# WIND DATA REPORT

# Mt. Lincoln – Pelham, MA

May 2009 to April 2010

Prepared for

Massachusetts Department of Energy Resources
100 Cambridge Street, Suite 1020
Boston, MA 02114

by

Jonathan D. Black
James F. Manwell
Utama Abdulwahid
Anthony F. Ellis

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**Wind Energy Center**
University of Massachusetts, Amherst
160 Governors Drive, Amherst, MA 01003
www.umass.edu/windenergy • (413) 545-4359 • rerl@ecs.umass.edu

# NOTICE AND ACKNOWLEDGEMENTS

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# EXECUTIVE SUMMARY


All the work presented in this Wind Data Report including installation and decommissioning of the meteorological tower and instrumentation, and the data analysis and reporting was performed by the Wind Energy Center (WEC) at the University of Massachusetts, Amherst.

Wind monitoring equipment was installed at the WFCR radio tower on April 17, 2009. The base of the radio tower is 377 meters above sea level. Anemometers were installed at heights of 65 and 86 meters (213.3 ft and 282.2 ft, respectively) above the tower base. A total of three anemometers and a wind vane were installed at both heights. A temperature sensor was installed near the base of the tower.

This report summarizes the wind data collected at the site for the one year period, between May 2009 and April 2010. The mean recorded wind speed was 6.99 m/s (15.64 mph*) at 86 meters, and the prevailing wind direction was from the northwest. The average wind shear component was 0.243 and the average turbulence intensity at 86 meters was 0.111.

The gross data recovery percentage (the actual percentage of expected data received) was 96.65% and the net data recovery percentage (the percentage of expected data which passed all of the quality assurance tests) was 95.36%

Based on site data collected during the reporting period and its correlation with a reference site, the estimated long-term mean wind speed at a hub height of 80 meters is 6.58 m/s.

Additional information about interpreting the data presented in this report can be found in the Fact Sheet, "Interpreting Your Wind Resource Data," produced by RERL and the Massachusetts Technology Collaborative (MTC). This document is found through the WEC website:

http://www.ceere.org/rerl/about_wind/RERL_Fact_Sheet_6_Wind_resource_interpretation.pdf

* 1 m/s = 2.237 mph.

## SECTION 1 - Station Location

The WFCR radio tower is located on Mt. Lincoln in Pelham, Massachusetts. The 100 m (328 ft) radio tower is located at 42° 21’ 49.56” North, 72° 25’ 22.80” West, approximately 1.25-miles west of Route 202 and 3-miles west of the Quabbin Reservoir. The tower base is 377 m (1,236.9 ft) above sea level. The tower is identified with a yellow box in the center of Figure 1 below.

