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Extended Statistical Short-Range Guidance for Peak Wind Speed Analyses at the Shuttle Landing Facility: Phase II Results

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Executive Summary

The peak winds near the surface are an important forecast element for both the Space Shuttle and Expendable Launch Vehicle (ELV) programs. As defined in the Shuttle Flight Rules (FR) and the Launch Commit Criteria (LCC), each vehicle is assigned certain peak wind thresholds that cannot be exceeded in order to ensure the safety of that vehicle during launch and landing operations. The 45th Weather Squadron (45 WS) and the Spaceflight Meteorology Group (SMG) indicate that peak winds are challenging to forecast. In Phase I of this task, the Applied Meteorology Unit (AMU) calculated the climatologies and probabilities of occurrence of the 5-minute peak and average winds for all towers in the Kennedy Space Center/Cape Canaveral Air Force Station (KSC/CCAFS) used in evaluating LCCs and FRs. However, SMG uses a 10-minute peak from the Shuttle Landing Facility (SLF) wind towers in evaluating wind speed FRs. The primary objective of this phase was to re-calculate the climatologies and probabilities using a 10-minute instead of 5-minute peak from the SLF towers. The secondary objective was to develop a tool to be used on a personal computer (PC) that will display the desired information quickly and easily. Both objectives were met successfully.

The 5-minute wind speed and direction observations from Towers 511/512/513 (the SLF towers) and Tower 313 for all months in the period 1995-2001 were used in this phase of the task. SMG uses the 10-minute peak associated with a 2-minute average wind, but 2-minute values could not be evaluated since only the 5-minute data were available to do the analysis. A Monte Carlo simulation was conducted to determine any differences in hourly means and standard deviations between the 2- and 5-minute values. The results showed that the hourly means of the 2- and 5-minute averages were identical, but the hourly standard deviation of the 2-minute average winds could be 60% greater than that for the 5-minute average winds. The hourly means and standard deviations of the 10-minute peaks for the 2- and 5-minute average winds were very similar. With the exception of the hourly standard deviations for the average winds, the user can assume that the climatologies and probabilities calculated with the 5-minute winds are likely very similar to values that would have been calculated using 2-minute winds.

The 10-minute peak for each 5-minute average wind in the SLF towers database was determined first by comparing the peak wind speed for the current record with the peak from the previous record. The larger of the two was chosen as the 10-minute peak wind speed for the current record. The 10-minute peak wind speeds were only slightly higher than the 5-minute peak speeds, with an average difference of 0.5 knots. The 10-minute peak winds were created and analyzed for the SLF towers only, not Tower 313 since it is not used for FR decisions.

The climatologies consisted of peak and average wind speed means and standard deviations. The data were stratified by tower number, height and month, then by hour, direction, and direction/hour. The means and standard deviations of the peak and average speeds were calculated, and the numbers of observations used in the calculations were tabulated. The probabilities of occurrence were calculated through probability density functions (PDFs). The empirical PDFs were calculated first. Tests indicated that the theoretical gamma distribution was the best fit for the empirical PDFs of the 10-minute peak speeds. This result was unexpected since the Weibull distribution is most widely used to describe wind speed distributions in the literature, with little support for the use of the gamma distribution. Repeated testing confirmed the gamma fit and the gamma parameters estimated from the empirical data were used to create theoretical peak-speed distributions.

Two products were created for SMG forecasters to access the climatology and probability values. The first is the Excel pivot charts and tables developed during Phase I and described in the Phase I report. These displays are very flexible, allowing changes to the charts and tables with point-click-drag techniques. However, they could be difficult to manipulate and interpret in a fast-paced operational environment. Therefore, a PC-based GUI tool was developed to display the peak wind speed climatologies and probabilities using the Visual Basic for Applications (VBA) in Excel. Development of the GUIs included many consultations with SMG forecasters to ensure the GUIs provided the information needed in an easy to read format. The set includes an input GUI with two tabs: one for entering input to retrieve climatology data and the other for input to retrieve probability data. Once the desired parameters are selected on the input GUI, an output GUI is displayed that shows the desired information.

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1. Introduction

The peak winds near the surface are an important forecast element for both the Space Shuttle and Expendable Launch Vehicle (ELV) programs. As defined in the Shuttle Flight Rules (FR) and the Launch Commit Criteria (LCC), each vehicle is assigned certain peak wind thresholds that cannot be exceeded in order to ensure the safety of that vehicle during launch and landing operations. The 45th Weather Squadron (45 WS) and the Spaceflight Meteorology Group (SMG) indicate that peak winds are challenging to forecast. The Applied Meteorology Unit (AMU) was tasked to develop tools to assist in short-range forecasts of peak winds in support of ELV and Shuttle launches and Shuttle landings.

In Phase I of this task (Lambert 2002), climatologies and probabilities of occurrence of the 5-minute peak winds were created for all towers in the Kennedy Space Center/Cape Canaveral Air Force Station (KSC/CCAFA) used in evaluating LCCs and FRs. However, SMG uses a 10-minute peak from the Shuttle Landing Facility (SLF) wind towers (Towers 511, 512, and 513) as the standard for determining and verifying wind speed FRs. The primary goal of Phase II was to use the results found in Phase I to re-calculate the climatologies and probabilities of occurrence using a 10-minute instead of 5-minute peak from the SLF towers. The secondary goal was to develop a tool to be used on a personal computer (PC) that will display the desired information quickly and easily.

The focus of this work was on the wind speeds from the 30-ft level of Towers 511, 512, and 513 and the 492-ft level of Tower 313 to the east of the SLF. Only data from the SLF towers, not Tower 313, are used to make operational decisions regarding FR. However, SMG forecasters monitor the 492-ft winds at Tower 313 as a possible indicator of surface gust strength. The locations of these towers are shown in Figure 1.

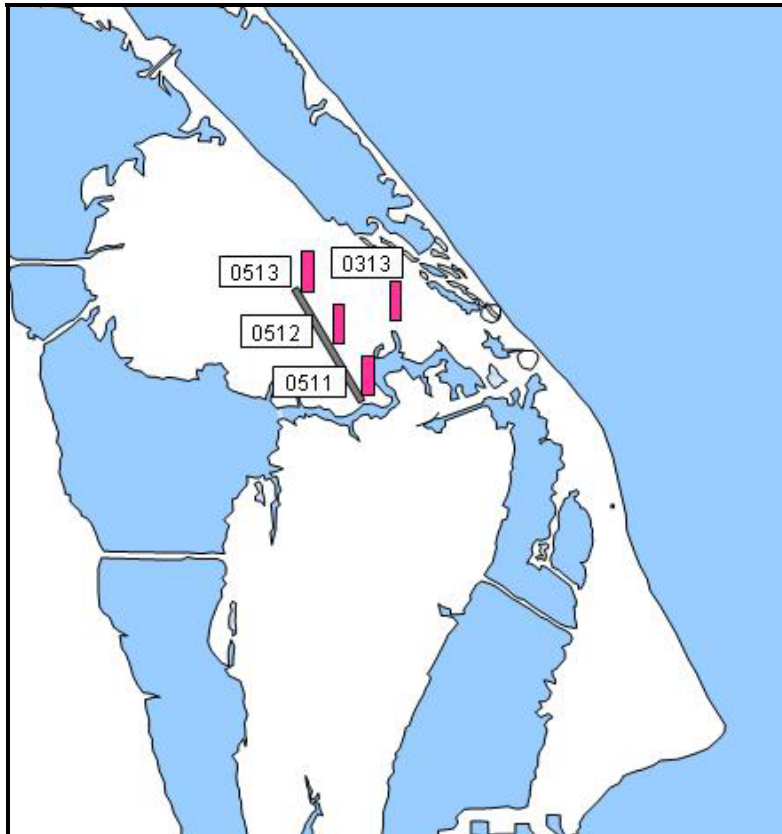


Figure 1. A map showing the locations of the wind towers and whose data were used in the task. The gray thin rectangle along which Towers 0511-0513 are situated represents the location of the SLF.

The 10-minute peak wind values were determined for the data set covering all months from the period of record (POR) 1995 – 2001. The processes of how these values were calculated and the creation of the climatologies and probabilities of occurrence are described in Section 2. Although they provide a useful visualization of the wind speed behavior with hour and direction, the Microsoft® Excel 2002 (hereafter Excel) pivot charts developed as products in Phase I could be difficult to use and interpret in a fast-paced operational environment. Therefore, the forecasters requested that a PC-based graphical user interface (GUI) be developed that would display the requested information quickly and in an easy-to-interpret format. The description of this tool's parameters and how it was developed is given in Section 3. The project summary is given in Section 4.

2. Data Analysis

The same wind tower network data set used in Phase I was used in this task, excluding all towers except 511, 512, 513, and 313. The data set included 5-minute average and peak wind speed and direction for all months in the POR 1995-2001 and was checked for quality prior to any analysis (Lambert 2002). The 10-minute peak winds were analyzed for the SLF towers only, not Tower 313 since it is not used for FR decisions. As in Phase I, the S-PLUS® software package (Insightful Corporation 2000) was used to process and analyze the data.

