
- Skewness coefficient
- Kurtosis coefficient

The computations were all done using Microsoft Excel®. The kurtosis coefficient produced by Excel was modified by adding 3.0 to provide a true fourth moment. So defined, the kurtosis coefficient for a Gaussian distribution is 3.0.

3.4 Combining Stratifications and Eliminating Anomalous Towers

Examination of the initial results showed several important things. First, with one exception to be described next, there were no significant differences between the two storms, between opposite sites of towers with dual instrumentation or between the different tall towers. The modeling could be based on stratification by height and wind speed only, thus increasing the sample size and, thus, the reliability of the resulting regression equations. Figures 2 and 3 demonstrate this commonality. Figure 2 shows the gust factors for Jeanne as a function of the gust factors for Frances in the same stratification by height, wind speed bin and tower. Figure 3 shows the gust factors from the opposite sides of tower 0002 at the same height and wind speed bin. The figure for tower 110 (not shown) was similar. Tower 313 is discussed next.

The exception mentioned earlier relates to data from the northeast side of tower 313 (313NE) during Frances.

They were not consistent with data from any of the other towers including 313 SW or with 313NE during Jeanne. Figure 4 shows the comparisons of tower 110 with towers 002, 313 NE and 313 SW. Although 002 and 313 SW stayed within about 10% of each other and 110, 313 NE differed by as much as 25 percent and in a non-systematic manner. In addition, there was some hint that 313NE was also compromised during Jeanne, though to a lesser extent, because 313SW and 313NE also did not agree well in that storm. As a result, the northeast side of tower 313 was eliminated from the data set in both storms. The southwest side of 313 was retained.

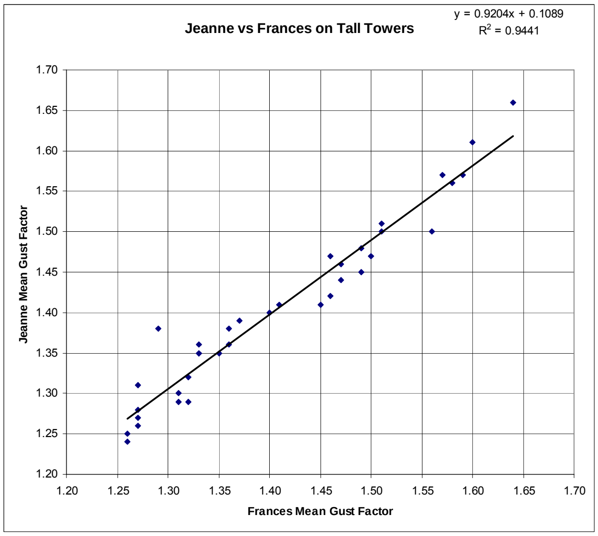

Figure 2. Mean gust factors in Jeanne as a function of the mean gust factor in Frances for the same tower, height and wind speed bin. The line is a linear regression with the equation J = 0.9204F + 0.1089 with r^2 = 0.9441.

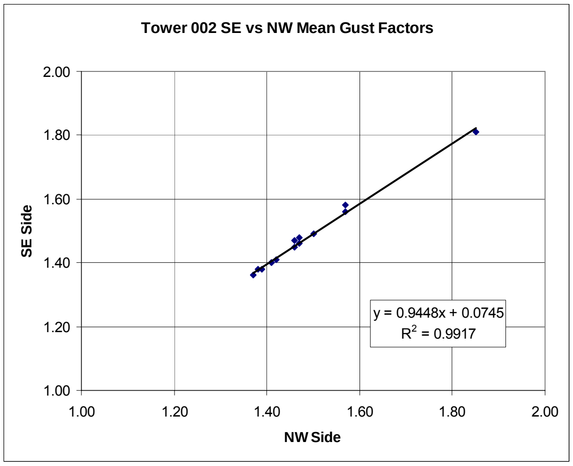

Figure 3. Comparison of the two sides of tower 0002. The line is a linear regression for which the equation and r^2 are shown on the figure.