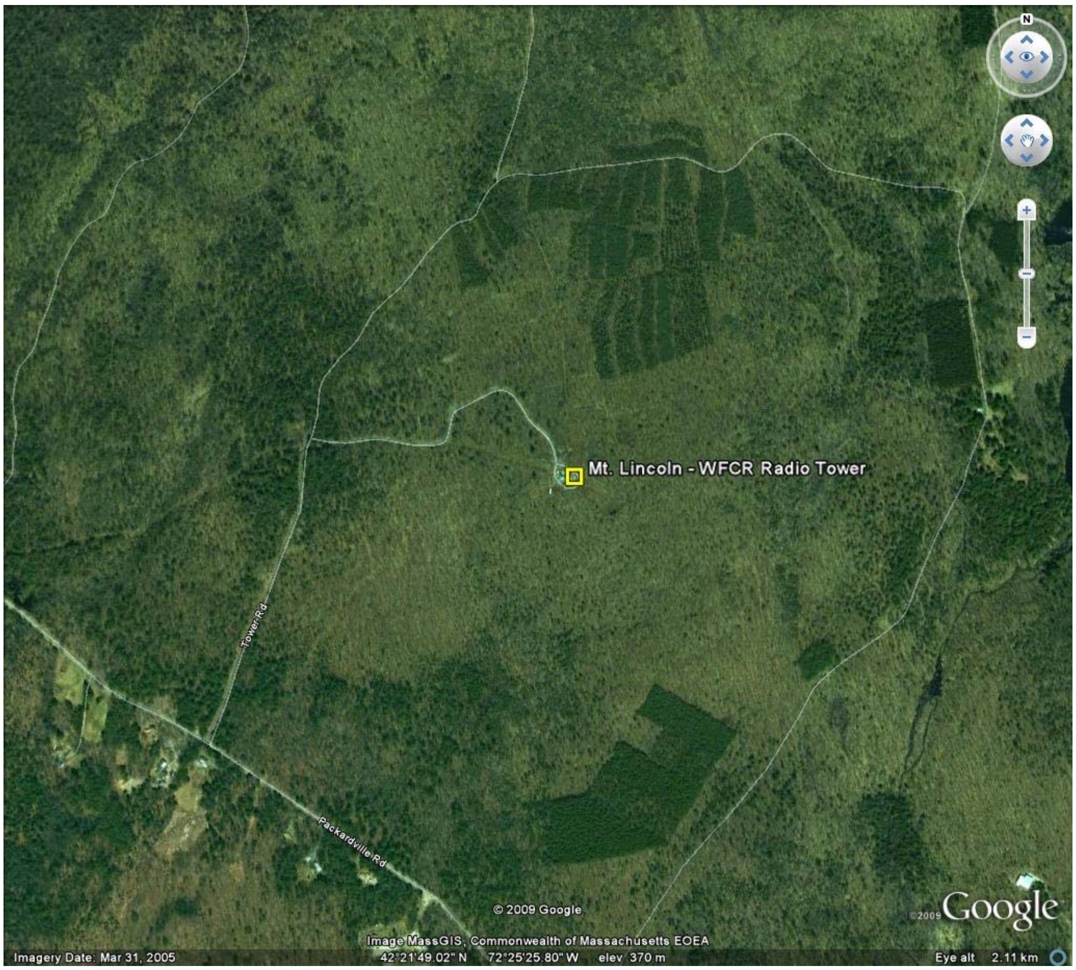


**Figure 1 – Site Location**

## SECTION 2 - Instrumentation and Equipment

The wind monitoring equipment is mounted on an existing radio tower, known as the WFCR broadcast tower. WFCR is a 13,000 watt FM station, and the tower consists of a guyed, 3-legged, solid-steel lattice tower that is triangular in cross-section. The wind monitoring equipment comes from NRG systems and consists of the following items:

- NRG Symphonie data logger with internal temperature.
- 6 – NRG #40 Anemometers, standard calibration (Slope – 0.765 m/s, Offset – 0.350 m/s). Three anemometers are located at 65 m (213.3 ft) and three anemometers are located at 86 m (282.2 ft).
- 2 – NRG #200P Wind direction vanes. The vanes are located at 65 m (213.3 ft) and 86 m (282.2 ft).

Data from the Symphonie logger is sent to WEC via a cellular modem once a day. The logger samples wind speed and direction once every two seconds. These samples are combined into 10-minute averages and are put into a binary file along with the maximum, minimum and standard deviation for each 10-minute interval. The binary files are converted to ASCII text files using NRG software. These text files are then imported into a database software program where they are subjected to quality assurance tests prior to data usage.

## SECTION 3 - Data Summary

A summary of the wind speeds and wind directions measured during the reporting period is included in Table 1. Table 1 includes the mean wind speeds measured at each measurement height, the maximum instantaneous wind speed measured at each measurement height and the prevailing wind direction measured at each measurement height. These values are provided for each month of the reporting period and for the whole reporting period.

## Table 1. Wind Speed and Direction Data Summary

| Date<br>Height<br>Units | Mean Wind Speed<br>86 m<br>[m/s] | Max Wind Speed<br>86 m<br>[m/s] | Prevailing Wind Direction<br>86 m<br>[deg] | Mean Wind Speed<br>65 m<br>[m/s] | Max Wind Speed<br>65 m<br>[m/s] | Prevailing Wind Direction<br>65 m<br>[deg] |
|---|---|---|---|---|---|---|
| May 2009 | 6.54 | 18.17 | SW | 6.15 | 17.43 | SSW |
| June 2009 | 5.33 | 13.72 | NE | 5.04 | 12.97 | NE |
| July 2009 | 5.85 | 16.22 | SW | 5.50 | 15.14 | SSW |
| Aug 2009 | 5.28 | 14.85 | SW | 4.91 | 13.95 | SSW |
| Sept 2009 | 6.41 | 14.15 | SW | 6.00 | 13.21 | ENE |
| Oct 2009 | 7.27 | 19.32 | NW | 6.72 | 18.56 | NW |
| Nov 2009 | 7.23 | 20.43 | ENE | 6.69 | 19.32 | ENE |
| Dec 2009 | 8.73 | 20.56 | NW | 8.09 | 19.19 | NW |
| Jan 2010 | 7.74 | 21.88 | NW | 7.17 | 20.75 | NW |
| Feb 2010 | 8.37 | 18.96 | NW | 7.78 | 18.06 | NW |
| Mar 2010 | 8.45* | 21.61* | E* | 7.98* | 20.40* | N* |
| Apr 2010 | 7.23** | 21.4** | NW** | 6.79** | 20.22** | WNW** |
| **May 2009 -Apr 2010** | **6.99** | **21.88** | **NW** | **6.53** | **20.75** | **NW** |

**Notes:** ***Approximately 82% of monthly data is valid**
****Approximately 77% of monthly data is valid**

Wind data statistics in the table are reported when more than 90% of the data during the reporting period are valid. In cases when a larger amount of data is missing, the percent of the available data that are used to determine the data statistics is noted.

No measurement of wind speed or direction can be perfectly accurate. Wind speed measurement errors occur due to anemometer manufacturing variability, anemometer calibration errors, the response of anemometers to turbulence and vertical air flow and due to air flows caused by the anemometer mounting system. Every effort is made to reduce the sources of these errors. Nevertheless, the values reported in this report have an expected uncertainty of about ± 2% or ± 0.2 m/s, whichever is greater. Wind direction measurement errors occur due to sensor measurement uncertainty, tower effects, boom alignment measurement errors and twisting of pipe sections during the raising of a pipe tower. Efforts are also made to reduce these errors, but the reported wind directions are estimated to have an uncertainty of +/- 5 degrees.