2.1. 2-Minute vs. 5-Minute Wind Speeds

When evaluating the FRs, SMG uses a 2-minute average wind speed and a 10-minute peak wind speed, both updated every 2 minutes. In order to calculate climatologies and probability distributions representative of this FR, wind tower data at a minimum time resolution of 2-minutes were needed. However, the database available to the AMU contained 5-minute average and peak winds, and the only option was to calculate the 10-minute peak wind based on the 5-minute values. This issue was discussed between SMG and the AMU early in the task and the groups discussed the possibility of assuming that the time resolution difference between 5 and 2 minutes was sufficiently small as to cause insignificant differences in the final calculations. This assumption could not be tested with real data since they were not available. Instead, the AMU conducted a Monte Carlo test with simulated wind speed data.

The wind speed averages and peaks in the wind tower network are calculated from 1-second observations. For the Monte Carlo test, 100 samples of one hour of 1-second wind speed observations (3600 observations in each sample) were generated. The 1-second winds were generated using low-pass filtered random numbers. A first order autoregressive low-pass filter (Merceret 1983) was used to give the simulated winds realistic spectral properties. The equation used to calculate the 1-second speeds was

$$y_k = \alpha y_{k-1} + (1-\alpha)x_k, \quad 1$$

where y_k is the current 1-second wind observation, y_{k-1} is the previous 1-second observation, x_k is a random number, and α is called the filter parameter that is set to 0.9 for this simulation (Dr. Merceret, personal communication). The random numbers, x_k , were generated with Excel's Random Number Generation utility using a uniform distribution within a range defined by

$$m \pm a*s, \quad 2$$

where m is the desired mean wind speed, s is a realistic standard deviation of the wind speed, and a is a constant that can be adjusted to yield a realistic gust factor. Merceret 1995 suggested that a typical standard deviation in fair weather can be defined by

$$s = 0.6*m^{0.6}. \quad 3$$

Using $m = 10$ knots, $a = 5$ yielded an average gust factor value of ~ 1.4 (Lambert 2002). With these values for m , a , and s , the range for the random numbers, x_k in Equation 1, was -1.94 to 21.94 . When $k = 1$, the initial value for y_{k-1} in Equation 1 was 10 knots, the mean wind speed.

One hundred sets of 3600 random numbers were created with the random number generator and were subsequently used in Equation 1 to calculate 100 sets of 3600 1-second wind speeds. The 2-minute and 5-minute block-average wind speeds were calculated for each set. Then the 10-minute peaks based on the 2- and 5-minute averages were determined. The hourly averages and standard deviations were calculated for each of the sets, as they were in the climatologies with the archived data. This resulted in four sets each of 100 hourly means and standard deviations. Four comparisons were done between the sets to determine differences between

1. The 2- and 5-minute average wind speed hourly means,
2. The 2- and 5-minute average wind speed hourly standard deviations,
3. The 2- and 5-minute 10-minute peak wind speed hourly means, and
4. The 2- and 5-minute 10-minute peak wind speed hourly standard deviations.

The hourly means of the 2- and 5-minute average wind speeds in the first comparison were identical. This result was expected. Regardless of how the data are blocked and averaged over the hour, the hourly average is calculated from the same set of numbers, resulting in the same hourly value whether averaging over all 3600 values or in 5-, 2-, or 1-minute block averages. The hourly values in the third and fourth comparisons were nearly identical. The ratios between the 2- and 5-minute peak wind values were calculated first, and then an overall average ratio was determined. The overall ratio between the 2- and 5-minute 10-minute peak hourly means was 0.998, and the ratio for the standard deviations was 0.975. However, the overall ratio between the 2- and 5-minute average hourly standard deviations in the second comparison was 1.61. When the means are equal, it can be shown that the ratio $\sigma_2/\sigma_5 = 1.58$ assuming that the samples are independent and conditions are statistically stationary (Wilks 1995). The 2- and 5-minute averages might be considered independent in the sense that they are block, not running, averages. But the fact that the value of each 1-second wind speed value was calculated using the previous 1-second value removes the assumption of complete independence in this case. The Monte Carlo values were calculated from a process with constant mean and variance consistent with the assumption of stationarity, but in real data this assumption breaks down during frontal passages, sunrise, sunset, and other phenomena that can cause changes in the current state of the wind field. Without real 2-minute wind data to determine the observed difference in standard deviations, it is difficult to determine the actual values.

Based on these results, the user can assume that the hourly means of the 5-minute averages are identical to the hourly means of the 2-minute averages, but the hourly standard deviations of the 2-minute averages could be 60% greater than those for the 5-minute averages. Although the hourly means and standard deviations of the 10-minute peak wind speeds for the 2- and 5-minute average winds were not identical, the differences were very small and the user can again assume that the 5-minute values developed in this task can be used as a proxy for the 2-minute values.

2.2. 10-Minute Peak Wind

The first calculation in this task was to determine the 10-minute peak for each 5-minute average wind in the data set. The 5-minute data for each individual SLF tower were sorted in chronological order from 0000 UTC 1 January 1995 to 2355 UTC 31 December 2001. An algorithm was developed in S-PLUS to compare a peak wind speed with its value five minutes earlier. An exception was added for the very first record in the file: the 5-minute peak wind was considered the 10-minute peak wind for that record. For the second and all subsequent records, the previous 5-minute peak wind was available for comparison to the value in the record being considered. The larger of the two was chosen as the 10-minute peak wind speed for that record. The 10-minute peak wind speeds were only slightly higher than the 5-minute peak speeds, with an average difference of 0.5 knots.

2.3. 10-Minute Peak Wind Climatology

The same climatologies calculated in Phase I for the 5-minute peak winds were also computed in this task for the 10-minute peak winds. The climatologies consisted of wind speed (peak and average) means and standard deviations (σ) for each of the stratifications. The data were stratified first by tower and month, then by three other ways prior to the calculations:

- By hour,
- By direction in 10° bins, and
- By direction in 45° bins and hour.

In addition to calculating the mean and σ of the wind speeds, the number of observations used to calculate these variables were tabulated. The results were then displayed in Excel pivot charts. Pivot charts of the climatologies were created as an interim product for SMG until the PC-based tool was developed. The figures in this section show the values for the 5-minute average winds with their associated 10-minute peak values. This is a result of the earlier discussion concerning SMG's use of a 2-minute average and 10-minute peak values to evaluate the wind speed FR. If the AMU had access to higher resolution data, the figures would show the climatologies for the 2-minute average winds. Since 5-minutes is the highest resolution in the dataset, the values were calculated for those average winds.

Hourly Climatology

For this climatology, the hourly mean and σ of the 5-minute average and 10-minute peak winds were calculated for each month and tower/height combination. The March hourly climatologies for Tower 512, located at the center of the SLF, are shown in Figure 2. The main feature seen in Figure 2 is the diurnal trend in both the mean peak and average wind speeds, evident in the other SLF towers as well. The local sunrise in March is between 1100 - 1200 UTC (0600 - 0700 EST), and sunset is between 2300 - 2400 UTC (1800 - 1900 EST). An increase in mean speed was apparent in the data after sunrise, as was the decrease in the late afternoon to evening hours. The increase at sunrise was likely due to the mixing down of higher momentum winds aloft by the convective updrafts and downdrafts created by daytime heating. Also noteworthy was the close correlation between the mean peak and average wind speeds. The σ curves indicated a large variability in the winds of approximately 6 knots for the 10-minute peak speeds. As stated in the Phase I report, the large variability indicated that the means are likely smoothed low frequency values of high frequency and highly variable data. While these smoothed mean values may be useful in revealing overall diurnal trends, they would be less useful in forecasting the value of a peak wind on any given day.

