# TWO EMPIRICAL MODELS FOR GUST FACTORS NEAR LAND-FALLING HURRICANES

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## Abstract

Gaussian and lognormal models for gust factors as a function of height and mean wind speed in the vicinity of land-falling hurricanes are presented. The models were empirically derived using data from 2004 Hurricanes Frances and Jeanne and independently verified using data from 2005 Hurricane Wilma. The data were collected from three wind towers at Kennedy Space Center and Cape Canaveral Air Force Station with instrumentation at multiple levels from 12 to 500 ft above ground level. An additional 200-foot tower was available for the verification. Five-minute mean wind speeds from 15 to more than 60 kt were included in the data. The models provide formulas for the mean and standard deviation of the gust factor, given the mean wind speed and height above ground. These statistics may then be used to assess the probability of exceeding a specified peak wind threshold of operational significance, given a specified mean tropical storm wind speed.

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## 1. Introduction

Both mean and peak wind speeds are important for protection of personnel and facilities at a spaceport like Kennedy Space Center (KSC)/Cape Canaveral Air Force Station (CCAFS). Of the two, the peak winds are significantly more difficult to forecast (Lambert et al. 2008). The 45th Weather Squadron (45WS) provides weather support services for both KSC and CCAFS (Harms et al. 1999). Weather support during hurricanes and tropical storms is one of their major responsibilities (Winters et al. 2006). 45WS requested development of a tool for estimating the probability of exceeding a specified peak wind speed threshold given an observed or forecast mean wind speed in land-falling tropical storms and hurricanes. The tool must predict the likelihood of exceeding various peak speeds at heights up to 500 ft to assess risk to tall structures at KSC/CCAFS. Operationally, the forecaster will provide the target height and peak wind speed threshold to the tool, along with a mean wind speed at that height. The mean wind speed may be that observed by the KSC/CCAFS wind tower network or based on an extrapolation of NHC forecast 10-meter winds. This paper describes the tool and presents the results of a verification of the tool against an independent data set.

In section 2, an overview of the methodology used to develop the tool is presented. The details are not presented in this paper since they are available elsewhere (Merceret 2008). Section 3 presents the procedures used in the independent verification and the results. A summary and discussion are presented in section 4.

## 2. Development of the Tool

### *a. General methodology*

The author based the development of the tool on empirical models for the gust factor as a function of height and mean wind speed. Other significant parameters such as roughness length (Schroeder et al. 2002; Paulsen and Schroeder 2005) and atmospheric stability (Hsu 2001) were not included. In the highly turbulent environment of tropical storm or hurricane winds, the surface layer of interest in this study was expected to be well mixed and close to neutral stability. The effective roughness length for the towers would be difficult to assess because the local terrain is highly variable and would be a complex function of wind direction and height. The study was limited to towers close to the seashore so that all of them were in similar environments.

The data from 2004 hurricanes Frances and Jeanne described in the next section were stratified by height and assigned to mean wind speed bins. Gust factors were derived by dividing the mean wind speed over a 5-minute period into the 1-second peak wind speed within the period. The gust factor is a function of the averaging time (Durst 1960). The averaging time used for this study was selected based on the data available operationally to the 45WS.

For each height and wind speed stratification, the mean (μ) and standard deviation (σ) of the gust factor were calculated along with the skewness and kurtosis. Initially, these statistics were derived separately for each tower and each storm. A subjective comparison indicated that the towers and the storms did not show any significant differences and thus their data could be combined. This both increased the sample size and resulted in models that were not tower or storm specific.

Using least squares methods described more specifically in section 2c below, separate models for the mean and the standard deviation of the gust factor as a function of height and mean wind speed were developed. For both the mean and the standard deviation, two models were built. The first was based on the gust factor (GF) being Gaussian, and the second on the gust factor minus one (GF-1) being lognormal. The tool uses the mean and standard deviation from the least squares fits to generate probabilities of exceeding a specified threshold given a specified mean wind speed and height from the distribution on which the model was based.