A summary of the turbulence intensity and mean wind shear measured at each measurement height during the reporting period is included in Table 2. These values are provided for each month of the reporting period and for the whole reporting period. Turbulence Intensity is calculated by dividing the standard deviation of the wind speed by the mean wind speed and is a measure of the gustiness of a wind resource. Lower turbulence results in lower mechanical loads on a wind turbine. Turbulence intensity varies with wind speed. The average turbulence intensity presented in Table 2 is the mean turbulence intensity when the wind speed at the highest measurement height is between 9.5 and 10.5 m/s.

Shear coefficients provide a measure of the change in wind speed with height. When data at multiple heights are available, shear wind speed, $U(z)$, at height $z$, when the average wind speed, $U(z_r)$, at height $z_r$ is known:

$$U(z)=U(z_r)\left(\frac{z}{z_r}\right)^{\alpha}$$

coefficients, α, have been determined. They can be used in the following formula to estimate the average

The change in wind speed with height is a very complicated relationship related to atmospheric conditions, wind speed, wind direction, time of day and time of year. This formula will not always provide the correct answer at any given site. Nevertheless the calculated shear coefficient, based on measurements at two heights, can be used to characterize the degree of increase in wind speed with height at a site.

The mean wind shear coefficient that is provided here is calculated based on the mean wind speeds in Table 1, where $z_{high}$ and $z_{low}$ are the heights of the higher and lower mean wind speeds used in the calculation and $U(z_{low})$ and $U(z_{high})$ are the mean wind speeds at the two heights.

$$\alpha = \log\left(\frac{U(z_{high})}{U(z_{low})}\right) \Big/ \log\left(\frac{z_{high}}{z_{low}}\right)$$

**Table 2. Shear and Turbulence Intensity Data Summary**

| Date<br><br>Height<br>Units | Turbulence Intensity at 10 m/s<br><br>65 m<br>[-] | Turbulence Intensity at 10 m/s<br><br>86 m<br>[-] | Mean Wind Shear Coefficient, α<br>Between 65 m and 86 m<br>[-] |
|---|---|---|---|
| May 2009 | 0.133 | 0.123 | 0.219 |
| June 2009 | 0.143 | 0.108 | 0.198 |
| July 2009 | 0.134 | 0.114 | 0.218 |
| Aug 2009 | 0.149 | 0.108 | 0.257 |
| Sept 2009 | 0.112 | 0.094 | 0.238 |
| Oct 2009 | 0.143 | 0.115 | 0.284 |
| Nov 2009 | 0.117 | 0.097 | 0.277 |
| Dec 2009 | 0.145 | 0.116 | 0.271 |
| Jan 2010 | 0.132 | 0.106 | 0.273 |
| Feb 2010 | 0.141 | 0.122 | 0.263 |
| Mar 2010 | 0.145 | 0.119 | 0.214 |
| Apr 2010 | 0.147 | 0.102 | 0.223 |
| **May 2009 –Apr 2010** | **0.136** | **0.111** | **0.243** |

**Notes:** ***Approximately 82% of monthly data is valid**
****Approximately 77% of monthly data is valid**

# SECTION 4- Long Term Estimate and Capacity Factor

Wind speed varies year by year and the mean obtained over the measurement period may be less or more compared to what is seen over a longer time period. Therefore, the use of the long term mean at the site is preferred when projecting the performance of a wind turbine. The long term mean at a site may be estimated by using the Measure-Correlate-Predict (MCP) method.

The MCP method correlates wind speed measurements at the target site to a reference site which collects data over the same period of time and has been collecting data for a much longer period. Based on this correlation, the reference wind speed data is used to predict long term mean at the site.

Long term data from the Massachusetts Department of Transport communications tower at the Blandford Maintenance Facility between October 15th, 2006 and May 27th 2010 is used as reference in the case of the Mt Lincoln site. A correlation between the two sites is obtained from concurrent data between April 17th, 2009 and May 27th, 2010. The long term mean at Mt Lincoln at 86 m is estimated to be 6.7 m/s with an uncertainty of 1.8% for the MCP process. This estimate may also be used to calculate the long term mean at different heights by using the mean wind shear at site and the equation described in the previous section.

The capacity factor of a wind turbine at a given site depends on the hub height, wind speed distribution at the hub height, the wind turbine power curve and any assumptions about down time and losses due to wake effects from upwind wind turbines, etc. If the hub height wind speed is estimated from data at lower heights, then the capacity factor will also depend on the estimated wind shear and the wind speeds measured at lower heights. No simple estimate of capacity factor at a site could take all of these effects and choices into account. Nevertheless, an estimate of the capacity factor of a wind turbine at this site is provided here to help the reader understand the order of magnitude of the wind resource at this site.

The estimates assume a GE 1.5 sl turbine with a hub height of 80 m and the long term mean wind speed estimate at the highest measurement height and the mean wind shear at the site, in order to determine the mean hub height wind speed, in this case 6.58 m/s. The wind speed probability distribution is assumed to be given by a Rayleigh distribution. The average wind turbine power is then estimated from:

$$\overline{P_W} = \int_0^\infty P_W(U)\,p(U)\,dU$$

where $P_W(U)$ is the wind turbine power curve and $p(U)$ is the wind speed probability distribution. The capacity factor is then calculated from:

$$CF = \frac{\overline{P_W}}{P_{rated}}$$

where $P_{rated}$ is the rated capacity of the turbine, i.e., 1500 kW. Based on this equation, the estimated capacity factor of a wind turbine at this site would be about 0.32].