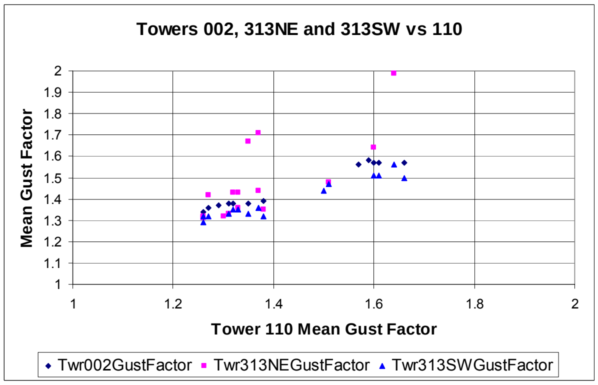

Figure 4. Mean gust factors for the towers 002, 313NE and 313SW as a function of the mean gust factor at tower 110 for each set having the same storm, height and mean windspeed bin.

4.0 THE MODELS

For both the mean of the gust factor (GF) and its standard deviation, models were derived from the measurements using the Pivot Table capability in Excel. The Pivot Tables displayed the gust factor or its standard deviation from each level at each tower for each storm and windspeed bin and averaged the results. These averages for each height and speed bin pair were used as the basis for the models. Regressions, not necessarily linear, were taken of each variable (GFmean or GFstddev) against height for each wind speed bin and against wind speed bin for each height.

Once regressions were obtained for the dependent variable Z (GFmean or GFstddev) as a function of either X (height) or Y (speed), the parameters of the regression equations were themselves then fitted against the remaining independent variable. That is, if Z(X, a, b) is obtained from the regression of Z against X where a and b are parameters that differ for each value of Y, then a and b are fitted to separate functions of Y. The result is a single model of the form Z = Z (X; a(Y; c, d), b (Y; e, f)) where c, d, e, and f are coefficients of the fits of the parameters to Y.

There are two ways of obtaining the final result since the original regression of Z may be taken against either X or Y. The method producing the simplest equations was selected and is reported below.

4.1 Modeling the Mean GF

The matrix for the mean of the gust factor is shown in Table 3. Empty cells are those for which no data were available. At higher levels, the wind speeds tended to be higher and the 20 Kt bin was often empty. At the highest wind speeds, only the higher levels had data.

Height [ft (m)]	Bin20	Bin30	Bin40	Bin50
12 (3.7)	1.96	1.77		
54 (16.5)	1.60	1.57	1.48	
90 (27.4)		1.49	1.47	
145 (44.2)		1.44	1.41	
162 (49.4)	1.46	1.37	1.35	1.31
204 (62.2)		1.35	1.34	1.28
295 (89.9)		1.28	1.27	1.26
394 (120.2)			1.23	1.22
492 (150)			1.21	1.20

Table 3. Mean gust factor as a function of height and wind speed bin

Figure 5 presents the data in graphical form. A power fit of the form GFmean = a * Hgt^b provided high values of r^2 and good visual appearance on the graphs. Table 4 presents the values of parameters a and b for each wind speed bin.

Figure 6 presents Table 4 in graphical form. Table 5 shows the parameters returned by a linear regression of a and b as a function of wind speed.

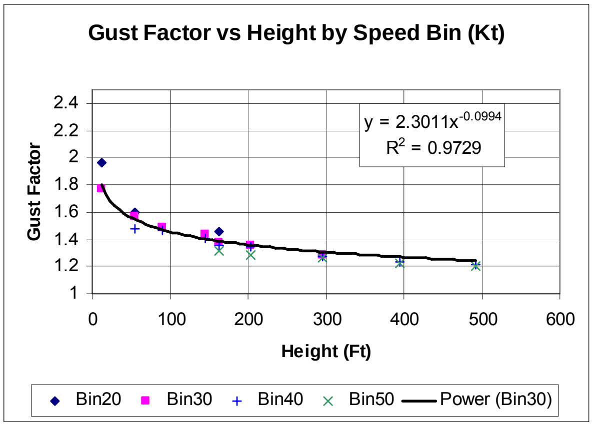

Figure 5. Mean gust factor as a function of height for each wind speed bin. The regression line for Bin30 is also shown.

Series	a	b	r2
Bin20	2.5811	-0.1145	0.9844
Bin30	2.3011	-0.0994	0.9729
Bin40	2.2763	-0.1014	0.9526
Bin50	1.9371	-0.0770	0.9818

Table 4. Parameters a and b of the power law fit for the mean gust factor as a function of height for each wind speed bin.