### *b. Data*

For this work, the GF was defined as the ratio of the peak 1-second wind speed in a 5-minute period to the average wind speed over that period. It applied at each height for which tower data were 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, personal communication, 2007). FMH1 defines "gust factor" based on a 10-minute averaging period and only at the standard surface observing height of 10 m. The professional literature relating to GFs 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. Limiting the definition of GF to observations at 10 m would defeat the requirement that the analysis provide guidance at heights up to 500 ft.

Wind measurements were obtained from the KSC archive (available online at: http://trmm.ksc.nasa.gov) of Eastern Range wind towers at KSC/CCAFS. Each tower is instrumented at one or more levels with commercial R.M. Young propeller/vane anemometers. The tower network and its instrumentation are described in detail in the Eastern Range Instrumentation Handbook (Computer Sciences Raytheon 2008). Three towers designated 002, 110 and 313 respectively were used to develop the GF statistics and models. These three towers plus Tower 006 were used for the verification. Their locations are shown in Figure 1. Each tower was instrumented on two sides. Initially, statistics were derived for the two sides separately for quality control purposes. That enabled the discovery and elimination of some erroneous data from Tower 313 as described in Merceret (2008). The heights at which wind instrumentation is installed on each tower ranged from 12 to 492 ft. Specifics are given in Table 1.

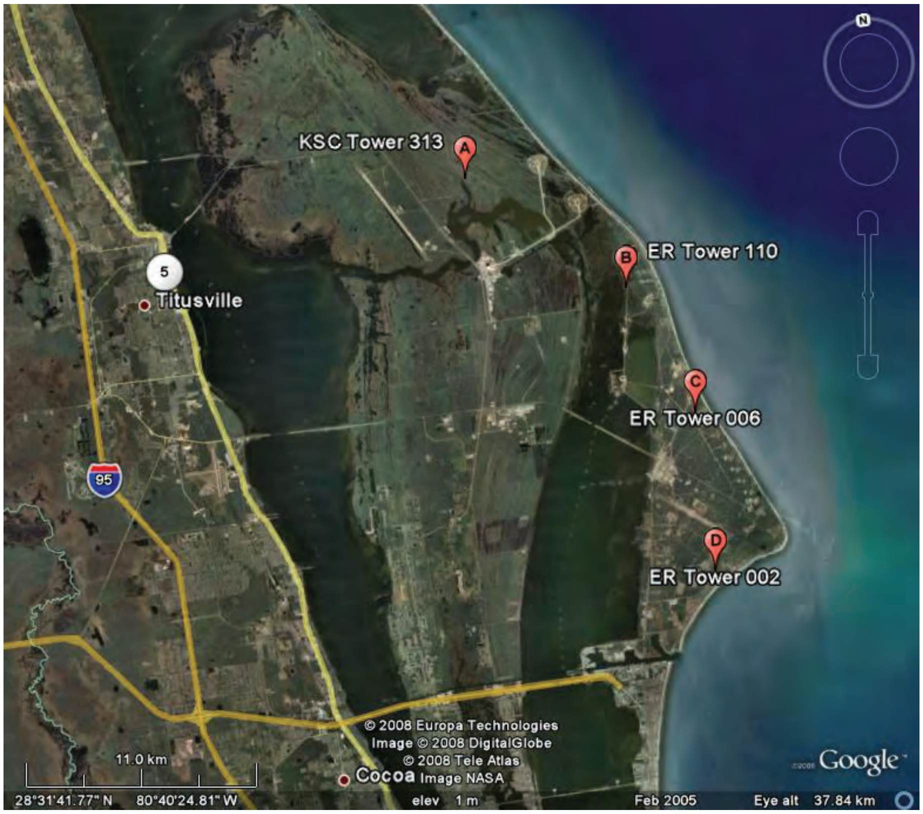


**Fig. 1.** Google Earth map of the locations of the wind towers that provided the data used in generating and verifying the statistical models presented in this paper.

The models were derived from data obtained in 2004 Hurricanes Frances and Jeanne. Both storms are described in detail in Franklin et al. (2006). The storms passed within 70 to 100 n mi south and west of KSC/CCAF providing a rare opportunity where tropical storm force winds occurred at the towers for an extended period of time before the loss of power to the instrumentation and data acquisition facilities. The verification data were from 2005 Hurricane Wilma (Beven et al. 2008) which provided data similar to that obtained from the 2004 storms and included Tower 006 which did not provide useful data in Frances and Jeanne. Wilma's closest point of approach was about 110 n mi south of KSC/CCAFS as it exited the Florida peninsula toward the Atlantic Ocean. For all three storms, the maximum observed mean wind speed did not exceed 64 kt at heights below 300 ft and only briefly approached 70 kt above 400 ft.