# SECTION 5- Graphs

This report contains several types of wind data graphs. Unless otherwise noted, each graph represents data from one calendar year (May 2009 to April 2010). The following graphs are included:

- Time Series – 10-minute average wind speeds are plotted against time. This graph includes all of the collected data.

- Wind Speed Distribution – A histogram plot giving the percentage of time that the wind is at a given wind speed.

- Monthly Average – A plot of the monthly average wind speed over a 12-month period. This graph shows the trends in the wind speed over the whole period of data collection.

- Diurnal – A plot of the average wind speed for each hour of the day.

- Turbulence Intensity – A plot of turbulence intensity as a function of wind speed. Turbulence Intensity is calculated as the standard deviation of the wind speed divided by the wind speed and is a measure of the gustiness of a wind resource. Lower turbulence results in lower mechanical loads on a wind turbine.

- Wind Rose – A plot, by compass direction showing the percentage of time that the wind comes from a given direction and the average wind speed in that direction.

With regards to the Mt. Lincoln site, the following observations are noted.

- Time Series, Figure 2: shows that the wind speed seldom exceeded 20 m/s at the site during the year of monitoring. Note the gap in data between March 26, 2010 and April 8, 2010.

- Wind Speed Distribution, Figure 3: wind speeds throughout the year are primarily between 3 and 10 m/s and the most common wind speed is between 6 and 8 m/s.

- Monthly Average, Figure 4: shows that the average monthly wind speeds were highest during the winter months and lowest during the summer months.

- Diurnal, Figure 5: shows that the wind speed at the site was lower during the day time hours.

- Turbulence Intensity, Figure 6: we can see the turbulence numbers predominantly cluster between 0 and 0.3 for wind speeds greater than 4 m/s.

- Wind Rose, Figure 7: shows that the prevailing winds at this site are from the northwest during the year of data collection, with a secondary prevalence in the southwesterly direction. The highest average wind speed was recorded from the east-northeast and northwest directions, but average annual wind speeds were above 5 m/s from all directions at a height of 86-meters.

Data for the wind speed histograms, monthly and diurnal average plots, and wind roses are included in APPENDIX B.