These results are combined into the final model for the mean gust factor as a function of height and windspeed. Given the height H and the windspeed WS, the mean gust factor GF is given by

$$GF = aH^b \quad \text{where} \quad a = 2.9588 - 0.0196\ WS \quad \text{and} \quad b = 0.0011\ WS - 0.1368 \qquad (1)$$

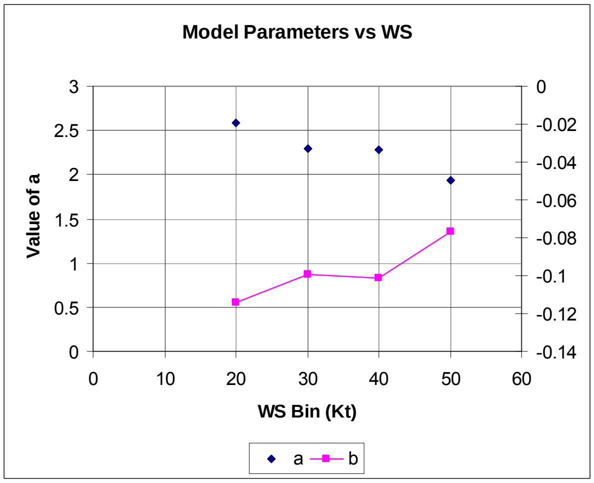

Figure 6. Values of the parameters presented in table 4 as a function of wind speed. The linear regression for parameter b is also shown. Regressions based on only four points should be used with caution.

Parameter	A	B	r2
a	2.9588	-0.0196	0.9180
b	-0.1368	0.0011	0.8401

Table 5. Linear fits of form Y=A + BX for parameters a and b as a function of wind speed.

Figure 7 shows the performance of the model against the observations.

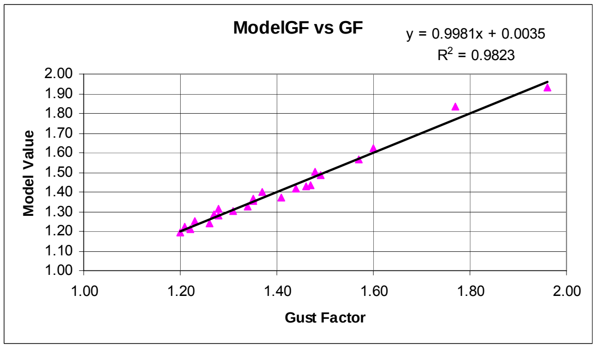

Figure 7. Modeled mean gust factor as a function of observed mean gust factor.

4.2 Modeling the Standard Deviation of the GF

Table 6 shows the standard deviation of the gust factor. Empty cells are those for which no data were available for the same reasons discussed in section 4.1. Figure 8 presents these data in graphical form. As with the mean, a power law fit the data well. Table 7 presents the regression results. Although the regressions account for less of the variance at the higher wind speeds, the end result works well at all wind speeds.

Height [ft (m)]	Bin20	Bin30	Bin40	Bin50
12 (3.7)	0.172			
54 (16.5)		0.103		
90 (27.4)		0.090		
145 (44.2)			0.065	
162 (49.4)		0.070	0.063	0.053
204 (62.2)		0.073	0.063	0.058
295 (89.9)		0.070	0.060	0.050
394 (120.2)			0.060	0.040
492 (150)			0.060	0.050

Table 6. Standard deviation of the gust factor as a function of height and wind speed bin

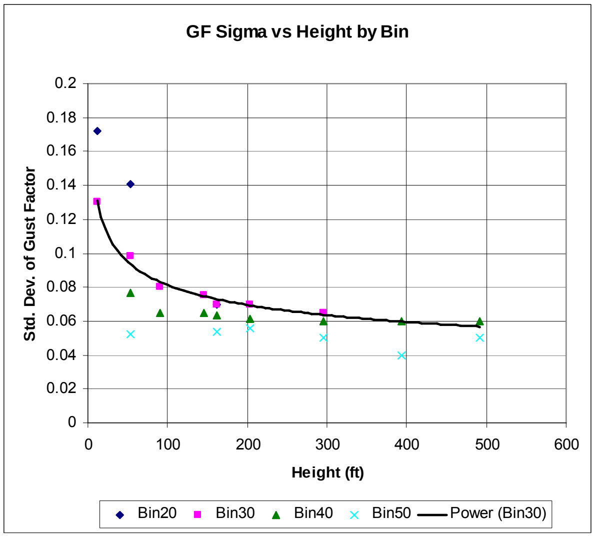

Figure 8. Standard deviation of the gust factor as a function of height for each wind speed bin. The regression line for Bin30 is also shown.