For each sensor on each tower and 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.

A brief perusal of the technical literature showed that GF is a function of averaging time (Durst 1960) and roughness length (Schroeder et al. 2002; Paulsen and Schroeder 2005). There was also a suggestion that it is a decreasing function of mean wind speed (Vickery and Skerlj 2005; Schroeder et al. 2005). Given these

| TowerID | 12 | 54 | 90 | 145 | 162 | 204 | 295 | 394 | 492 | Notes |
|---|---|---|---|---|---|---|---|---|---|---|
| 0020 | X | X | X | X |  | X |  |  |  | Tower 002 NW |
| 0021 | X | X | X | X |  | X |  |  |  | Tower 002 SE |
| 0061 | X | X |  |  | X | X |  |  |  | Tower 006 NW |
| 0062 | X | X |  |  | X | X |  |  |  | Tower 006 SE |
| 1101 | X | X |  |  | X | X |  |  |  | Tower 110 NW |
| 1102 | X | X |  |  | X | X |  |  |  | Tower 110 SE |
| 3131 | X | X |  |  | X | X | X | X | X | Tower 313 SW |
| 3132 | X | X |  |  | X | X | X | X | X | Tower 313 NE |

**Table 1.** Height (ft) above ground level of wind instrumentation at each tower used in this work.

dependencies, it seemed likely that it might also be a function of height above ground and stability. In addition, the scatter (variance) in the GF as a function of wind speed appears to increase markedly at lower wind speeds (Vickery and Skerlj 2005; Schroeder et al. 2005).

For these reasons, the data were stratified by storm, tower, height and mean wind speed for analysis. Wind speeds were grouped into bins as shown in Table 2. Mean wind speeds less than 15 kt were excluded because a quick visual examination of scatter plots showed that, consistent with the literature, the variability of the GF became too large for quantitative analysis below that speed. This provided statistically significant sample sizes (N ≥ 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 for the reasons given in section 2a above, and those dependencies are not part of this study. For each stratification, the mean, standard deviation, skewness and kurtosis of the GF was computed.

For development of the statistical models, comparison of the statistics from the opposite sides of each tower identified some erroneous measurements at some levels on the northeast side of Tower 313 in Frances; otherwise the two sides of each tower could be combined. Intercomparison of the towers and of Frances and Jeanne with each other showed that the stratified statistics did not significantly depend on which tower or storm was being processed. To increase the sample size, these stratifications were combined leaving stratification only by height and wind speed bin.

### *c. Models*

#### 1) Systematic behavior of the mean and standard deviation of the GF

Both the mean and the standard deviation of the GF decreased with height and wind speed consistent with Vickery and Skerlj (2005). The results are presented in Tables 3 and 4. Some combinations of height and wind speed contained from zero to less than ten records from which μ and σ could be computed. These are presented as empty cells in the tables.

#### 2) Gaussian models

The simplest model from which to make a prediction of the probability of the GF exceeding a specified threshold is a Gaussian model. If μ and

| Bin (Nominal Mean WS in Kt.) | Minimum WS | Maximum WS |
|---|---|---|
| 20 | 15 | 24 |
| 30 | 25 | 34 |
| 40 | 35 | 44 |
| 50 | 45 | none |

**Table 2.** Wind speed stratification bins. Although the 50 kt bin had no upper limit, few of the entries in this bin exceeded 55 kt and none exceeded 70 kt.

| Height (ft) | Bin20 | Bin30 | Bin40 | Bin50 |
|---|---|---|---|---|
| 12 | 1.96 | 1.77 | | |
| 54 | 1.60 | 1.57 | 1.48 | |
| 90 | | 1.49 | 1.47 | |
| 145 | | 1.44 | 1.41 | |
| 162 | 1.46 | 1.37 | 1.35 | 1.31 |
| 204 | | 1.35 | 1.34 | 1.28 |
| 295 | | 1.28 | 1.27 | 1.26 |
| 394 | | | 1.23 | 1.22 |
| 492 | | | 1.21 | 1.20 |