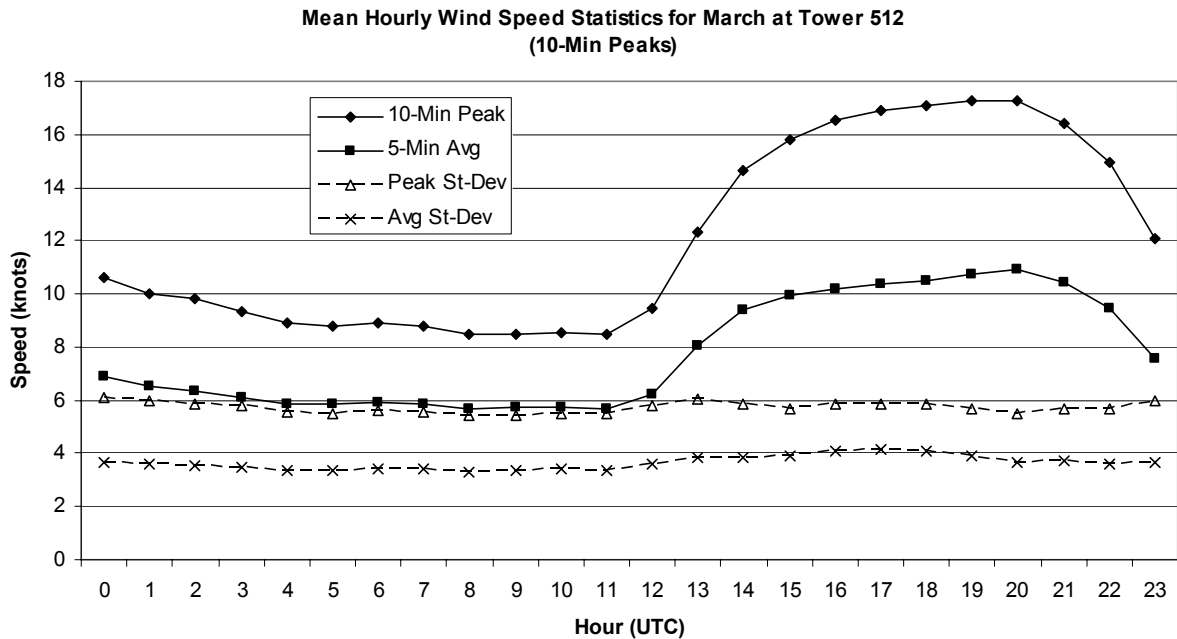


Figure 2. Mean hourly wind speed statistics for March at the 30-ft level of Tower 512. The first (top) solid line is the hourly mean of the 10-minute peak wind speed, the second solid line is the mean of the 5-minute average wind speed, the first dashed line is the standard deviation (σ) of the peak speed, and the second dashed line is the σ of the average speed.

Directional Climatology

This climatology was calculated to determine if there was a monthly pattern in direction for stronger or weaker winds and a preferred monthly direction based on the number of observations in each direction bin. The mean and σ of the 5-minute average and 10-minute peak winds were calculated for each of 36 10° -direction bins. This climatology for March at Tower 512 is shown in Figure 3. It is difficult to discern any kind of trend in wind speed with direction. Each month showed slightly different characteristics, but no obvious pattern. Maximum mean values for Tower 512 in March were from the N ($14.7/9.8$ knots) and SSE ($14.5/10$ knots) directions and minimum values were found in the NNE ($8.9/5.3$ knots), S ($8.9/5.9$ knots), and NNW ($9.3/6.2$ knots) sectors. The large decrease in values from 160° to 180° may have been due partially to an obstruction of flow south of Tower 512 that existed sometime during the POR. The mean speed values for Towers 511 and 513 (not shown) indicated a decrease through the same sectors, but the magnitudes were not as large as seen in Figure 3.

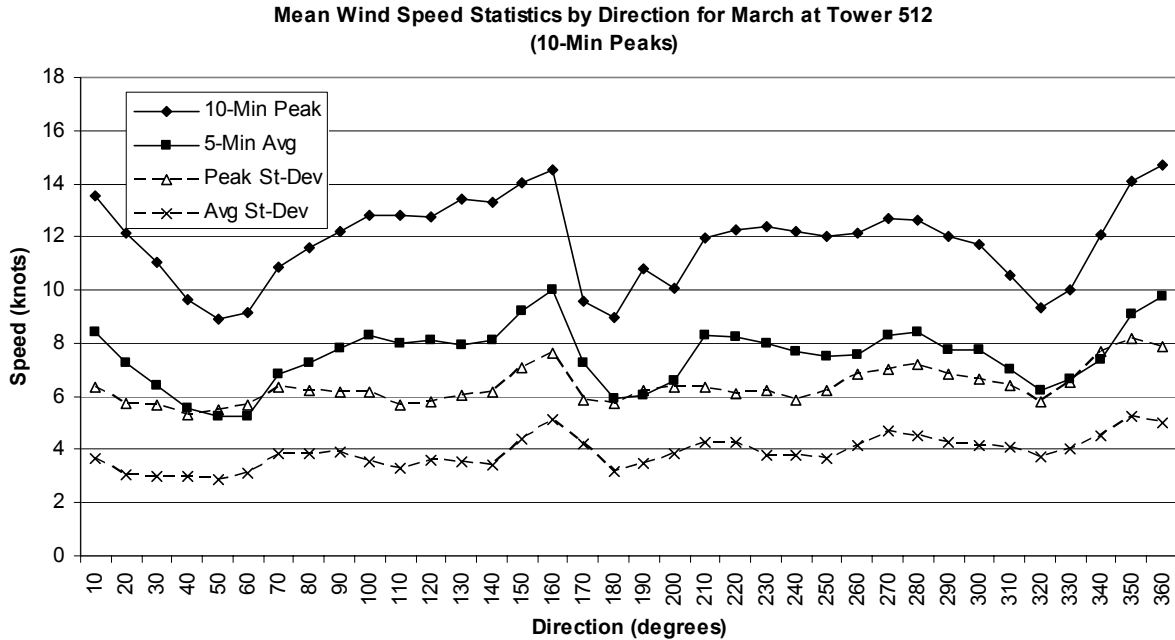


Figure 3. Mean winds speed statistics as a function of 10° wind direction bins for March at the 30-ft level of Tower 512. The values on the x-axis represent the upper range of the direction-bins. The first (top) solid line is the hourly mean of the 10-minute peak wind speed, the second solid line is the mean of the 5-minute average wind speed, the first dashed line is the standard deviation (σ) of the peak speed, and the second dashed line is the σ of the average speed.

The number of peak and average wind speed observations used in the calculations for Figure 3 are shown in Figure 4. This chart was used to reveal the predominant wind direction(s) for each month. Along with the mean speed maximums from the N and S sectors, there were also maximums in the number of observations from these directions. Note the increase in observations for both the 10-minute peaks and the 5-minute averages from the trough at 50° to the peak at 150/160°. This was followed by a large amplitude fluctuation, decrease then increase, in the number of peak wind observations between 160° and 200°. The decrease in the number of average wind observations was more moderate and did not fluctuate. The large variation in the number of peak winds may have been caused by turbulence around an obstruction south of the tower. The drop in the number of observations between 160° and 180° for the 5-minute average winds is consistent with what was observed in the other two SLF towers.

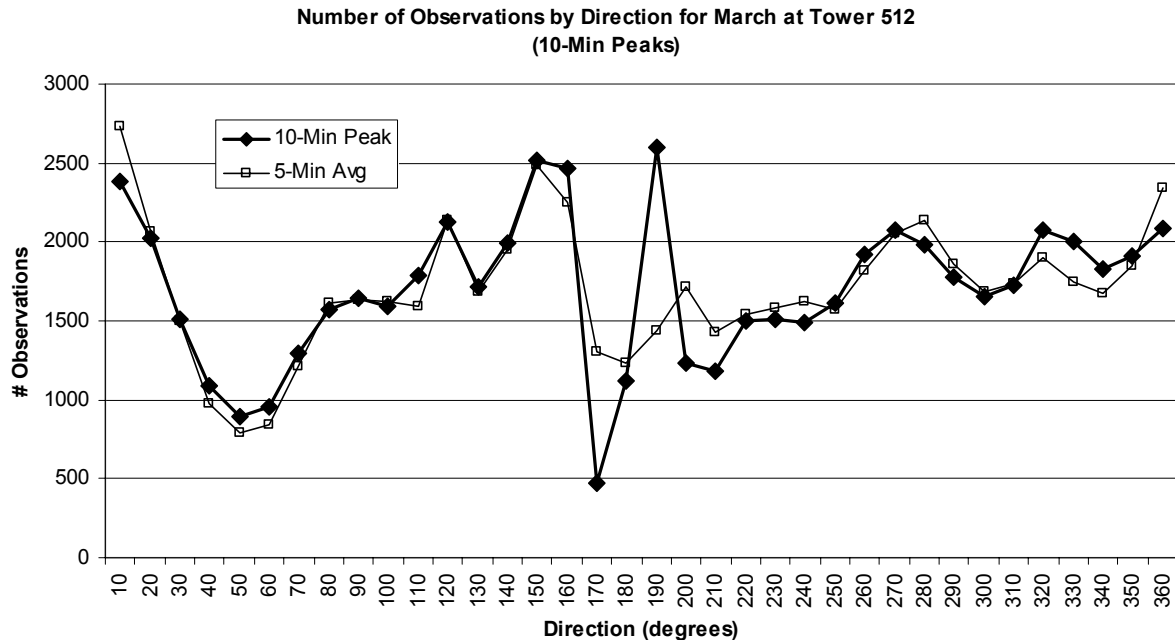


Figure 4. The number of observations used in the statistics calculations as a function of 10° wind direction bins for March at the 30-ft level of Tower 512. The values on the x-axis represent the upper range of the direction-bins. The thick line with diamonds is the count of the 10-minute peak winds, the thin line with boxes is the count of the 5-minute average winds.

