7.7 DEVELOPING A PEAK WIND PROBABILITY FORECAST TOOL FOR KENNEDY SPACE CENTER AND CAPE CANAVERAL AIR FORCE STATION

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1. INTRODUCTION

The peak winds are an important forecast element for the Expendable Launch Vehicle (ELV) and Space Shuttle programs at Kennedy Space Center (KSC) and Cape Canaveral Air Force Station (CCAFS) in east-central Florida. Launch Commit Criteria (LCC) define specific peak wind speed and direction thresholds for each launch operation that cannot be exceeded in order to ensure the safety of the vehicle. Peak speeds and directions are measured every second and displayed in real time in 1- and 5-minute intervals. A forecast of just one peak speed beyond the LCC threshold during the launch window can scrub a launch operation. The peak wind LCC cover heights from 54 to 230 ft at the launch pad or nearby instrumented weather tower, depending on the launch vehicle, can extend up to eight hours depending on the launch window, and have a small dependence on direction based on sheltering effects from the tower. The details of the peak wind requirements for each operation are specified by the launch customer well before the launch window.

The 45th Weather Squadron (45 WS) launch weather officers (LWOs) must provide forecasts of the peak winds to the launch customers, but their experience shows that peak winds are a challenging parameter to forecast, particularly in the cool season months of October through April. This is expected, given the complex terrain of land and water in very close proximity across the KSC/CCAFS area. Peak winds are also difficult to forecast during the warm season months of May – September, but their magnitudes are usually well below the LCC limits except during convective or tropical cyclone events. Launch operations will not take place when these events occur. Research has confirmed that forecasting such low altitude peak winds is a challenge. Both climatological (Coleman 2000) and neural network methods (Storch 1999 and Cloys 2000) have been investigated but were shown to be inferior to even simple persistence.

The Applied Meteorology Unit (AMU) (Bauman et al. 2004) was tasked to alleviate some of the difficulty in making this forecast, by providing cool season climatologies and distributions of 5-minute average and peak winds from the KSC/CCAFS wind tower network in a Phase-I study using data collected in the years 1995 – 2001 (Lambert 2002). The 45 WS requested that the AMU update these climatologies with more data collected over the last several years and to use new stratifications. These modifications will likely make the statistics more robust and useful to operations. The 45 WS also requested a graphical user interface (GUI) that will display the climatological values requested by the user for improved speed, accuracy, and ease of use.

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2. BACKGROUND

In Phase I (Lambert, 2002), the AMU created cool season climatologies and frequency distributions for all wind sensors used in evaluating LCCs in the seven-year period of record (POR) 1995–2001. The values included climatologies of the 5-minute mean and peak winds by month, hour, and direction, and distributions of the peak winds as a function of 5-minute mean wind speeds in 1-knot (0.514 m s^{-1}) intervals. The distributions were used to determine the probability of meeting or exceeding an LCC-associated peak speed given the current mean speed. The climatologies were displayed using the PivotChart feature in Microsoft® Excel, which allows flexibility in displaying the data by hour, direction, month, and variable. Similar climatologies were created in Phase II (Lambert, 2003) for the towers used in evaluating Shuttle Flight Rules. In addition to the PivotCharts, the AMU created a GUI within Excel that allowed the forecasters to display only the values of interest.

The climatologies calculated in Phases I and II were diagnostic rather than prognostic. The mean and peak wind speed values observed at the same time were analyzed as pairs. The peak wind speed distributions were also based on the peak speeds that were observed at the same time as the mean speeds. The forecasters used these values in a prognostic sense by forecasting a mean wind speed and then determining the peak speeds associated with that mean speed. The current Phase-III work will add a prognostic element to the probability distributions. The same diagnostic distributions as in the previous work will be calculated along with new distributions of peak winds observed within 2, 4, 8, and 12 hours after an observed mean wind.

3. DATA

There are 44 instrumented weather towers in the KSC/CCAFS area whose data are used for launch, safety decisions, and local forecasting. The mean and peak wind data used in this work are from the specific towers used in making launch decisions for the Space Shuttle, Atlas, Delta II and Delta IV vehicles. Figure 1 shows the locations of these towers on KSC/CCAFS.