WS Bin [Kt (ms^{-1})]	a	b	r2
20 (10.3)	0.4297	-0.3329	0.8507
30 (15.5)	0.2294	-0.2253	0.9813
40 (20.6)	0.1075	-0.1003	0.7880
50 (25.8)	0.0742	-0.0732	0.2413

Table 7. Parameters a and b of the power law fit for the standard deviation of the gust factor as a function of height for each wind speed bin.

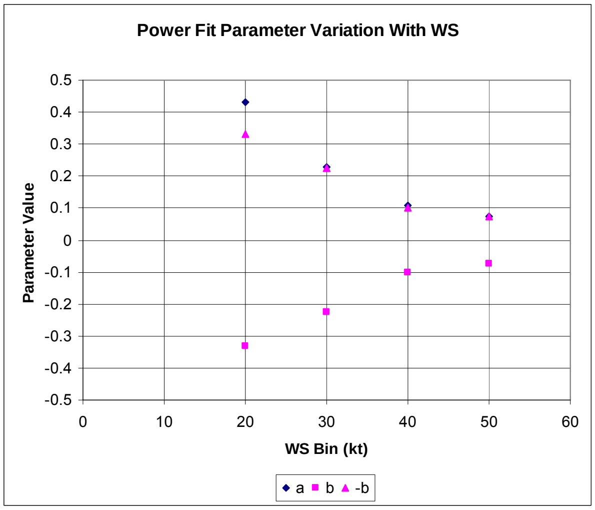

Figure 9. Values of the parameters presented in table 7 as a function of wind speed. The negative of b was included to enable testing a power law fit since Excel cannot fit a power law to negative numbers and b is negative.

The graphs in figure 9 are obviously curved and so a linear fit was not attempted. Instead, both logarithmic and power fits were tried. The best results were as follows:

$a = 165.77\ WS^{-1.9711}$ with $r^2 = 0.988$ and

$b = 0.2995 \ln(WS) - 1.2312$ with $r^2 = 0.976$.

As noted regarding Figure 6, regressions based on only four data pairs should be viewed with caution.

These results are combined into the final model for the standard deviation of the gust factor as a function of height and windspeed. Given the height H and the windspeed WS, the gust factor standard deviation (GFs) is given by

$GFs = aH^b$ where
$a = 165.77\ WS^{-1.9711}$ and
$b = 0.2995 \ln(WS) - 1.2312.$ (2)

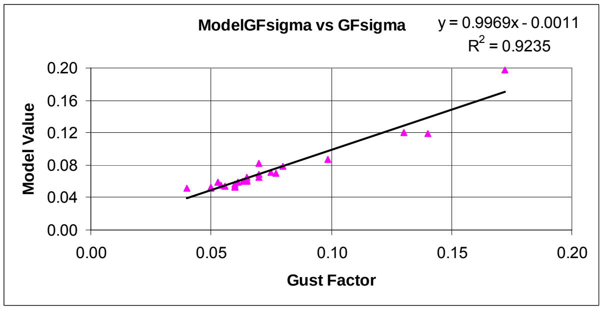

Figure 10. Modeled gust factor standard deviation as a function of observed gust factor standard deviation.

Figure 10 shows the performance of the model against the observations.

5.0 DISCUSSION

The work reported here provides a starting point for the 45WS and others to systematically capture the relationship between mean and peak winds at the CCAFS/KSC spaceport under tropical storm conditions. It provides quantitative guidance for estimating the average and the standard deviation of the gust factor as a function of windspeed and height for strong wind situations. It does not provide probabilities of exceeding a specified peak wind limit given a specified mean wind. This section discusses the specific strengths and weaknesses of the work reported here as well as what more can and should be done with the data.

5.1 The Strengths of the Current Analysis

The results presented here are consistent with those already in the literature. For example, Schroeder and Smith (2003) found gust factors averaging 1.55 at a height of 10.7 m at an airport during hurricane Bonnie (1998) and Krayer and Marshall (1992) found values near 1.6 at 10 m. Similarly, Paulsen and Schroeder (2005, Figure 5) as well as Vickery and Skerlj (2005, Figure 1) found both the magnitude of the gust factor and its scatter tend to decrease with increasing windspeed.