The number of peak and average wind observations in Figure 4 were often close, but rarely equal for the same direction bin. The large difference in the number of observations in each hour is the result of the binning process. The direction for each 5-minute average wind is averaged over the 5-minute period, while the 10-minute peak wind direction is a 1-second value. Most often, the two direction values were different, with an average difference of ~7°, which could cause them to be counted in different direction bins. Even with a difference of just 1°, e.g. 90° and 91°, the values could be counted in adjacent direction bins, not the same bin. Larger differences would cause the values to be put in bins not adjacent to each other.

Directional/Hourly Climatology

This climatology was calculated to determine if there were preferential times of day during each month for stronger wind speeds from specific directions. The data were stratified first by direction bin, then hour. Several direction-bin increments were tested in combination with the 24 hourly bins. The direction increments had to be small enough to derive meaningful wind direction climatologies, yet large enough such that a sufficient number of observations were available to calculate dependable values. Eight 45°-direction bins provided the best balance.

Figure 5 shows mean hourly wind speed parameters from the NNW (316 - 360°) for March at Tower 512. This direction bin was chosen to illustrate what time of day the NNW maximum in mean speed seen in Figure 3 was most likely to occur. There was an obvious diurnal trend in the mean speeds, but not σ . The mean speeds as a function of direction and time of day suggest that the strongest winds in March from the NNW were between 18 and 20 knots and occurred between 1900 and 2200 UTC (1400 – 1700 EST). The number of observations used to calculate the values in Figure 5 are shown in Figure 6. There is a broad peak centered at approximately 1200 UTC, local mid-morning, showing that winds from the NNW were more likely to occur between local morning and noon in March.

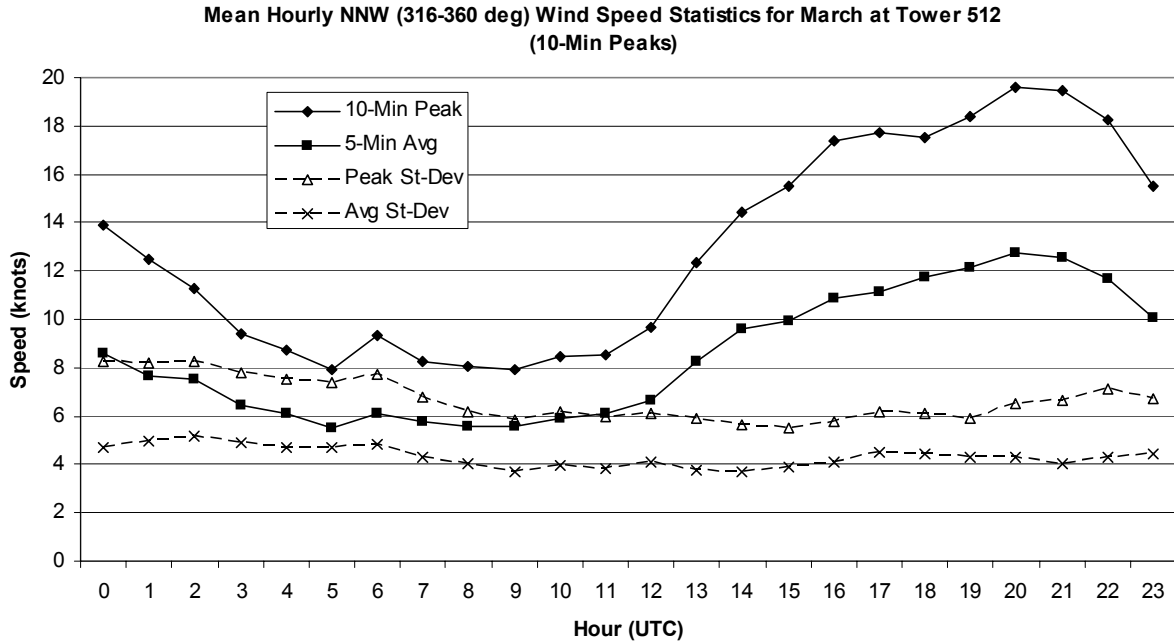


Figure 5. Mean hourly wind speed (kts) for a NNW wind (316 - 360°) in March at the 30-ft level of Tower 512. The first (top) solid line is the hourly mean of the 10-minute peak wind speed, the second solid line is the mean of the 5-minute average wind speed, the first dashed line is the standard deviation (σ) of the peak speed, and the second dashed line is the σ of the average speed.

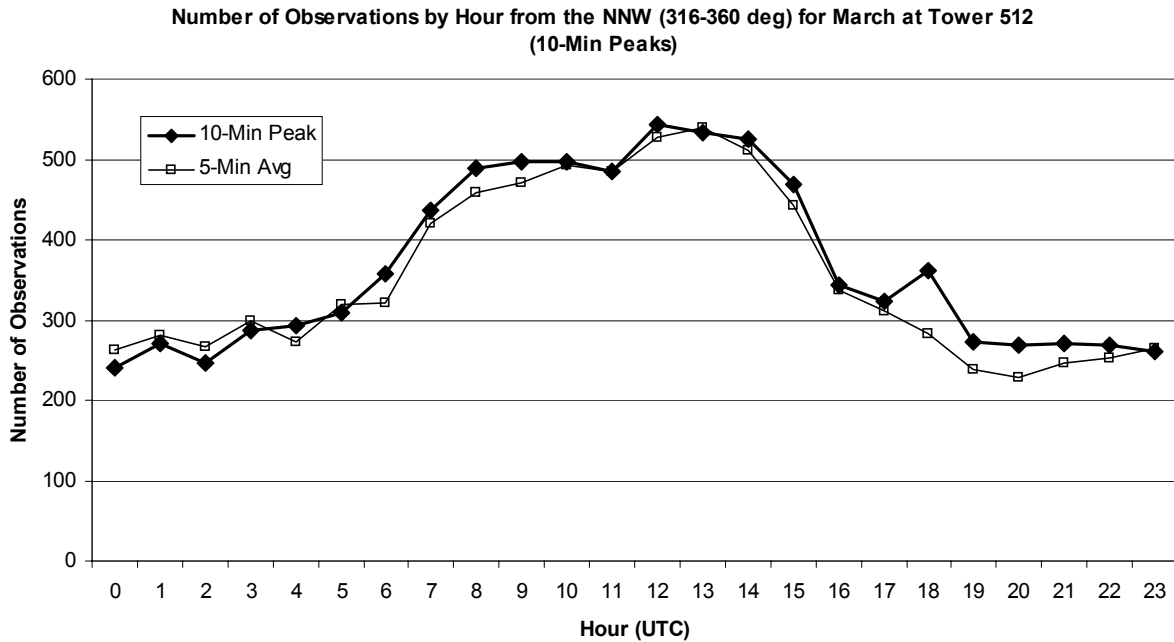


Figure 6. The number of observations used in the mean and σ calculations as a function of hour for NNW winds (316 - 360°) in March at the 30-ft level of Tower 512. The thick line with diamonds is the count of the 10-minute peak wind speeds, and the thin line with boxes is the count of the 5-minute average wind speeds.

2.4. 10-Minute Peak Wind Distribution

Another goal of this task was to calculate the probability of meeting or exceeding specific 10-minute peak speed values, similar to the 5-minute peak values in Phase 1. For the reasons stated earlier, 5-minute average winds are used in place of the 2-minute average winds used in the FR. The observed, or empirical, distributions, in the form of probability density functions (PDFs), were calculated first. Then an appropriate distribution model was fit to the data, followed by creation of modeled distributions.

Empirical Distributions

The empirical PDFs were calculated to show the observed distribution of 10-minute peak wind speeds for each knot of 5-minute average wind speed. They can also be used to determine the climatological probability of meeting or exceeding a given 10-minute peak speed based on the average speed. The calculation to create a PDF is straightforward: the number of individual peak speed observations in the distribution is divided by the total number of observations of the associated average wind speed. This produces a value that represents the fractional occurrence of each peak speed in the distribution. The sum of all the fractional numbers in the distribution is 1, and a graph of these fractional values is called the PDF. The empirical PDFs for Tower 512 in March are shown in Figure 7. Each curve represents the range of 10-minute peak wind values associated with each 5-minute average speed (legend in Figure 7). The value on the y-axis is the fractional occurrence of a particular peak speed for a given average speed. To determine the probability of meeting or exceeding a certain peak value, integrate the area under the curve from the value of interest forward. The PDF for the 5-minute average speed of 10 knots in Figure 7 is displayed in the inset as an example. The curve is dashed up to 15 knots, and solid thereafter. Integrating under the solid line shows that the probability of meeting or exceeding 15 knots when the average speed is 10 knots is 0.78, or 78%.

One feature seen in Figure 7 is that most of the PDFs had a continuous shape, and their height and width decreased and increased, respectively, with increasing average speed. When the average speed reached 18 knots, however, the PDFs no longer had a continuous shape nor continued the height/width trend of the previous PDFs. The number of observations used to calculate the PDFs for 18 knots and up was less than 600, with that number dropping quickly from 438 at 18 knots to 4 at 25 knots. It may not be appropriate to use these PDFs to determine a climatological probability of exceeding certain peak speeds because of the lack of observations. The gray curves in Figure 7 show which PDFs were calculated with less than 600 samples. The number of observations for the average wind speeds decreased very rapidly with speed at higher wind speeds for all towers.