**Wind Speed Time Series**

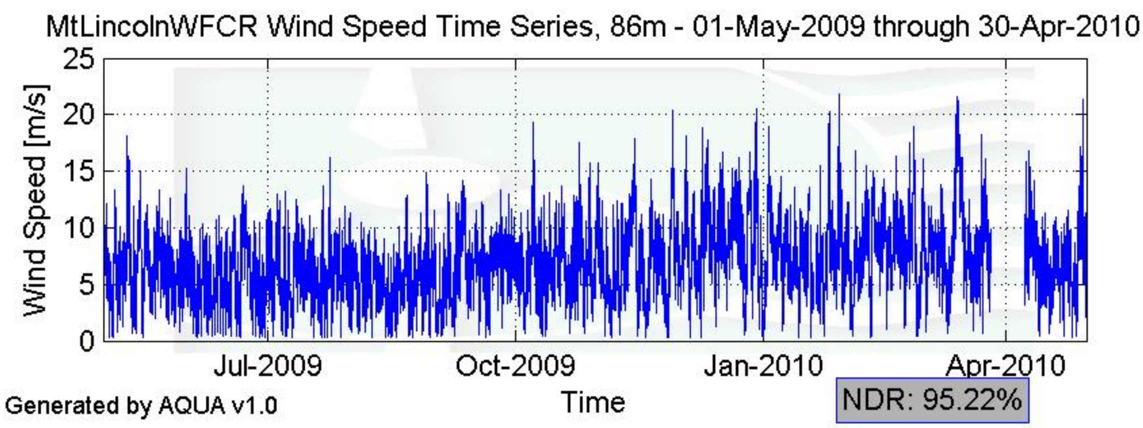


**Figure 2 - Wind Speed Time Series, May 1, 2009 – April 30, 2010**

**Wind Speed Distributions**

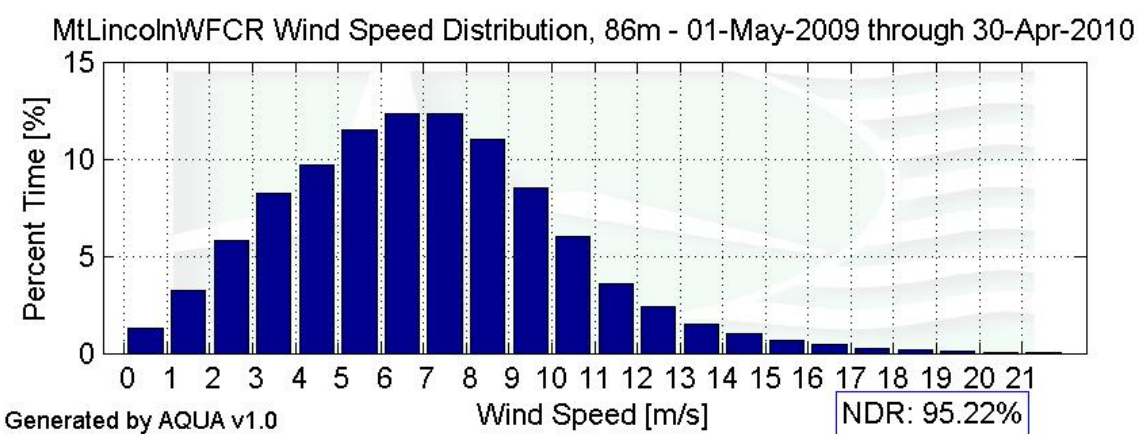


**Figure 3 - Wind Speed Distribution, May 1, 2009 – April 30, 2010**

## Monthly Average Wind Speeds

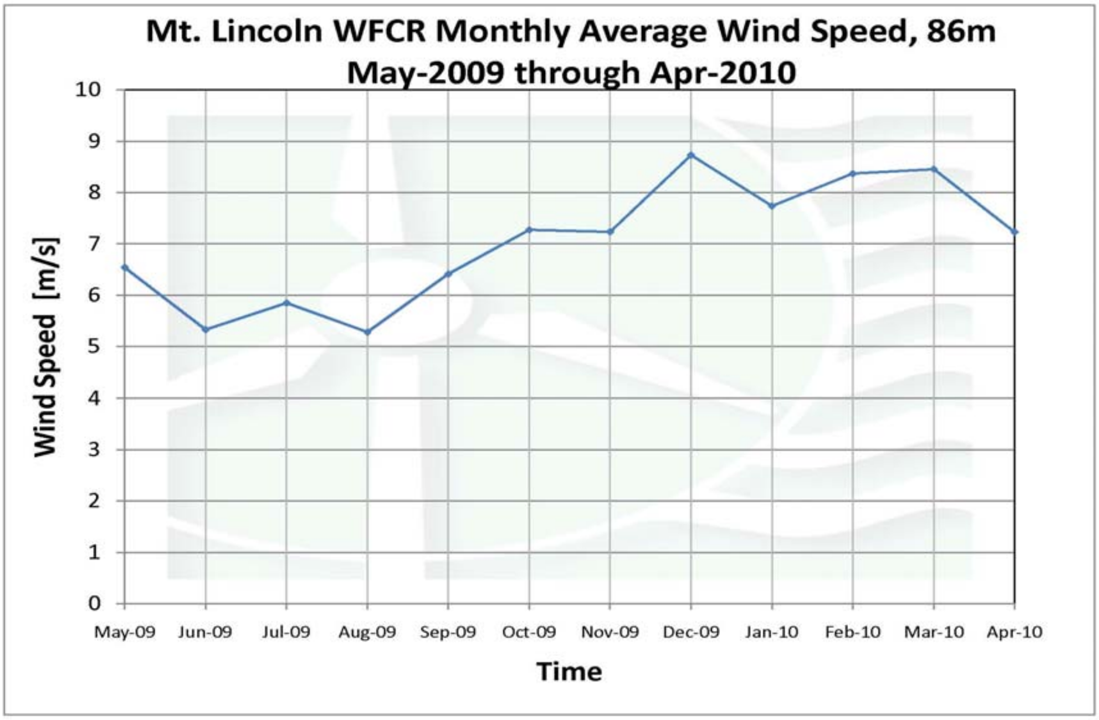


**Figure 4 - Monthly Average Wind Speed, May 1, 2009 – April 30, 2010**

## Diurnal Average Wind Speeds

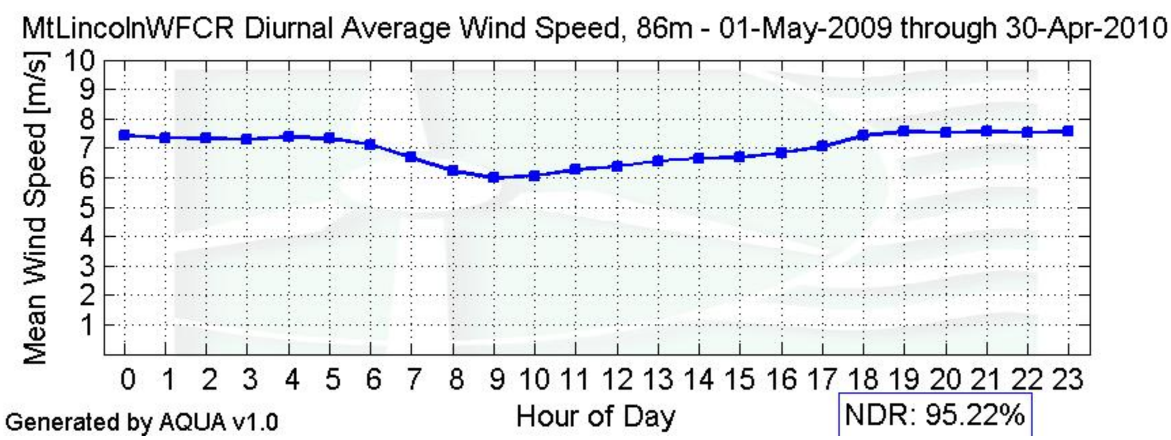