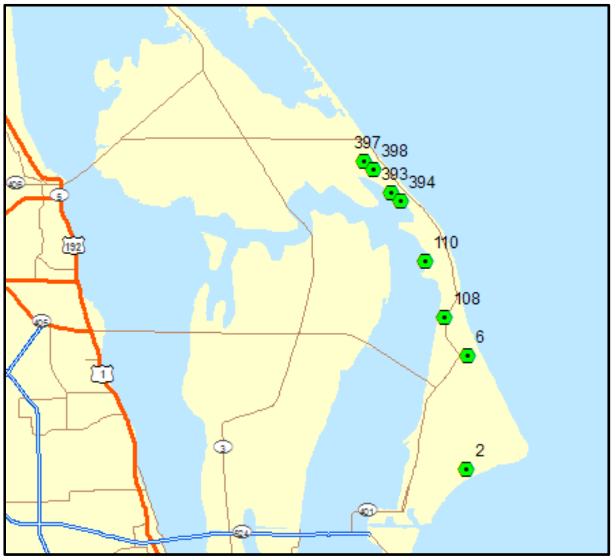

Figure 1. A map of the KSC/CCAFS area showing the locations and numbers (green dots) of the towers used to evaluate the peak wind LCC.

Table 1 shows the tower numbers and sensor heights used in evaluating the LCC for each vehicle. If the data from the sensor at the primary height are not available, data from the sensor at the backup height are used in evaluating peak wind LCC.

The wind data are the 5-minute mean and peak speeds and directions from each sensor in Table 1. The mean wind is the average of 300 1-second observations collected over 5 minutes, and the peak is the highest 1-second wind in the 5-minute period.

Table 1. Launch vehicles and their associated wind towers (Figure 1) and sensor heights used to evaluate the LCC.

Launch Vehicle	*Tower(s)*	*Primary Height*	*Backup Height*
Shuttle	393/394 *(SLC 39A)* 397/398 *(SLC 39B)*	60 ft	N/A
Atlas	110	204 ft	54 ft
Delta II	2	90 ft	54 ft
Delta IV	6, 108	54 ft	12 ft

The POR includes the cool season months from January 1995 to April 2007. The data were quality controlled (QC) using an automated QC program developed in the AMU specifically for the KSC/CCAFS wind tower network (Lambert 2002). Once QC-d, the data were processed using the S-PLUS® software package (Insightful Corporation 2005).

4. CLIMATOLOGICAL PRODUCTS

Five climatological products will be created for each cool season month, October – April:

- Hourly means and standard deviations (σ) of the 5-minute mean and peak speeds,
- Directional means and σ of the 5-minute mean and peak speeds in 10-degree increments,
- Hourly means and σ of the 5-minute mean and peak speeds further stratified by direction in 45-degree increments,
- Empirical cumulative distribution functions (CDFs) of peak speed probability, conditional on the 5-minute mean speed, and
- CDFs created by fitting a parametric distribution to the empirical CDFs.

The first three products show the mean behavior and variability of the wind speeds for different times of the day and from different directions. The last two products determine the probability of meeting and exceeding each of the peak speeds in the distributions associated with each mean speed. They will include the diagnostic and prognostic 2-, 4-, 8-, and 12-hour peak wind PDFs.

All of these products are described in the following subsections. For ease of reference, all charts will show the data from the Delta IV Tower 6 at 54 ft in December (1995–2006).

4.1 Hourly Climatology

For this climatology, the data were first stratified by hour. The hourly mean and σ of the 5-minute average and peak winds were calculated using the 12 5-minute values in each hour including minutes 00 – 55. Figure 2 shows the December hourly climatology for Tower 6 at 54 ft. The difference in UTC and EST is five hours. Local midnight is at 0500 UTC and noon is at 1700 UTC. Sunrise in December is near 1200 UTC and sunset is near 2230 UTC. The increase in the mean and peak speeds is evident during daytime mixing.