**Table 3.** Mean gust factor as a function of height and wind speed bin. Empty cells are stratifications for which insufficient data were available for statistical analysis.

| Height (ft) | Bin20 | Bin30 | Bin40 | Bin50 |
|---|---|---|---|---|
| 12 | 0.172 | 0.130 | | |
| 54 | 0.140 | 0.103 | 0.077 | |
| 90 | | 0.090 | 0.065 | |
| 145 | | | 0.065 | |
| 162 | 0.070 | 0.070 | 0.063 | 0.053 |
| 204 | | 0.073 | 0.063 | 0.058 |
| 295 | | 0.070 | 0.060 | 0.050 |
| 394 | | | 0.060 | 0.040 |
| 492 | | | 0.060 | 0.050 |

**Table 4.** Standard deviation of the gust factor as a function of height and wind speed bin. Empty cells are stratifications for which insufficient data were available for statistical analysis.

σ can be predicted by the model, the probability of exceeding any value X can be obtained directly from Gaussian distribution tables, including those in standard software packages like Excel®. Given Z = (X - μ)/σ, the tables directly give the probability, P (Z), that the GF will not exceed X. The desired probability of exceeding X is simply 1-P. Thus the goal of the model will be to provide analytic formulas for the GF mean and SD as functions of height and wind speed.

The procedure used to develop the models for the GF mean and SD was the same. For each wind speed bin, a least squares fit of the target variable as a function of height was generated. Linear and nonlinear functional forms were tried. The best fits were of the form $y = aH^b$, where y is the GF mean or SD; H is the height above ground level (ft); and the parameters a & b are functions of wind speed (WS) only. Once a & b were determined for each wind speed, then the least squares method was used to fit them to functions of wind speed. Again, both linear and non-linear functions were tried. Extensive details of this process and its success are provided in Merceret (2008). For this paper the following results (equations 1-2) of that process are taken as the starting point:

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

$$\sigma = aH^b \text{, where } a = 165.77WS^{-1.9711} \text{ and } \\ b = 0.2995 \ln(WS) - 1.2312 \qquad (2)$$

Although these models reproduced μ and σ extremely well with $r^2$ values greater than 0.99, there are some fundamental conceptual problems with using a Gaussian distribution for the GF. First, the GF is bounded from below by 1 whereas a Gaussian distribution is unbounded in either direction. Secondly, a Gaussian distribution has a skewness of 0 and kurtosis of 3 (or zero if the analysis software defines it by subtracting 3 from the normalized fourth central moment.). Both the skewness and the kurtosis of the GF data were significantly larger than the Gaussian values, consistent with GF observations by others such as Paulson and Schroeder (2005). This suggested trying other distributions as a basis for modeling the GF probability distribution.

## 3) Lognormal models

A variety of non-Gaussian distributions were tried without success, including the widely used Gumbel and Weibull extreme value distributions (Reiss and Thomas 2007). The ratio distribution (Geary 1930) was examined closely, but its mathematical complexity (Hinkley 1969) was prohibitive unless simplifications were made to facilitate its use. These simplifications required knowing the separate distributions of both the mean and the peak wind speeds (Hayya et al. 1975; Geary 1930), but if we already knew the distribution of the peak wind speeds for a given mean, we would not need to build the GF models. The lognormal distribution, however, showed promise.