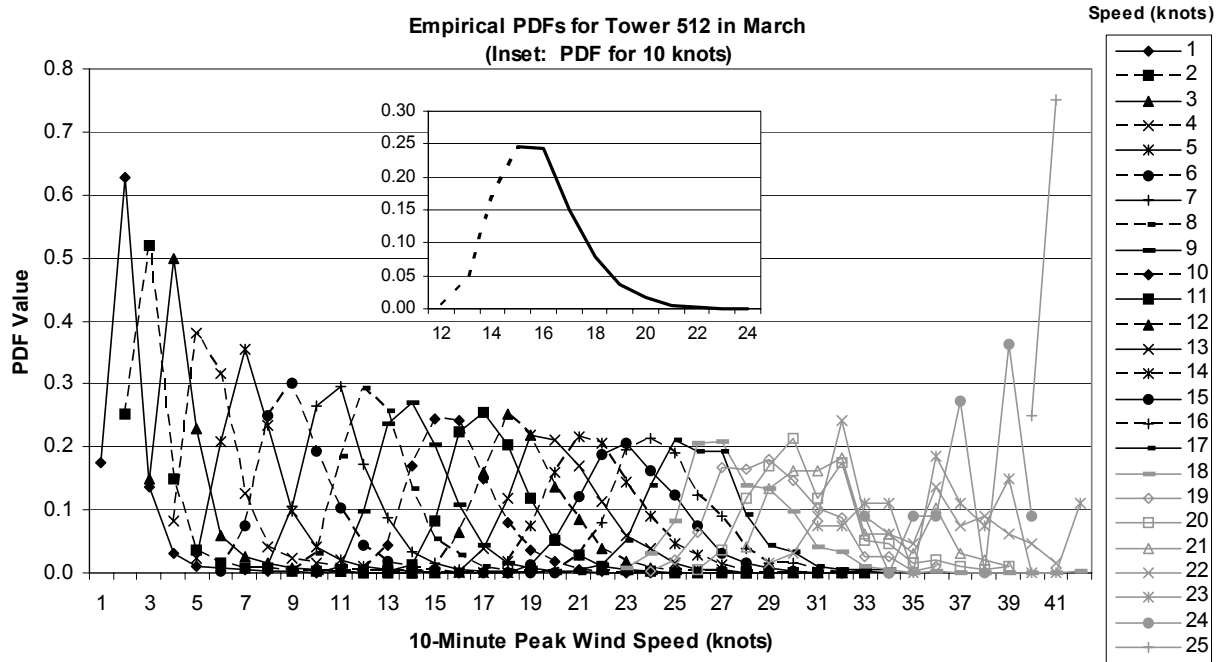


Figure 7. The empirical PDFs of the March 10-minute peak wind speed distributions associated with each 5-minute average wind speed (see legend) from 1 - 25 knots for Tower 512 at 30 ft. The gray PDFs were calculated from distributions with less than 600 observations. The legend shows the 5-minute average speeds associated with each PDF. The black PDF lines alternate solid and dashed to make them easier to distinguish. The value on the y-axis is the fraction of events for a particular 10-minute peak speed. The inset is the PDF for the 5-minute average speed of 10 knots in reference to the example in the text. Integrating the area under the solid line shows that the probability of meeting or exceeding 15 knots is 78%.

Distribution Model Determination

There are several reasons for fitting a distribution model to an empirical distribution defined in Wilks (1995), two of which applied in this study. The first was to smooth and interpolate over the variations in empirical distributions due to possible under-sampling of a specific peak gust. The second reason was to estimate probabilities of peak gusts associated with average wind speeds outside the range of the observations in the data sample. The assumption here is that the distribution model would also represent the peak wind distributions for rarely or as-yet unobserved average wind speeds. Determining the validity of this assumption proved to be difficult for peak wind speeds.

The PDFs shown in Figure 7 and for the other towers were asymmetrical and, therefore, not Gaussian. They were also bounded on the left-hand side by the value of the average wind speed. Two possible theoretical distributions identified by Wilks (1995) for data with these characteristics are the gamma and Weibull distributions, although he identifies the Weibull distribution as being more widely used to model wind speeds. There is little support in the literature for using the gamma distribution for peak winds, and strong advocacy for using the Weibull distribution (see Reference section in Lambert 2002). In Phase I, the 5-minute peak distributions were decidedly Weibull. However, given the change in peak-speed time interval, it was not assumed in this phase of the task that the 10-minute peak winds would behave similarly to their 5-minute counterparts. Therefore, both the gamma and Weibull distributions were compared to ensure that the most appropriate distribution model was used.

The gamma and Weibull distributions were compared by using their respective built-in distribution estimation functions in S-PLUS. The peak wind observations for a given average wind speed (per tower/height) were input to the function. This function output the corresponding gamma and Weibull parameters that defined the best fit to the observed PDFs (as in Figure 7). Once the best-fit parameters were determined, they were input to another S-PLUS function that modeled the PDFs for both the gamma and Weibull distributions. The modeled PDFs were plotted and compared qualitatively with the observed PDFs to determine which distribution model fit the observed distribution best. This was done for all PDFs for every month at each tower and height. For PDFs with more than 600 observations, the gamma fit to the observed PDFs was superior.

There are few results in the literature to support the use of a gamma distribution for wind speeds. An extensive search uncovered only four journal articles: Romanenko (1976), Neumann (1977), Roldan-Cañas et al. (1982), and Yan et al. (2002). In a preliminary test, Romanenko (1976) found that the gamma distribution was a reasonable fit to an entire 10-year data set of hourly surface wind observations from 10 surface stations with no stratification by season, time of day, or station. Neumann (1977) assumed that wind speeds were gamma-distributed based on a qualitative analysis of a 20-year record hourly wind speed data. Roldan-Cañas et al. (1982) assumed a gamma distribution for their wind speed observations referring to Romanenko (1976) and Neumann (1977). While noting that the Weibull distribution was the most commonly used for analyzing wind speed, Yan et al. (2002) contended that the gamma and Weibull distributions are sufficiently similar in their shape that the outcome of their study would not be affected by the choice of one over the other.

To confirm the AMU result quantitatively, the Kolmogorov-Smirnov test was performed (Wilks 1995). This test calculates the largest difference between the empirical and model probabilities. If this number was sufficiently large, the null hypothesis that the sample was drawn from a population with a gamma distribution could be rejected. In each case, the difference was sufficiently small that the null hypothesis could not be rejected at any level for the gamma distribution. Neither distribution model could be fit to the empirical PDFs created from fewer than 600 observations (gray PDFs in Figure 7). There appears to be not enough observations of those particular average wind speeds to create representative estimates of peak wind distributions.

It should be noted here that the cutoff value of 600 observations is approximate, and not supported by any findings in the literature. An extensive manual data analysis revealed the cutoff number to produce a viable gamma fit was approximately between 500 and 700. In one case, an average speed of 16 knots with 650 observations was fit successfully, while the following speed at 17 knots with 532 observations was not. This feature may be unique to the KSC/CCAFS wind tower network. Researchers following the methodology described here should be aware of this feature and examine their own data for their particular cutoff parameter.

Estimated Probability Density Functions

In Phase I (Lambert 2002), test results suggested strongly that the validity of modeling the peak speed distributions at higher wind speeds was in question. There were far too few observations at these speeds to determine the appropriate theoretical distribution. Given that the data set used in this study was identical and the same dearth of observations existed at higher wind speeds, it was assumed that the peak wind distributions for the higher wind speeds could not be estimated reliably. However, the abundance of observations at lower speeds allowed the assumption that their peak speed distributions were gamma. The estimated gamma PDFs for Tower 512 at 30 ft in March are shown in Figure 8. These PDFs are more likely represent the PDFs of the entire wind speed population. Figure 9 shows the probability curves for the PDFs in Figure 8. A forecaster can identify the curve for a 5-minute average speed of interest, then locate the point on that curve for the 10-minute peak speed of interest and determine the probability of meeting or exceeding that peak speed by the values on the y-axis. For example, if the average wind is observed or forecast to be 10 knots (dashed line with solid diamonds), the probability of meeting or exceeding 15 knots is 0.78, or 78%.