**Figure 5 - Diurnal Average Wind Speeds, May 1, 2009 – April 30, 2010**

## Turbulence Intensities

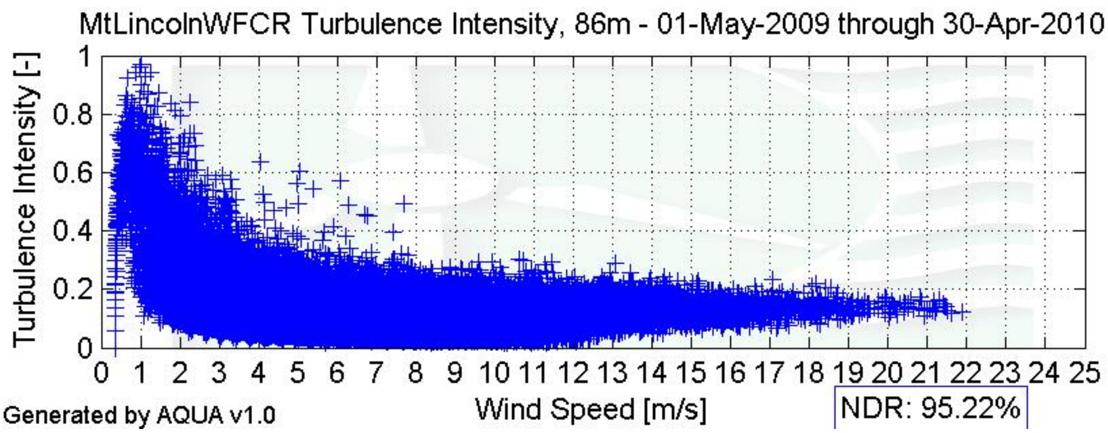


**Figure 6 - Turbulence Intensity vs. Wind Speed, May 1, 2009 – April 30, 2010**

## Wind Roses

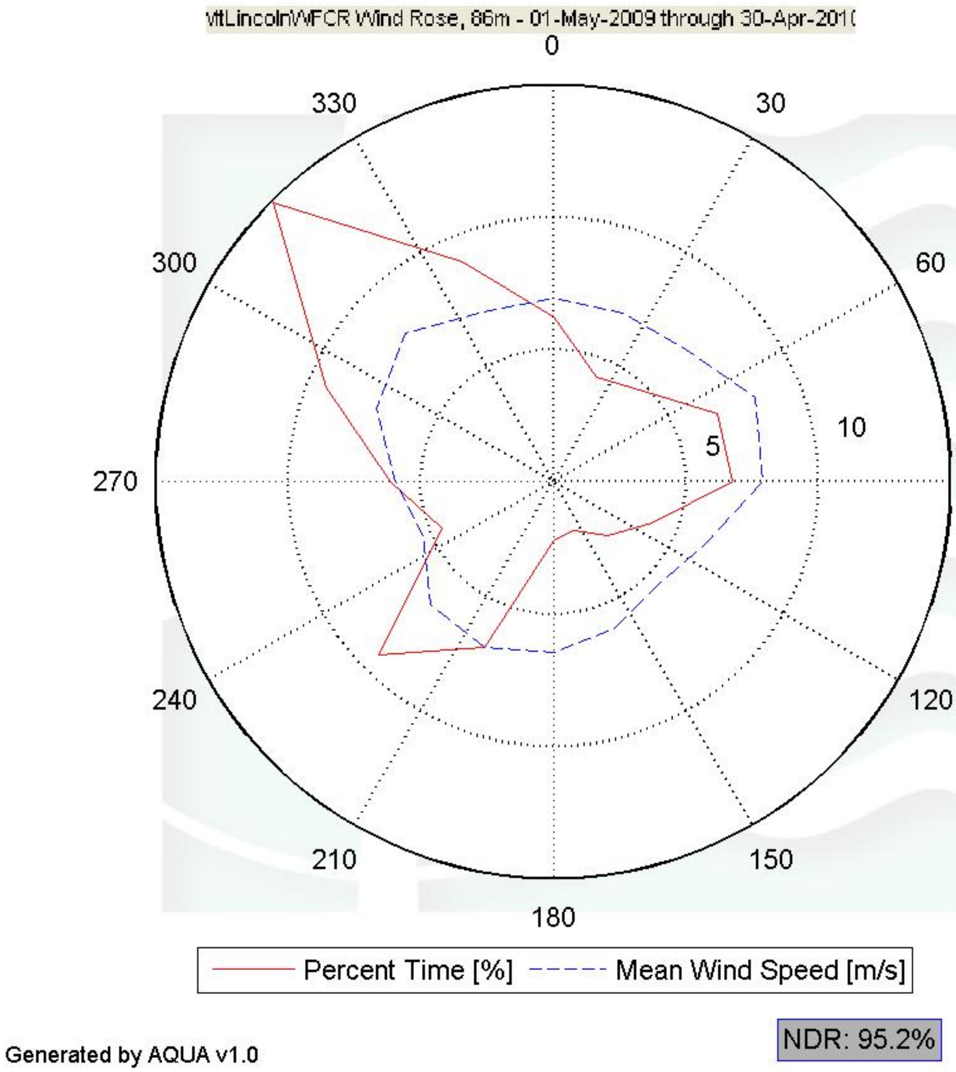


**Figure 7 - Wind Rose, May 1, 2009 – April 30, 2010**

# SECTION 6 - Significant Meteorological Events

There were no extreme metrological events during this data collection period. The highest recorded wind speed was 21.88 m/s (48.95 mph) at 86 meters.