The lognormal distribution is frequently encountered in nature in general and wind features in particular (Smith and Merceret 2000). It has two properties that make it a likely candidate for modeling the statistical properties of the GF: (1) it is bounded on the left by 0; and (2) it can produce distributions with large skewness and kurtosis relative to Gaussian. Since the GF by definition is bounded on the left by 1, the quantity (GF-1) was fitted to a lognormal distribution. This was accomplished by modeling the mean, M, and standard deviation, S, of the natural logarithm of (GF-1). The lognormal models were created after the Gaussian models reported in Merceret (2008), but because the same least squares methodology was used, only the results are presented here. The equations are:

$$M = e(\ln(H))+f \text{, where } e= 0.0009WS-0.3543 \text{ and } \\ f = 1.15-0.015WS \qquad (3)$$

$$S = gH+h \text{, where } g = 0.000009WS-0.00009 \text{ and } \\ h = 0.85WS^{-0.51} \qquad (4)$$

The lognormal models can be used to compute the GF mean and SD from M and S as follows:

$$\mu = \exp(M+S^2/2) \qquad (5)$$

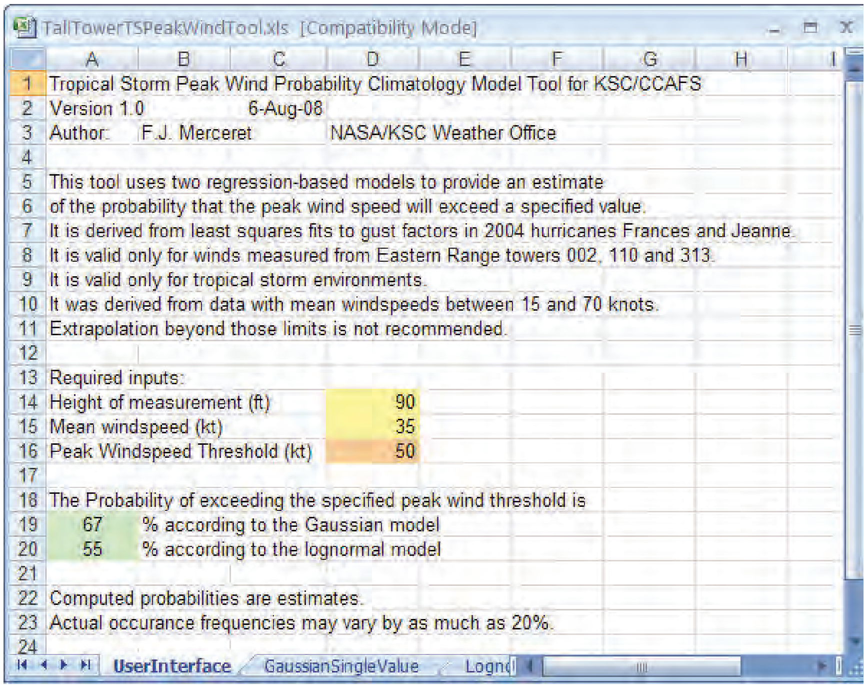
$$\sigma = \mathrm{sqrt}(\exp(2M+2S^2) - \mu^2) \qquad (6)$$

In fact, they reproduce μ and σ about as well as the Gaussian models, but not significantly better.

## 4) Building the tool

An extensive analysis of both the Gaussian and lognormal models (not presented) revealed that the Gaussian distribution fit the complete distribution of some of the data very well; the lognormal fit other data very well; and sometimes neither of these two distributions matched the observations. After discussing the matter with the 45WS, it was decided to have the tool present the probability results from both the Gaussian and lognormal models. That would provide the operator with some objective measure of the reliability of the probability estimate. If the models significantly disagree, the operator will have less confidence in either than when they give similar values. In addition it allows the operator to choose the higher probability of exceeding the threshold, thus providing a forecast that errs toward safety.

The tool was built into an Excel® workbook with three worksheets. The user interacts only with the first worksheet which contains a user interface. The interface provides instructions and unprotected cells in which to enter the target height, mean wind speed and peak wind threshold of interest. The values are range checked to assure that they are within the range of values on which the models were based. The data from the interface worksheet are accessed by separate, protected Gaussian and lognormal calculation worksheets that use the models to compute the desired probabilities. These probabilities are then accessed by the interface sheet for viewing by the user. The interface worksheet is shown in Fig. 2.