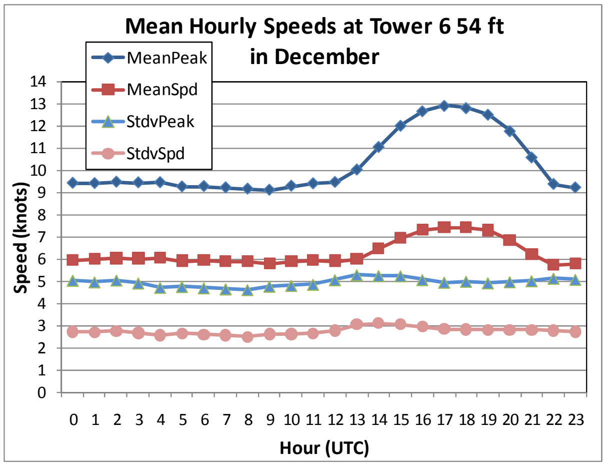

Figure 2. The hourly means and σ of the 5-minute mean and peak winds for Tower 6 at 54 ft in December. The legend shows the symbols and colors for the mean speeds (MeanSpd) and peaks (MeanPeak) and their σ (StdvSpd, StdvPeak).

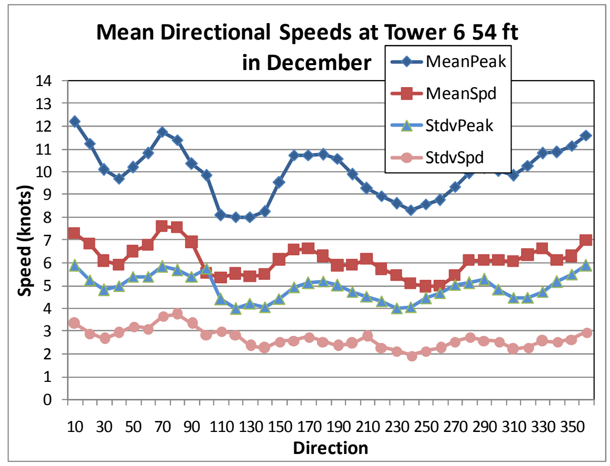

Figure 3. The directional means and σ, in 10° bins, of the 5-minute mean and peak winds for Tower 6 at 54 ft in December. The legend shows the symbols and colors for the mean speeds (MeanSpd) and peaks (MeanPeak) and their σ (StdvSpd, StdvPeak).

4.2 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 peak winds were calculated in 10° direction bins. The December values for Tower 6 at 54 ft are shown in Figure 3. The strongest winds in December during the POR were from the NNW – NE sector, with a secondary maximum from the ENE and S sector. Such winds can be expected with passing cold fronts in December: southerly winds increasing with approaching fronts and strongest winds out of the northwest after cold front passages. The number of peak and average wind speed observations used in the calculations for Figure 3 are shown in Figure 4. This climatology was used to reveal any predominant wind direction(s) for each month. It is clear from Figure 4 that the predominant wind direction for December is from the NW – NNE sector.

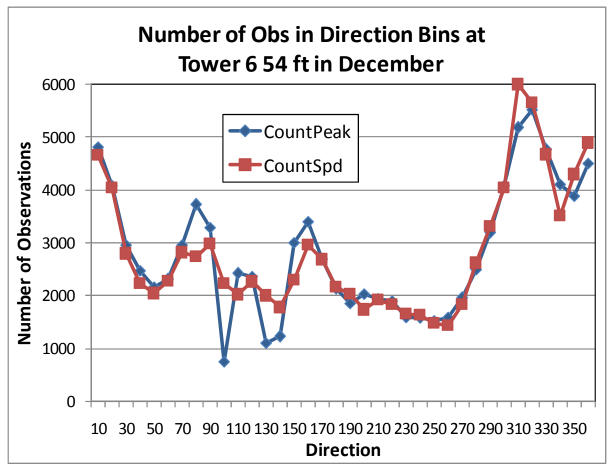

Figure 4. The number of 5-minute mean and peak wind observations in 10° bins for Tower 6 at 54 ft in December. The legend shows the symbols and colors for the number of mean observations (CountSpd) and peaks (CountPeak).