The current analysis allows the generation of operating aids which the forecaster can use to make objectively-based quantitative estimates of the peak winds at any height given the observed or forecast mean wind at that height. The models presented in Section 4 above can be used to produce tables similar to Tables 8 and 9 below. Given the mean wind, the average peak wind may be forecast by multiplying the mean by the gust factor from Table 8. For a more conservative forecast, one or more GFs from Table 9 may be added to the mean GF from Table 8 before multiplying by the mean wind to obtain the peak wind forecast.

GF: H(ft)\WS (Kt)	**20**	**30**	**40**	**50**
12	1.93	1.83	1.73	1.61
54	1.62	1.57	1.50	1.43
90	1.53	1.49	1.43	1.37
145	1.45	1.41	1.37	1.32
162	1.43	1.40	1.36	1.31
204	1.39	1.37	1.33	1.28
295	1.34	1.31	1.28	1.24
394	1.29	1.27	1.25	1.21
492	1.26	1.25	1.22	1.19

Table 8. Model mean gust factor as a function of height and wind speed.

GFs: H(ft)\WS (Kt)	**20**	**30**	**40**	**50**
12	0.197	0.120	0.084	0.064
54	0.119	0.087	0.070	0.059
90	0.101	0.078	0.065	0.057
145	0.086	0.071	0.061	0.055
162	0.083	0.069	0.061	0.055
204	0.077	0.066	0.059	0.054
295	0.068	0.061	0.056	0.053
394	0.061	0.057	0.054	0.052
492	0.057	0.054	0.053	0.051

Table 9. Model standard deviation of gust factor as a function of height and wind speed.

The forecaster can generate tailored similar tables tailored for operationally significant heights and wind speeds by using the equations provided in Section 4. The equations could be included in software packages for automated application without the need for tables. Either way, the guidance thus provided has the advantage of being objective and quantitative.

Avoiding the complication of attempting to include the effects of roughness length and stability greatly simplifies both the result and its application. The environments at many of the sites change frequently depending on grounds-keeping, controlled burns for fire management, natural or controlled flooding, and natural growth cycles. These environmental changes are not readily assessable by the 45th Weather Squadron and cannot be easily translated to roughness length. Stability parameters calculated from the towers involve small differences between large numbers to determine the temperature gradients, and the thermodynamic data are not always available in tropical storm conditions. The practical difficulties of attempting to include these factors in the models would outweigh the reduction in unexplained variance that might result from including them.

5.2 The Weaknesses of the Current Analysis

The ultimate goal is to provide a numerical probability of exceeding a specified peak wind threshold given the mean wind. Unfortunately, a model for the mean and standard deviation is not sufficient for this purpose unless the probability distribution of the gust factor is known and its parameters are derivable from its mean and standard deviation. This initial analysis did not determine the probability distribution, but an examination of the skewness (S) and kurtosis (K) values indicates that it is certainly not Gaussian.

For a Gaussian distribution, S = 0 and K = 3. A few individual runs, each consisting of data from one storm, one tower, one height and one wind bin, had near Gaussian S and K. In most cases, S was significantly positive and K significantly larger than 3 indicating a skewed, long-tailed distribution. This is consistent with the highly skewed distribution of gust factors observed by Paulson and Schroeder (2005). In a few cases, S was slightly negative and K less than 3. Clearly the problem of characterizing the probability distribution is not simple, and the analysis methodology presented here is inadequate to handle it.

In addition, the roughness length at each tower site and the stability in the boundary layer probably affect the results. Since these were not measured or analyzed, they appear in the data as unmodeled sources of variance as noted above. This is especially evident in the 54 ft data when the analysis is not restricted to the tall towers. There is a large spread in the means of the distributions that may be due to the fact that while the tall towers are all located within three miles of the coastline, some of the others are farther inland with significantly different surface properties and exposure.

5.3 Future Analyses

There are several approaches to determining if there is an underlying universal probability distribution that describes the statistical behavior of the gust factor. One method is to explore a large number of well-known distributions to see whether one of them fits the data much of the time.

Given that peak winds are intuitively an "extreme value" phenomenon, one possibility is to investigate the use of extreme value distributions such as the Gumbel or Weibull distributions (Reiss and Thomas, 2007). A preliminary examination indicates that neither of these distributions works well.

From an analytical perspective, the mean wind and the peak wind come from separate populations, each having its own distribution which may be close to Gaussian (Schroeder and Smith, 2003). Given that the gust factor is the ratio of the peak to the mean, it should be governed by a ratio distribution (Geary, 1930). Unfortunately, the ratio distribution is extremely complex mathematically (Hinkely, 1969). In some cases there are simplifications that can facilitate its use (Hayya *et al*., 1975; Geary, 1930), but they require that the distributions of both the numerator and denominator be known and that is not the case operationally.