|  | A | B | C | D |
|---|---|---|---|---|
| 1 | Tropical Storm Peak Wind Probability Climatology Model Tool for KSC/CCAFS |  |  |  |
| 2 | Version 1.0 |  | 6-Aug-08 |  |
| 3 | Author: | F.J. Merceret |  | NASA/KSC Weather Office |
| 4 |  |  |  |  |
| 5 | This tool uses two regression-based models to provide an estimate |  |  |  |
| 6 | of the probability that the peak wind speed will exceed a specified value. |  |  |  |
| 7 | It is derived from least squares fits to gust factors in 2004 hurricanes Frances and Jeanne. |  |  |  |
| 8 | It is valid only for winds measured from Eastern Range towers 002, 110 and 313. |  |  |  |
| 9 | It is valid only for tropical storm environments. |  |  |  |
| 10 | It was derived from data with mean windspeeds between 15 and 70 knots. |  |  |  |
| 11 | Extrapolation beyond those limits is not recommended. |  |  |  |
| 12 |  |  |  |  |
| 13 | Required inputs: |  |  |  |
| 14 | Height of measurement (ft) |  |  | 90 |
| 15 | Mean windspeed (kt) |  |  | 35 |
| 16 | Peak Windspeed Threshold (kt) |  |  | 50 |
| 17 |  |  |  |  |
| 18 | The Probability of exceeding the specified peak wind threshold is |  |  |  |
| 19 | 67 | % according to the Gaussian model |  |  |
| 20 | 55 | % according to the lognormal model |  |  |
| 21 |  |  |  |  |
| 22 | Computed probabilities are estimates. |  |  |  |
| 23 | Actual occurance frequencies may vary by as much as 20%. |  |  |  |
| 24 |  |  |  |  |

**Fig. 2.** Screen capture of active part of the user interface sheet for the peak wind probability tool.

## 3. Independent Verification of the Models

### *a. Methodology*

At the time the models were developed, Frances and Jeanne observations from towers 002, 110 and 313 were the only suitable data to which the author had access. The sample size was too small to support both the extensive stratification required for the analysis and the sequestering of an independent data set of statistically significant size. Subsequently, Kathy Winters of 45WS provided the Wilma data. In addition to being a completely independent storm, it had data from Tower 006, a tower that was not used in the development of the models.

The Wilma data were processed and stratified in the same manner as the previous storms. Again, data from opposite sides of the towers and from the different towers were not significantly different and were combined. There were no anomalies of the kind detected for the NE side of Tower 313 in Frances. The mean wind speeds were within the same range as those in Frances and Jeanne. The mean wind direction in Wilma ranged from 310 to 050 degrees compared with 0 to 050 degrees for Frances and Jeanne.

The mean and standard deviations of the GF were computed from the measured data for each height and wind speed bin. For each height and wind speed bin μ and σ of the GF were computed from the Gaussian and lognormal models using the height and observed mean wind speed as inputs. The resulting model values for the GF statistics were plotted as functions of the observed values in the same stratification. Linear least squares fits of the model values as functions of the observed values were also computed.

### *b. Results*

Figures 3 and 4 respectively show the performance of the Gaussian models in reproducing the mean and standard deviation of the GF in Wilma. Figures 5 and 6 present the same information for the lognormal models. If the models perfectly reproduced the observations, the least squares fits would have a slope of 1, an intercept of 0 and $r^2 = 1$.

Both the Gaussian and lognormal models for the GF mean performed well for Wilma. They accounted for more than 80% of the variance in the data ($r^2 > 0.8$) with slopes near unity and small intercepts. The Gaussian model was slightly superior in all three of these measures.

The models for the standard deviation did not perform quite as well, but still accounted for more than 40% of the variance with slopes around 0.85 and small intercepts. Although the Gaussian model $r^2$ was slightly larger than