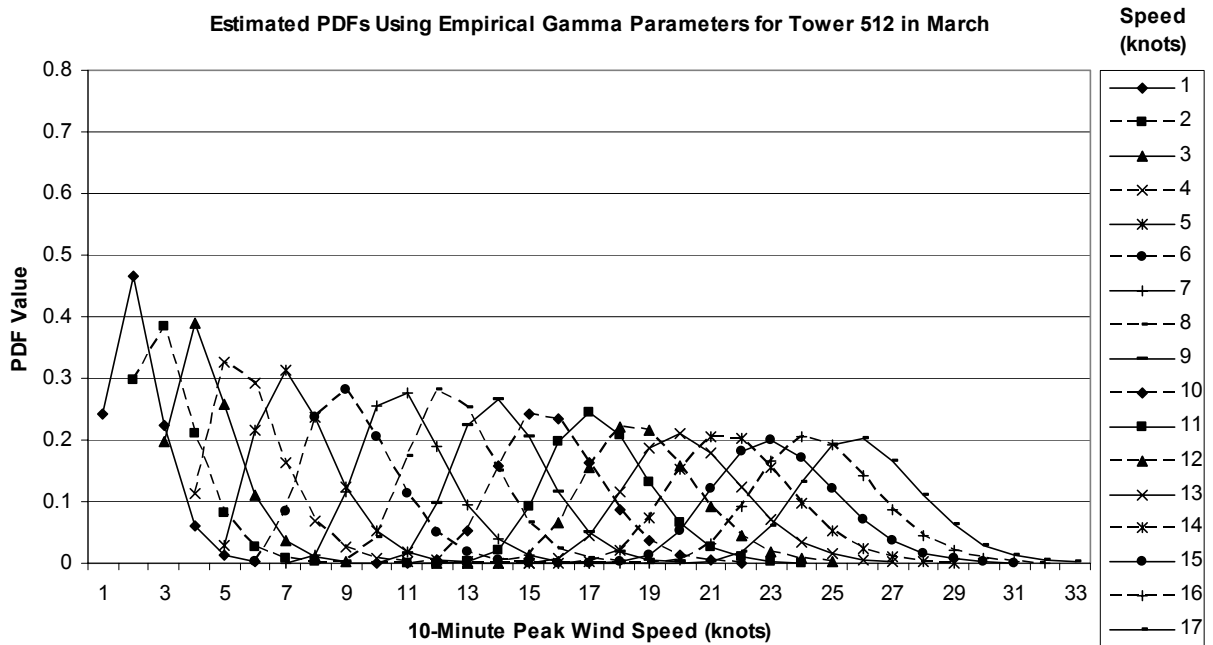


Figure 8. The estimated gamma PDFs of the March 10-minute peak wind speed distributions associated with each 5-minute average wind speed (see legend) from 1 - 17 knots for Tower 512 at 30 ft. The legend shows the 5-minute average speeds associated with each PDF. The PDFs alternate solid (even) and dashed (odd) lines to make them easier to distinguish.

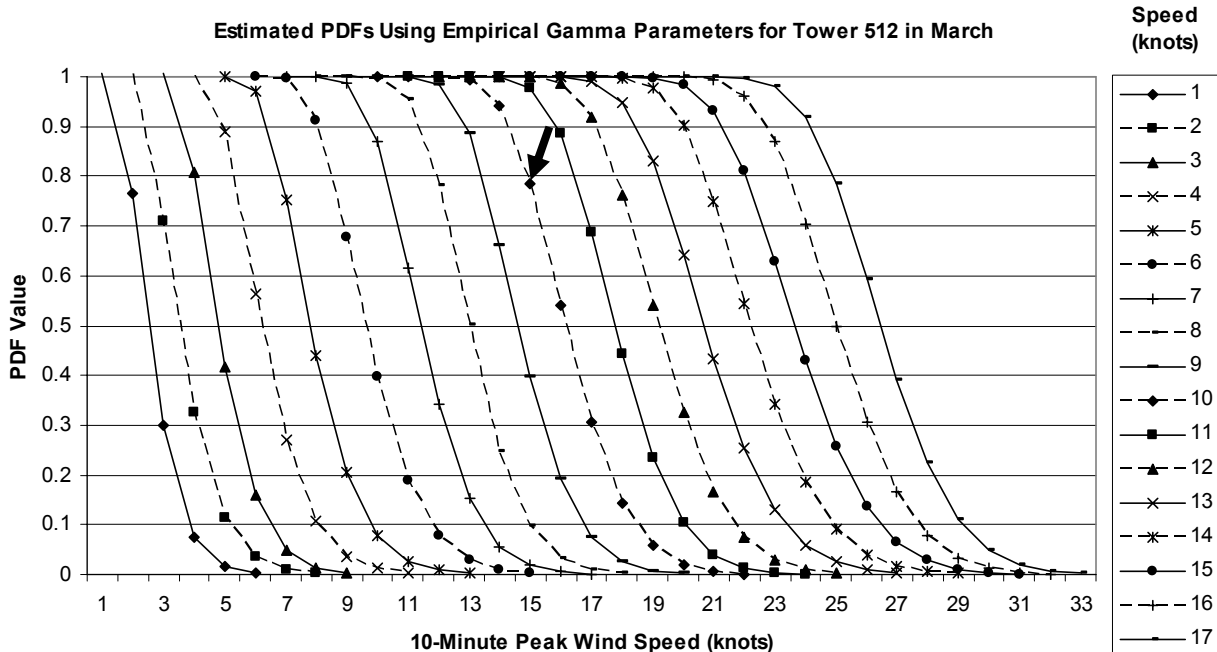


Figure 9. The probability curves for the estimated gamma PDFs in Figure 8. The curves alternate solid (even) and dashed (odd) lines to make them easier to distinguish. The black arrow points out the location of the 15 knot peak wind speed on the curve for 10 knots that is used as an example in the text.

3. Graphical User Interface

Two basic products are available for SMG forecasters to access the climatology and probability values discussed in the previous section. The first is the Excel pivot charts and tables similar to those developed during Phase I. These displays are very flexible, allowing changes to the charts and tables with point-click-drag techniques. Axes can be switched, multiple variables can be represented on one axis, and specific curves can be temporarily removed from the display to facilitate closer examination of the remaining curves. Although they provide a useful visualization of the wind speed behavior with hour and direction, confident use of the pivot charts requires training and experience. Even with experience, the charts could still be difficult to manipulate and interpret in a fast-paced operational environment. The forecasters requested that a PC-based GUI be developed that would display the requested information quickly and in an easy-to-interpret format. Therefore, a PC-based GUI tool was developed to display the 5- and 10-minute peak wind speed climatologies and probabilities using the Visual Basic for Applications (VBA) in Excel. Given that the pivot charts were described in the Phase I final report (Lambert 2002), only the GUI will be described in this section.

3.1. Input GUI

The GUI that prompts the user for the input is shown in Figure 10. The input GUI has separate pages for climatology and probability analyses, with tabs at the top for the user to select the page for the analysis is desired. In Figure 10, the page for input to retrieve climatology data is on the left and the page for input to retrieve probability data is on the right.

On the Climatology page, the user first chooses the peak speed time interval. The 5-minute peak speed climatologies are for the SLF towers (Towers 511, 512, and 513) and Tower 313 and the 10-minute peak wind climatologies for the SLF towers only. After choosing the peak speed time interval of interest, the user chooses the tower and month of interest from the appropriate drop-down lists. The final step is to choose one of the three stratifications and the desired hour and/or direction sector in the associated drop-down list(s). The label 'True North' was added to the GUI next to the Direction option to remind the user that the wind sensors are aligned on true north. After all choices are made, the user will click on the Get Climatology command button and an output GUI with the retrieved information will be displayed (Section 3.2).

The inputs are the same on the Probability page, except that the user chooses the empirical or modeled distribution of the time interval/tower/month combination of interest instead of an hourly and/or directional stratification. The user will then select the 5-minute average wind speed of interest. The range of values in the Empirical and Model drop-down lists changes according to the choices made for time interval, tower, and month. The Empirical range includes all 5-minute wind speeds observed for a particular tower and month, while the Model range only includes the 5-minute wind speeds with enough observations ($> \sim 600$) to be fit with a distribution model. The Get Probabilities command button will display an output GUI with a range of peak speeds associated with the input average speed and their probabilities of occurrence (Section 3.3).