4.3 Hourly/Directional Climatology

This climatology was calculated to determine if there were preferential times of the day during each month for stronger wind speeds from specific directions. The data were stratified first by direction bin, then hour. In Phase I, 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 the mean hourly wind speed parameters from the NNW (316–360°) sector in December for Tower 6 at 54 ft. This direction bin makes up part of the sector where the highest winds occurred in Figure 3. There was a diurnal trend in mean and σ as in Figure 2, but the daytime mean and peak speeds were 1–2 kt higher when focused in this direction.

The number of observations used to calculate the values in Figure 5 are shown in Figure 6. Winds from this sector occurred mostly after midnight, peaking just before sunrise. There is a sharp drop-off in numbers as the winds begin to increase, with a minimum at 2000 UTC, near the peak in the wind speed curves. There is a second maximum in the hours after sunset.

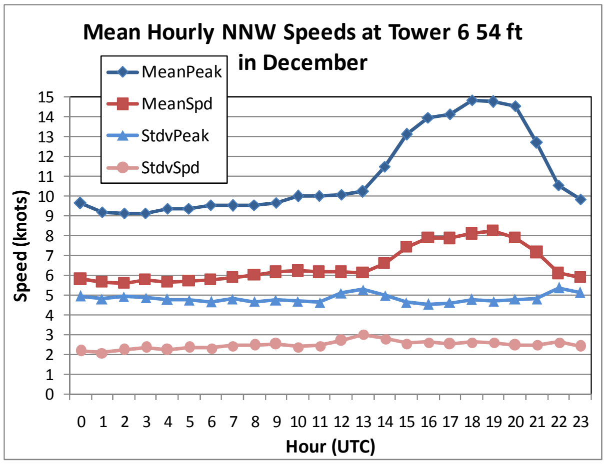

Figure 5. The hourly means and σ of the 5-minute mean and peak winds for Tower 6 at 54 ft in December from the NNW sector. The legend shows the symbols and colors for the mean speeds (MeanSpd) and peaks (MeanPeak) and their σ (StdvSpd, StdvPeak).

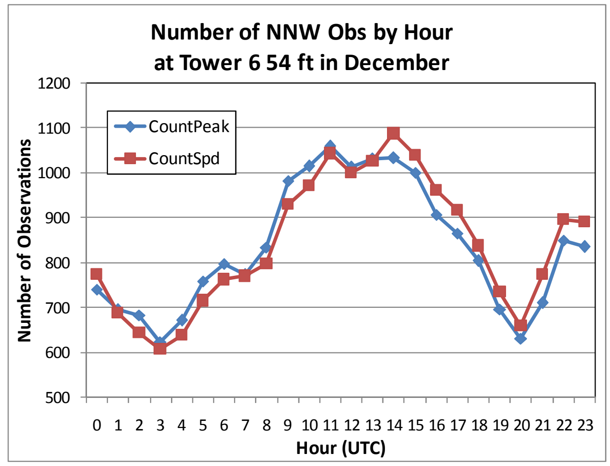

Figure 6. The number of 5-minute mean and peak wind observations for Tower 6 at 54 ft in December from the NNW sector. The legend shows the symbols and colors for the number of mean observations (CountSpd) and peaks (CountPeak).

4.4 Empirical CDF

One of the goals of this task is to calculate the probability of meeting or exceeding a given peak wind speed depending on the specific LCC. To calculate these probabilities, the peak winds were stratified by 5-minute mean wind speed in 1-kt (0.514 m s^{-1}) intervals and empirical probability density functions (PDFs) of the stratified peak winds were created.