A visual examination of plots of the data suggests that the distribution of the quantity (GF-1) is close to lognormal. This will be examined further, and at the time this paper is being prepared it seems to be the most promising alternative.

The current plan is to undertake an exploratory analysis to determine whether any of the distributions mentioned above can be reasonably fit to a large portion of the data. If one of them can, then an examination to determine whether there is a systematic variation of the parameters of that distribution with mean wind speed and height will be undertaken. That could lead to a model that would provide a numerical probability of exceeding a specified peak wind threshold given the mean wind.

Notice

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Acknowledgments

The author thanks Kathy Winters and William Roeder of the 45th Weather Squadron for their suggestions for the content and conduct of the study. John Schroeder of Texas Tech University provided many of the references that have been of considerable value in designing the study and interpreting the results. Winnie Lambert, William Roeder and Kathy Winters reviewed an earlier draft of this manuscript, and their comments and suggestions are much appreciated.

References

Beven, J. L., 2004: Tropical Cyclone Report, Hurricane Frances, 25 August - 8 September 2004, National Hurricane Center, http://www.nhc.noaa.gov/2004frances.shtml.

Computer Sciences Raytheon, 2006: *Eastern Range Instrumentation Handbook*, CDRL A209, Contract F08560-00-C-0005, 15 January 2006.

Durst, C.S., 1960: Wind Speeds Over Short Periods of Time, *Meteorological Magazine*, **89**, 181 - 186.

Federal Coordinator for Meteorological Services and Supporting Research (2005): *Federal Meteorological Handbook Number 1, Surface Weather Observations and Reports*, FCM-H1-2005, Office of the Federal Coordinator for Meteorology, Washington, D.C., 104pp.

Geary, R.C., 1930: The Frequency Distribution of the Quotient of Two Normal Variates, *J. Royal Stat. Soc.,* **93** (3), 442 - 446.

Hayya, J., D. Armstrong and N. Gressis, 1975: A Note on the Ratio of Two Normally Distributed Variables, *Management Science*, **21** (11), 1338 - 1341.

Hinkley, D.V., 1969: On the Ratio of Two Correlated Normal Random Variables, *Biometrika*, **56** (3) 635 - 639.

Krayer, W.R. and R.D. Marshall, 1992: Gust Factors Applied to Hurricane Winds, *Bull. Am. Met. Soc.*, **73** (5), 613 - 617.

Lambert, W., D. Short and W.P. Roeder, 2008: Developing a Peak Wind Probability Forecast Tool for Kennedy Space Center and Cape Canaveral Air Force

Station, Paper 7.7, 19th AMS Conference on Probability and Statistics, New Orleans, LA, 28-31 January 2008.

Lawrence, M. B. and H. D. Cobb, 2005: Tropical Cyclone Report, Hurricane Jeanne, 13-28 September 2004, National Hurricane Center, http://www.nhc.noaa.gov/2004jeanne.shtml.

Paulsen, B.M. and J.L. Schroeder, 2005: An Examination of Tropical and Extratropical Gust Factors and the Associated Wind Speed Histograms, *J. Appl. Meteor.*, **44**, 270 - 280.

Reiss, R.D. and M. Thomas, 2007: *Statistical Analysis of Extreme Values*, Third Edition, Birkhauser Verlag AG, Basel, Switzerland, 511 pp.

Schroeder, J.L., M.R. Conder and J.R. Howard, 2002: Additional Insights Into Hurricane Gust Factors, Preprints, 25th Conference on Hurricanes and Tropical Meteorology, American Meteorological Society, 29 April - 2 May, 2002, San Diego, CA, pp 39 - 40.

Schroeder, J.L. and D.A. Smith, 2003: Hurricane Bonnie wind flow characteristics as determined from WEMITE, *J. Wind Eng. and Industrial Aerodynamics*, **91**, 767 - 789.

Schroeder, J.L., B.P. Edwards and M. Martinez, 2005: A Study Coupling Hurricane Wind Speed and Radar Observations, *Proceedings, Tenth American Conference on Wind Engineering*, Baton Rouge, Louisiana.

Vickery, P.J. and P.F. Skerlj, 2005: Hurricane Gust Factors Revisited, *J. Struct. Eng.,* May 2005, 825 - 832.