# SECTION 7 - Data Collection and Maintenance

The original data logger was damaged due to a lightning strike during a storm on March 26, 2010. The logger was replaced on April 8, 2010. Although data collected between March 26 and April 8, 2010 was recovered from the damaged logger, upon close examination it was determined to be faulty and was thus discarded. It is also noted that anemometers Anem65b and Anem86a experienced significantly higher percentages of fault than the other two anemometers at each station. This is believed to be due to tower shadow effects, and suggests that these sensors were aligned directionally when the tower was instrumented.

# SECTION 8 - Data Recovery and Validation

All raw wind data are subjected to a series of tests and filters to weed out data that are faulty or corrupted. Definitions of these quality assurance (QA) controls are given below under Test Definitions and Sensor Statistics. These control filters were designed to automate the quality control process and used many of the previous hand-worked data sets made at UMass to affect a suitable emulation. The gross percentage of data recovered (ratio of the number of raw data points received to data points expected) and net percentage (ratio of raw data points which passed all QA control tests to data points expected) are shown below. [Statistics over whole period of data collection].

| | |
|---|---|
| Gross Data Recovered [%] | 96.65 |
| Net Data Recovered [%] | 95.36 |

**Test Definitions**

All raw data were subjected to a series of validation tests, as described below. The sensors tested and the parameters specific to each sensor are given in the Sensor Performance Report which is included in APPENDIX A. Data which were flagged as invalid were not included in the statistics presented in this report.

**MinMax Test:** All sensors are expected to report data values within a range specified by the sensor and logger manufacturers. If a value falls outside this range, it is flagged as invalid. A data value from the sensor listed in Test Field 1 (TF1) is flagged if it is less than Factor 1 (F1) or greater than Factor 2. This test has been applied to the following sensors (as applicable): wind speed, wind speed standard deviation, wind direction, temperature, and solar insolation.

$$F1 > TF1 > F2$$

**MinMaxT Test:** This is a MinMax test for wind direction standard deviation with different ranges applied for high and low wind speeds. A wind direction standard deviation data value (TF1) is flagged either if it is less than Factor 1, if the wind speed (TF2) is less than Factor 4 and the wind direction standard deviation is greater than Factor 2, or if the wind speed is greater than or equal to Factor 4 and the wind direction standard deviation is greater than Factor 3.

$$(TF1 < F1)$$
$$\text{or } (TF2 < F4 \text{ and } TF1 > F2)$$
$$\text{or } (TF2 \geq F4 \text{ and } TF1 > F3)$$

**Icing Test:** An icing event occurs when ice collects on a sensor and degrades its performance. Icing events are characterized by the simultaneous measurements of near-zero standard deviation of wind direction, non-zero wind speed, and near- or below-freezing temperatures. Wind speed, wind speed standard deviation, wind direction, and wind direction standard deviation data values are flagged if the wind direction standard deviation (CF1) is less than or equal to Factor 1 (F1), the wind speed (TF1) is greater than Factor 2 (F2), and the temperature (CF2) is less than Factor 3 (F3). To exit an icing event, the wind direction standard deviation must be greater than Factor 4.

$$CF1 \leq F1 \text{ and } TF1 > F2 \text{ and } CF2 < F3$$

**CompareSensors Test:** Where primary and redundant sensors are used, it is possible to determine when one of the sensors is not performing properly. For anemometers, poor performance is characterized by low data values. Therefore, if one sensor of the pair reports values significantly below the other, the low values are flagged. At low wind speeds (Test Fields 1 and 2 less than or equal to Factor 3) wind speed data are flagged if the absolute difference between the two wind speeds is greater than Factor 1. At high wind speeds (Test Fields 1 or 2 greater than Factor 3) wind speed data are flagged if the absolute value of the ratio of the two wind speeds is greater is greater than Factor 2.

$$[\ TF1 \leq F3 \text{ and } TF2 \leq F3 \text{ and } abs(TF1 - TF2) > F1\ ]$$
$$\text{or } [\ (TF1 > F3 \text{ or } TF2 > F3) \text{ and } (abs(1 - TF1 / TF2) > F2 \text{ or } abs(1 - TF2 / TF1) > F2)\ ]$$

## Sensor Statistics

A summary of the results of the data collection and filtering are given in the Sensor Performance Report which is included in APPENDIX A. The following categories of information, tabulated for each sensor, are included in that report.

**Expected Data Points:** the total number of sample intervals between the start and end dates (inclusive).

**Actual Data Points:** the total number of data points recorded between the start and end dates.

**% Data Recovered:** the ratio of actual and expected data points (this is the *gross data recovered percentage*).

**Hours Out of Range:** total number of hours for which data were flagged according to MinMax and MinMaxT tests. These tests flag data which fall outside of an expected range.

**Hours of Icing:** total number of hours for which data were flagged according to Icing tests. This test uses the standard deviation of wind direction, air temperature, and wind speed to determine when sensor icing has occurred.