To help determine the probability of meeting or exceeding each peak speed in a distribution, complementary cumulative distribution functions (CDFs) were calculated from the PDFs. A CDF would display the probability that a peak speed would not exceed a certain value. The 45 WS forecasters need to know just the opposite: the probability of the peak speed meeting or exceeding a certain value based on the LCC. The complementary peak speed CDFs for each 5-minute mean speed observed from Tower 6 at 54 ft in December are displayed in Figure 7. Each symbol on a mean speed curve corresponds to a peak speed on the horizontal axis and a probability of meeting or exceeding that peak speed on the vertical axis.

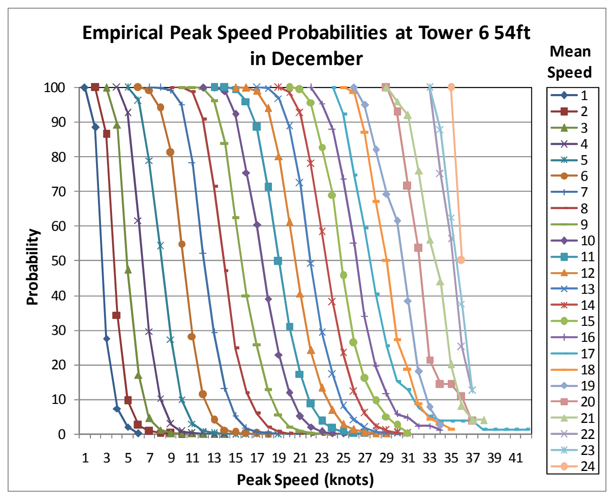

Figure 7. The empirical complementary CDFs for the 5-minute mean winds from Tower 6 at 54 ft in December. The legend shows the symbols and colors for each mean speed.

4.5 Parametric CDF

Note in Figure 7 that the CDFs for the lower mean speeds are smooth, but the tails become noisy for mean speeds higher than 14 kt. For 17 kt and higher, the entire curve becomes noisy. The number of 5-minute mean speed observations of 15 kt and higher drops below 200 and goes to just 2 observations at 24 kt. Fitting a parametric distribution to the data will help smooth and interpolate over variations in the empirical CDFs due to under-sampling of certain peak speeds and possibly estimate probabilities for peak speeds outside the range of observations in the POR.

Fitting the CDFs with the proper parametric distribution is necessary for calculating the appropriate probability values, especially for extreme values that are observed only occasionally. In this work, the Gumbel distribution will be used since it has been proven as the best distribution for winds at KSC/CCAFS in studies conducted at Marshall Space Flight Center. Wilks (2006) identifies the Gumbel as an often-used extreme value distribution and, as such, is appropriate for peak winds. The Gumbel CDF is defined by the following equation in Wilks (2006):

$$\text{Gumbel CDF} = exp\left\{-exp\left[-\frac{x-\theta}{\beta}\right]\right\},$$

where x is the peak speed variable, θ is the location parameter, and β is the scale parameter. The location and scale parameters will be determined using two methods. The Method of Moments will be used first to calculate first-guess values

$$\hat{\beta} = \frac{s\sqrt{6}}{\pi} \text{ and } \hat{\theta} = \overline{x} - \gamma\hat{\beta}$$

where s is the standard deviation of the peaks, $\overline{x}$ is the mean of the peaks, and γ is Euler's Constant (0.57721…). The X^2 goodness-of-fit test will be used to find the optimal values for these parameters by minimizing X^2 *in the equation*

$$X^2 = \sum \frac{(\#Observed - \#Expected)^2}{\#Expected},$$

Where *#Observed* is the number of observations for a particular peak value, and *#Expected* is the number of observations for that peak based on the fitted distribution. When the parametric distribution is fitted perfectly to the observed, $X^2 = 0$.

4.6 Prognostic CDFs

Empirical and parametric complementary CDFs will be created for the diagnostic and prognostic elements of this work. The diagnostic CDFs represent the distribution of peak speeds for each mean speed observed at the same time. The prognostic CDFs will provide probabilities of meeting or exceeding a range of peak speeds that occurred 2, 4, 8, and 12 hours after the time of the mean wind observation. Complementary prognostic CDFs like those in Figure 7 will be calculated for each hour of the day in each month.