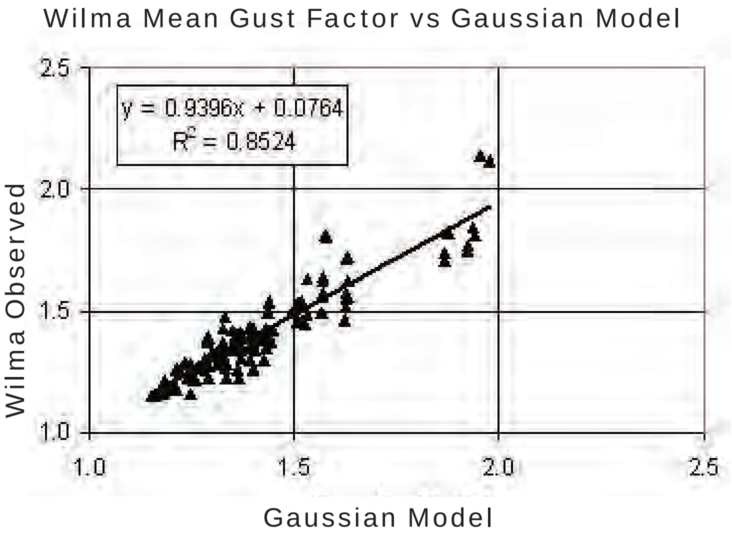


**Fig. 3.** Gaussian model GF means as a function of observed Wilma GF means. Each point represents one stratification of height and wind speed.

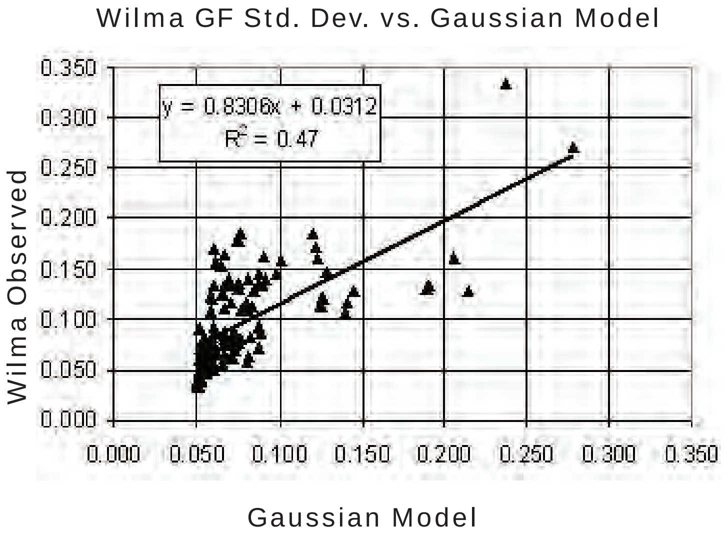


**Fig. 4.** Gaussian model GF standard deviations as a function of observed Wilma GF standard deviations. Each point represents one stratification of height and wind speed.

that of the lognormal model, the slope and intercept of the lognormal model were closer to the ideal values.

Overall, the models performed remarkably well on this completely independent set of measurements. This was so even though the wind direction in Wilma had a significant offshore component for part of the data set, whereas the other two storms had only onshore winds. In addition, Frances and Jeanne were clearly and completely tropical systems, while there is the possibility that Wilma was beginning to be influenced by the entrainment of cold, dry mid-latitude air which could affect the stability of the boundary layer. It is encouraging that these differences did not prevent the models from providing useful probability guidance.

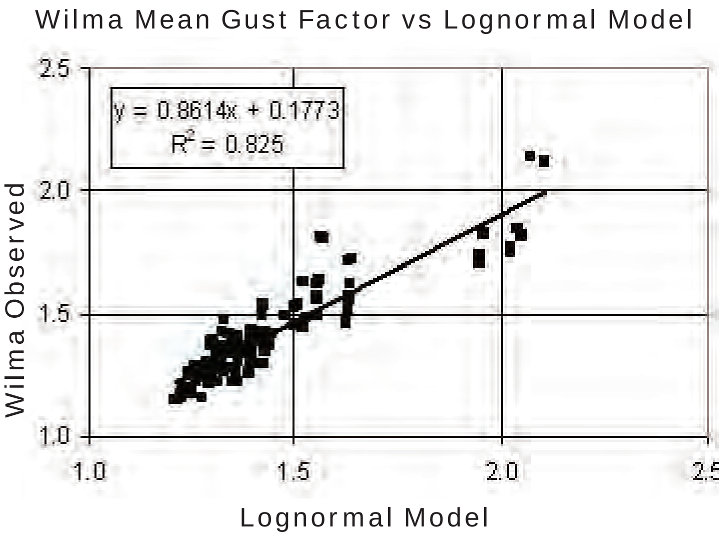


**Fig. 5.** Lognormal model GF means as a function of observed Wilma GF means. Each point represents one stratification of height and wind speed.