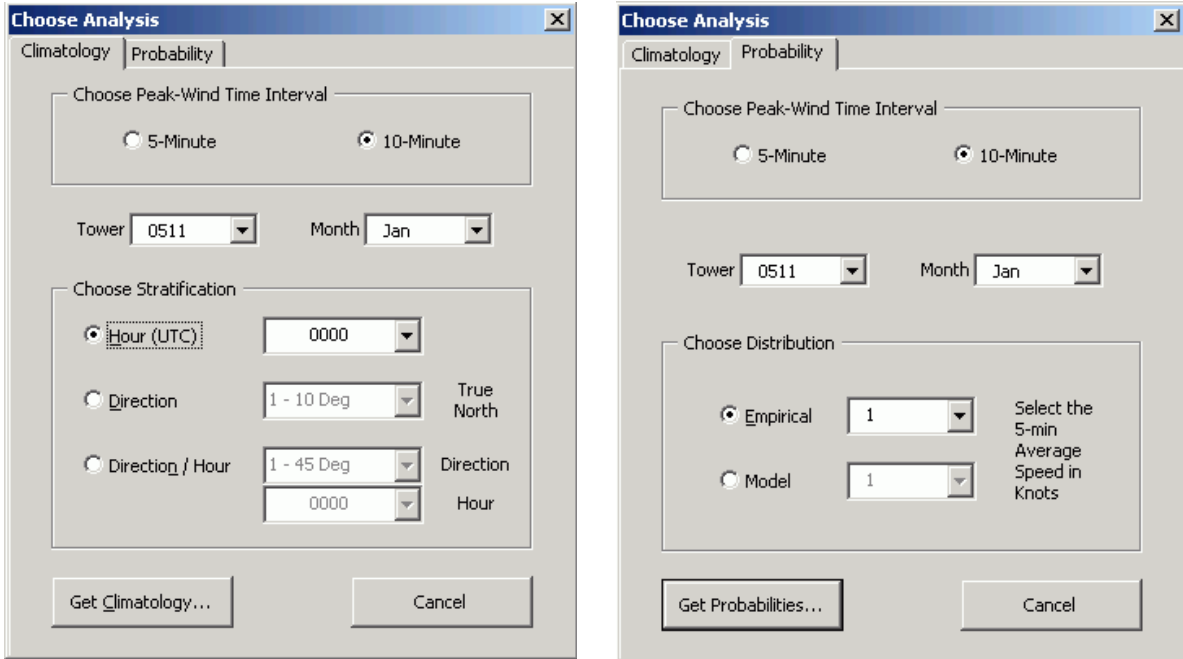


Figure 10. The two pages in the input GUI used to retrieve the requested climatological or probability of occurrence data. The left panel inputs the information needed to retrieve the climatology data, and the right panel inputs the information needed to retrieve the probability data.

3.2. Climatology Output GUI

Once the Get Climatology button is clicked, one of three GUIs is displayed depending on the choice of stratification in the Climatology input GUI. Each GUI is identical to the other except for some minor differences to be described below. The same output GUI design was used for all three stratifications for more efficient coding in Excel VBA.

The GUI in Figure 11 is the result of choosing the hourly climatology. At the very top, the user's choice of peak wind time interval, tower, and month are displayed along with the height of the sensor. In the Stratification area below, the user's choice of hour is displayed, with the label 'Hour (UTC)' activated to show that the choice from the input GUI was for the hourly stratification. The label 'Direction' and its associated text box are deactivated and set to light gray so there is no confusion to the user which climatology is being displayed. The climatologies of interest are displayed in the 'Wind Statistics' section. This includes the mean, standard deviation, and number of observations for the peak and average wind speeds. Next to this section is the 'Choose Another Analysis' button that is used to close the GUI and allow the user to choose another analysis from the input GUI. The notice at the bottom is intended to remind the users that the values displayed are calculated from historical data, not currently observed data, and should not be used as an absolute forecast for future winds.

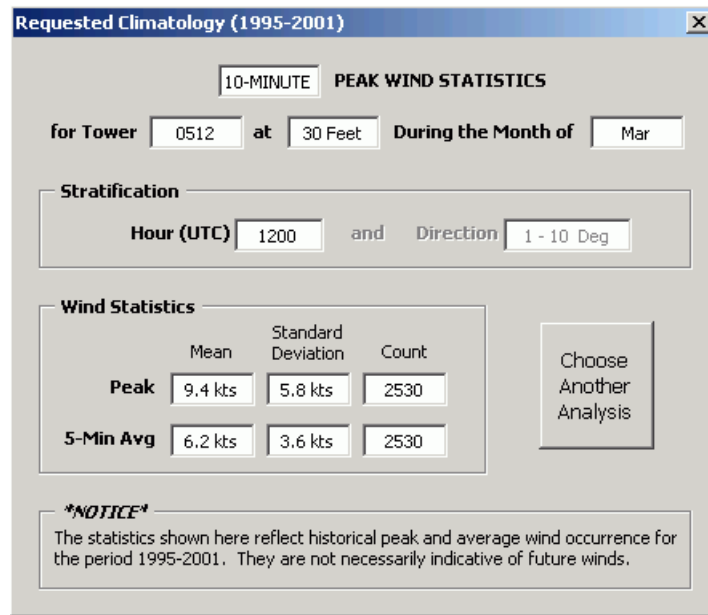


Figure 11. Output GUI for the hourly climatology choice. The GUI displays the peak speed time interval, tower number, sensor height, month, and hour of the climatology in the top half. The mean, standard deviation, and number of observations are shown for both the peak and 5-minute average winds. The Choose Another Analysis button closes the GUI. The notice reminds the user that the data used are historical and not based on current observations.

The GUI in Figure 12 is the result of choosing the directional climatology. The type of information displayed at the top is the same as for the hourly climatology. Below this, the user's choice of direction bin is displayed, with the label 'Direction' activated to show that the choice from the input GUI was for the directional stratification. The label 'Hour (UTC)' and its associated text box are de-activated and set to light gray so there is no confusion to the user which climatology is being displayed. The climatologies of interest are displayed in the 'Wind Statistics' section, and includes the same statistics as for the hourly climatology. The 'Choose Another Analysis' button and notice at the bottom are the same as discussed previously.

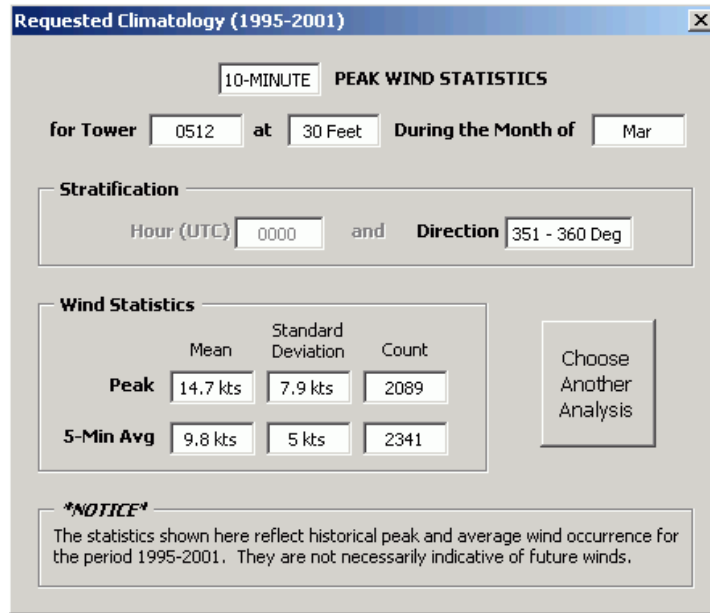


Figure 12. Output GUI for the directional climatology choice. The GUI displays the peak speed time interval, tower number, sensor height, month, and direction bin of the climatology in the top half. The mean, standard deviation, and number of observations are shown for both the peak and 5-minute average winds. The Choose Another Analysis button closes the GUI. The notice reminds the user that the data used are historical and not based on current observations.

The GUI in Figure 13 is the result of choosing the directional/hourly climatology. Similarities to the previous two GUIs include the tower, month, and peak speed interval at the top, the ‘Choose Another Analysis’ Button, and the notice at the bottom. In the Stratification box, both the hour and direction labels and text boxes are activated to show that the choice from the input GUI was for the directional/hourly stratification. The text boxes contain the choice for hour and direction bin. The climatologies displayed in the ‘Wind Statistics’ section include the same statistics as for the other two GUIs, except that the number of observations is replaced by the percent of total observations in the hour. Since the total number of observations from a particular direction sector can vary for any hour, displaying the number of observations did not provide enough information about whether wind from a certain direction was more or less common for a particular hour. If all observations in a particular hour were evenly divided between all eight sectors, the value in this box would be 12.5% for every sector. Values larger or smaller than this would show forecasters whether winds from a particular sector were more or less prevalent for a certain hour.

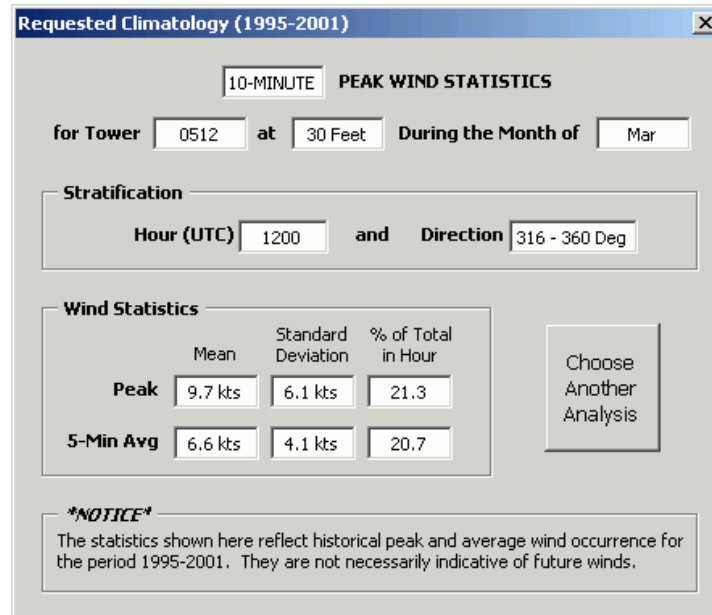


Figure 13. Output GUI for the directional/hourly climatology choice. The GUI displays the peak speed time interval, tower number, sensor height, month, hour, and direction bin of the climatology in the top half. The mean, standard deviation, and percent of observations in the hour are shown for both the peak and 5-minute average winds. The Choose Another Analysis button closes the GUI. The notice reminds the user that the data used are historical and not based on current observations.