**Hours of Fault:** total number of hours for which data were flagged according to CompareSensors tests. These tests compare two sensors (e.g. primary and redundant anemometers installed at the same height) and flag data points where one sensor differs significantly from the other.

**% Data Good:** the filter results are subtracted from the gross data recovery percentage to yield the *net data recovered percentage*.

# APPENDIX A - Sensor Performance Report

**Sensor Statistics**

| Sensor | Expected Data Points | Actual Data Points | % Data Recovered | Hours Out of Range | Hours of Icing | Hours of Fault | % Data Good |
|---|---|---|---|---|---|---|---|
| Temp | 52560 | 50798 | 96.648 | 0 | 0 | 0 | 96.648 |
| Volt | 52560 | 50798 | 96.648 | 0 | 0 | 0 | 96.648 |
| Anem65a | 52560 | 50798 | 96.648 | 0.333 | 84.5 | 26.333 | 95.403 |
| Anem65b | 52560 | 50798 | 96.648 | 0.833 | 84.833 | 201.167 | 93.396 |
| Anem65c | 52560 | 50798 | 96.648 | 0.333 | 84.167 | 0 | 95.683 |
| Vane65 | 52560 | 50798 | 96.648 | 1 | 85.5 | 0 | 95.66 |
| Anem86a | 52560 | 50798 | 96.648 | 0.333 | 124.5 | 49.833 | 94.654 |
| Anem86b | 52560 | 50798 | 96.648 | 0.333 | 124.667 | 11.5 | 95.099 |
| Anem86c | 52560 | 50798 | 96.648 | 0.333 | 124.333 | 0 | 95.225 |
| Vane86 | 52560 | 50798 | 96.648 | 1.5 | 124.833 | 0 | 95.205 |
| | | | | | | | |
| Total | 525600 | 507980 | 96.648 | 5 | 837.333 | 288.833 | 95.362 |

# APPENDIX B - Plot Data

**Wind Speed Distribution Data**

| Bin Center Wind Speed [m/s] | May 2009 – April 2010 86 meters [%] |
|---|---|
| 0.5 | 1.26 |
| 1.5 | 3.25 |
| 2.5 | 5.82 |
| 3.5 | 8.23 |
| 4.5 | 9.69 |
| 5.5 | 11.47 |
| 6.5 | 12.32 |
| 7.5 | 12.35 |
| 8.5 | 10.98 |
| 9.5 | 8.49 |
| 10.5 | 5.99 |
| 11.5 | 3.61 |
| 12.5 | 2.37 |
| 13.5 | 1.47 |
| 14.5 | 1.02 |
| 15.5 | 0.65 |
| 16.5 | 0.45 |
| 17.5 | 0.26 |
| 18.5 | 0.17 |
| 19.5 | 0.08 |
| 20.5 | 0.05 |
| 21.5 | 0.03 |
| 22.5 | 0 |
| 23.5 | 0 |
| 24.5 | 0 |

**Monthly Average Wind Speed Data**

| Date | Wind Speed at 86 m 10 min Average [m/s] |
|---|---|
| May | 6.539 |
| June | 5.327 |
| July | 5.846 |
| August | 5.279 |
| September | 6.414 |
| October | 7.273 |
| November | 7.233 |
| December | 8.728 |
| January | 7.735 |
| February | 8.369 |
| March | 8.453* |
| April | 7.227* |

*Note: Less than 90% data valid for month

## Diurnal Average Wind Speed Data

| Hour of Day | May 2009 – April 2010 Mean Wind Speed at 86 meters [m/s] |
|---|---|
| 0 | 7.42 |
| 1 | 7.36 |
| 2 | 7.32 |
| 3 | 7.31 |
| 4 | 7.38 |
| 5 | 7.33 |
| 6 | 7.12 |
| 7 | 6.67 |
| 8 | 6.21 |
| 9 | 5.99 |
| 10 | 6.06 |
| 11 | 6.27 |
| 12 | 6.38 |
| 13 | 6.55 |
| 14 | 6.65 |
| 15 | 6.68 |
| 16 | 6.85 |
| 17 | 7.05 |
| 18 | 7.42 |
| 19 | 7.56 |
| 20 | 7.54 |
| 21 | 7.56 |
| 22 | 7.54 |
| 23 | 7.55 |

## Wind Rose Data

| Direction | May 2009 – April 2010 (86 meters) | |
|---|---|---|
| | Percent Time [%] | Mean Wind Speed [m/s] |
| N | 6.23 | 6.92 |
| NNE | 4.25 | 6.89 |
| NE | 4.84 | 7.07 |
| ENE | 6.72 | 8.27 |
| E | 6.79 | 7.89 |
| ESE | 4.05 | 6.18 |
| SE | 2.91 | 5.57 |
| SSE | 1.99 | 6.03 |
| S | 2.24 | 6.48 |
| SSW | 6.79 | 6.8 |
| SW | 9.3 | 6.56 |
| WSW | 4.54 | 5.32 |
| W | 6.16 | 5.95 |
| WNW | 9.28 | 7.23 |
| NW | 14.94 | 7.9 |
| NNW | 8.98 | 6.95 |