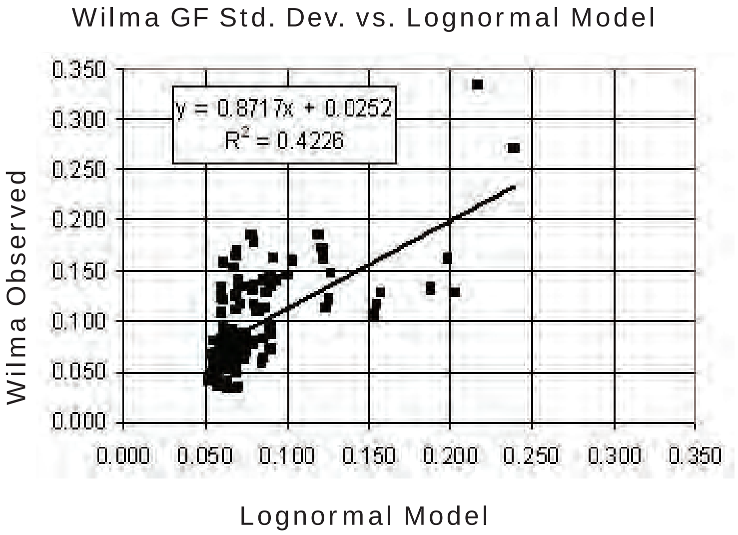


**Fig. 6.** Lognormal model GF standard deviations as a function of observed Wilma GF standard deviations. Each point represents one stratification of height and wind speed.

## 4. Summary and Discussion

Using measurements of winds from three instrumented coastal wind towers at Kennedy Space Center and Cape Canaveral Air Force Station in 2004 Hurricanes Frances and Jeanne, empirical models were developed for the mean and standard deviation of the GF as a function of height and mean wind speed. Separate models were developed for Gaussian and offset lognormal distributions for the GF. Using the models, an operational tool was built in Excel® to provide estimates of the probability that a specified peak wind would be exceeded given a specified mean wind. The models were validated using data from the same three towers plus one additional tower in 2005 Hurricane Wilma. The models performed well on the Wilma data, indicating that they are not storm-specific or tuned to the exact characteristics of the fitted data set rather than the statistical process of which they are a sample.

The successful independent validation of the models will allow the tool based on them to be used operationally in estimating the probability of violating peak wind constraints on operations and facilities at KSC and the Eastern Range, given forecast or observed mean winds. The tool has two distinct advantages over the peak winds included in routine hurricane forecasts. First, rather than merely forecasting a single, specific peak wind value that may not have any relation to operationally significant peak wind speeds, the tool provides a probability of exceeding a specified operationally significant value. Secondly, the probability is provided as a function of height. This allows the result to be applied at a height appropriate to the operation or facility to which the constraint applies. Peak winds forecast for the standard 10 meter height can seriously underestimate the peak winds found near the top of a vehicle assembly building or launch complex, which can exceed 500 ft above ground level.

There are limits to the application of the models that should be kept clearly in mind when using them or the tool based on them. First, they were developed and validated only in tropical storm conditions associated with the periphery of hurricanes. Extrapolation to the higher wind speed core of hurricanes may not be warranted. Winds of similar speed produced by non-tropical systems such as frontal squalls may have different turbulence dynamics and stability, and may not have GFs that have the same statistical characteristics. Second, since the GF is known to be a function of the roughness length, and these models were derived in the specific coastal environment of the Cape Canaveral seashore, they probably will not produce valid results for inland sites or even for coastal sites with markedly different topography. Although this specific tool cannot be generalized for use in other environments such as urban areas or the vicinity of tall structures like bridges, the methodology could be applied in those locations to develop a similar tool tuned to those local environments. The qualitative observations that GFs decrease systematically with both mean wind speed and height are probably of general validity, and that alone may be of value in other applications.

If the limitations of the tool are recognized, it can provide a major improvement to the process of estimating the probability of violating operational constraints during land-falling tropical storms and hurricanes. Future improvements to the tool, including updating the regressions with the Wilma data, may be undertaken as resources permit.

## Author

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