3.3. Probability Output GUI

The GUI in Figure 14 is displayed when the Get Probabilities button is clicked. The first line displays the user’s choice of empirical or modeled distribution and the peak wind time interval. The second line shows the choice of tower and month, including the height of the sensor. The third line shows the choice of 5-minute average wind speed. The probabilities of interest are displayed in the ‘Peaks and Probabilities’ section, which contains three rows, each with 12 text boxes. The first row shows the first 12 values in the distribution of peak speeds associated with the chosen 5-minute speed (10 knots in Figure 14). If there are less than 12 values in a range, N/As are displayed in the boxes after the last value in the range. Each box in the second row shows the probability, in percent, of meeting or exceeding the peak speed in the box directly above it rounded to the nearest whole number. The last row contains the probability of occurrence (the PDF values) in percent for each individual peak speed in the range. In Figure 14, a peak speed of 15 knots has the highest probability of occurrence at 24%, and the probability of meeting or exceeding 15 knots is 78%. The notice at the bottom is the same as that in the climatology output GUIs. To the right of the notice is the ‘Retrieve Another Probability Range’ button that is used to close the GUI and allow the user to choose another analysis from the input GUI.

The values in the second line were calculated by summing over the PDF distribution values in the third line from the peak speed of interest to the end of the distribution on the right-hand side. The user may notice that the values in the second line are not always the exact sum of the corresponding values in the third line. The numbers displayed in both rows are rounded to the nearest integer value for display, but the probabilities in the second line were calculated by summing over real numbers in the PDF. This introduces small rounding errors in the display of the values. Also, the calculations for the probabilities in the second line were carried out over the entire distribution, not just over the first 12 values as displayed.

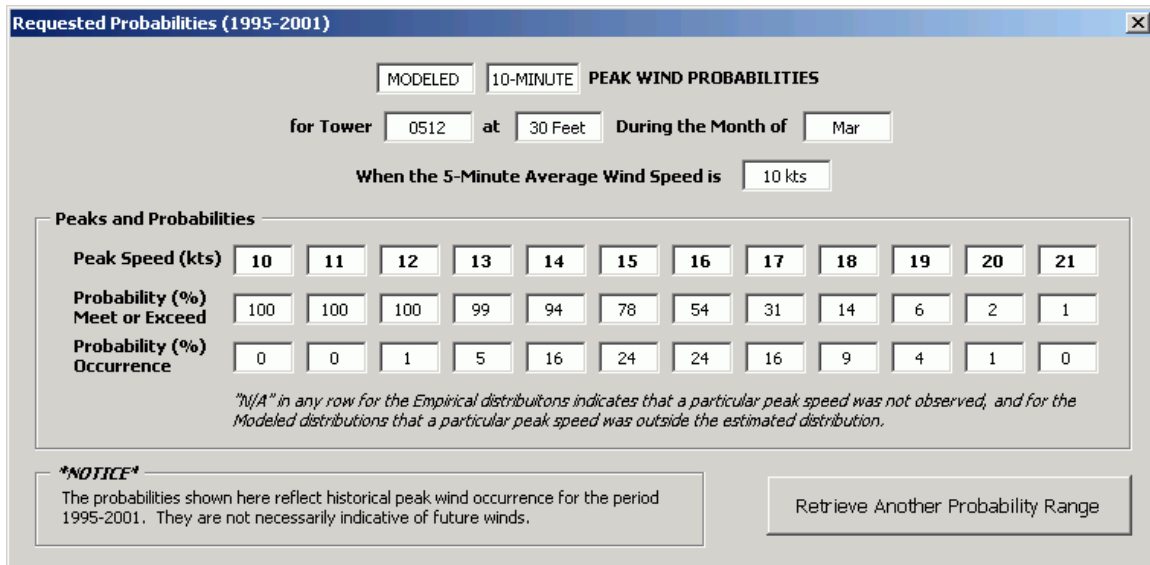


Figure 14. Output GUI for the probabilities. The GUI displays chosen distribution type, the peak speed time interval, tower number, sensor height, month, and 5-minute average wind speed of the probabilities in the top half. The first 12 values in the peak speed distribution and their associated probabilities of being met or exceeded and PDF values are shown in the Peaks and Probabilities section. The Retrieve Another Probability Range button closes the GUI. The notice reminds the user that the data used are historical and not based on current observations.

The reason for displaying only the first 12 values in the distribution range should be noted here. It is the result of two issues. The first is the inability of the software to be flexible in the number of text boxes displayed in the GUI. To the extent of the programmer's knowledge, the number of boxes must be fixed. The number of boxes is the result of a FR that defines a violation when the peak speed is 11 or more knots greater than the average speed. Displaying the first 12 values in the range will ensure that the probabilities for the peak speeds in question will be displayed. Using this particular FR in Figure 14, a violation would occur if the peak speed reached 21 knots or more. The values for 21 knots are displayed, which is enough to help SMG forecasters evaluate this FR.

4. Summary

The goal of this task was to extend the results found in Phase I (Lambert 2002) to include the 10-minute peak winds from the SLF towers, as SMG uses the 10-minute peak from these towers as the standard for determining and verifying wind speed FRs. The first objective of this phase was to re-calculate the climatologies and probabilities for the 10-minute peak wind speed and display them in Excel pivot charts as in Phase I. The second objective was to develop a GUI to be used on a PC that would display the climatologies and probabilities quickly and easily. Both objectives were met successfully.

4.1. 10-Minute Peak Winds Analysis

The next step was to calculate the 10-minute peak value in the data set for the SLF towers, since only the 5-minute values were archived. Once that data base was available, the climatologies were calculated according to the stratifications outlined in Phase I. This involved stratification by tower and month first, and then three separate stratifications including

- Hour,
- Direction (10° sectors), and
- Direction (45° sectors) and hour.

The means and standard deviations of the 10-minute peak and 5-minute average wind speeds were calculated according to the stratifications.

The next analysis involved creating 10-minute peak wind speed distributions for the 5-minute average wind speeds in 1-knot intervals. The data for each tower/month combination were stratified by average wind speed, and the peak speed PDFs for each observed average wind speed was created. Tests revealed that the peak speed PDFs for average speeds that were observed at least 600 times resembled the gamma distribution, not the Weibull distribution as was found in Phase I for the 5-minute peak winds. This was unusual as there is very little support in the literature for using the gamma distribution in this capacity. As was found in Phase I, peak-speed PDFs for the average wind speeds with less than 600 observations were erratic and not amenable to fitting with a distribution model. The empirical PDFs for every observed 5-minute average wind speed and the modeled PDFs for average wind speeds with ~600 observations or more were created, and probabilities of peak-speed occurrence were calculated from them.

4.2. Operational Products

All of the climatologies, PDFs, and probability curves were displayed in Excel Pivot Charts and were delivered to the SMG forecasters for their use while the PC-based GUI was being developed. These displays are very flexible, allowing changes to the charts with point-click-drag techniques. Axes can be switched, multiple variables can be represented on one axis, and specific curves can be temporarily removed from the display to facilitate closer examination of other curves. Some examples of pivot charts are shown in Section 2.

Confident use of the pivot charts requires training and experience and could be difficult to manipulate and interpret in the operational environment. Therefore, the forecasters requested that a GUI be developed that would display the requested information quickly and in an easy-to-interpret format. The GUI was developed using VBA in Excel and displays the 5- and 10-minute peak wind speed climatologies and probabilities. The GUIs described and shown in Section 3 are the result of several consultations between the AMU and forecasters at SMG. They were shown the GUI at several steps in the development to test and make suggestions for modifications, all of which were incorporated. This ensured that the end product met their needs, was easy to use, and produced useful information in a readable format. These GUIs have been delivered to SMG and are in current operational use.

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List of Acronyms

45 WS	45th Weather Squadron
AMU	Applied Meteorology Unit
CCAFS	Cape Canaveral Air Force Station
ELV	Expendable Launch Vehicle
EST	Eastern Standard Time
FR	Flight Rules
GUI	Graphical User Interface
KSC	Kennedy Space Center
LCC	Launch Commit Criteria
PC	Personal Computer
PDF	Probability Density Function
POR	Period of Record
SLF	Shuttle Landing Facility
SMG	Spaceflight Meteorology Group
UTC	Universal Coordinated Time
VBA	Visual Basic for Applications

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