Data collection for the prognostic CDFs will involve a re-sampling technique that will use all 5-minute mean and peak speeds in the data set. Figure 8 demonstrates how the data will be collected for 2-hour time interval after 0000 UTC. The mean speeds in the 30 minute intervals before and after the central time of 0000 UTC, and will represent the mean speed CDFs. This time period is 2330–0025 UTC in Figure 8 and is highlighted in blue. The brackets above the timeline encompass the range of times from which the peaks are drawn for the first and last times in the blue area. The peak speeds associated with the mean at 2330 UTC will begin at 2335 and end at 0125 UTC, and the peaks associated with the mean at 0025 UTC will being at 0030 and end at 0220 UTC. The same procedure will be followed for every time between 2330 to 0025 UTC for each 0000 UTC in each month.

Each set of 23 peak values will be binned according to its associated mean speed at the beginning of its 2-hour (or 4-, 8-, 12-hour) period. Each mean speed in the range will then have a distribution of peak speeds associated with it. These distributions will be used to calculate empirical and parametric CDFs.

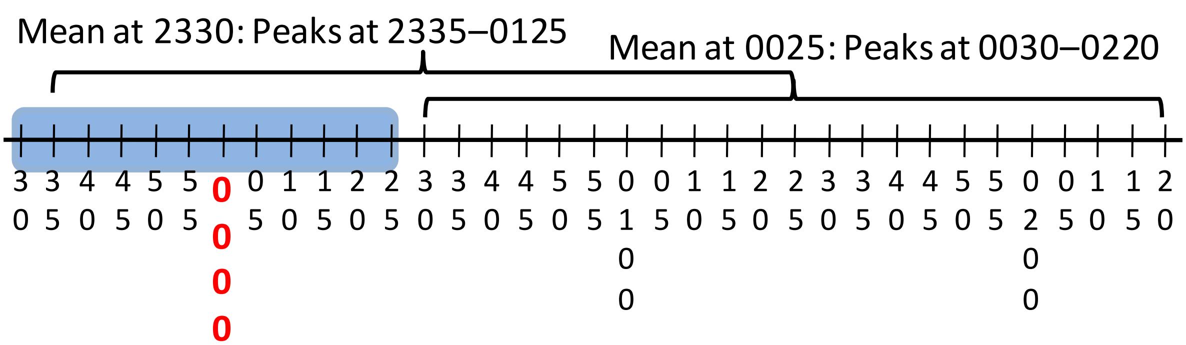

Figure 8. Timeline demonstrating how the data for the 2-hour probabilities at 0000 UTC are collected. The time begins at 2330 UTC and ends at 0220 UTC. The times highlighted in blue are those from which the 5-minute means are collected. The brackets above the timeline represent the range of times over which the 5-minute peaks are collected for the first and last mean speed observations in the blue shaded area. The time of interest, 0000 UTC, is highlighted in red.

5. CONTINUING WORK

Work on this task is ongoing and is scheduled for completion in April 2008. Statistical work to be done includes creating Gumbel distributions for the CDFs and collecting the data for the prognostic CDFs.

Another important part of this work is to create a GUI that will provide easy and intuitive access to the climatology and probability values. The LWOs were provided with PivotCharts in Phase I. While these charts are flexible and show the information desired, they can be difficult to interpret in a fast-pace operational environment. In Phase II (Lambert 2003), a GUI was created for the forecasters at the Spaceflight Meteorology Group (SMG) at Johnson Space Center in Houston, TX. The 45 WS LWOs requested a similar GUI, but one that is tailored to their operations. The AMU will work closely with the 45 WS while developing the GUI to ensure it will provide the best support to their operations.

6. SUMMARY

The goals of this task are to

- Update the climatologies and probabilities calculated in Phase I with data from 2002 – 2007,
- Create prognostic peak wind probabilities in the 2-, 4-, 8-, and 12-hour periods following an observation time, and
- Create a GUI that will meet the operational needs of the 45 WS and display information easily and quickly in a readable format.

Forecasters will use these data as an additional tool along with current observations, trends, and model output when making peak wind forecasts for launch operations.

7. REFERENCES

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