WIND DATA REPORT

Blandford Rest Area

December 2008 to February 2009

Prepared for

Massachusetts Technology Collaborative
75 North Drive
Westborough, MA 01581

by

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

June 9, 2009

Report template version 3.1.2

Renewable **E**nergy **R**esearch **L**aboratory
University of Massachusetts, Amherst
160 Governors Drive, Amherst, MA 01003
www.ceere.org/rerl • (413) 545-4359 • rerl@ecs.umass.edu

NOTICE AND ACKNOWLEDGEMENTS

This report was prepared by the Renewable Energy Research Laboratory (RERL) at the University of Massachusetts, Amherst in the course of performing work sponsored by the Renewable Energy Trust (RET), as administered by the Massachusetts Technology Collaborative (MTC). The opinions expressed in this report do not necessarily reflect those of MTC or the Commonwealth of Massachusetts, and reference to any specific product, service, process, or method does not constitute an implied or expressed recommendation or endorsement of it.

Further, MTC, the Commonwealth of Massachusetts, and RERL make no warranties or representations, expressed or implied, as to the fitness for particular purpose or merchantability of any product, apparatus, or service, or the usefulness, completeness, or accuracy of any processes, methods or other information contained, described, disclosed, or referred to in this report. MTC, the Commonwealth of Massachusetts, and the contractor make no representation that the use of any product, apparatus, process, method, or other information will not infringe privately owned rights and will assume no liability for any loss, injury, or damage directly or indirectly resulting from, or occurring in connection with, the use of information contained, described, disclosed, or referred to in this report.

TABLE OF CONTENTS

TABLE OF FIGURES

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 Renewable Energy Research Laboratory (RERL) at the University of Massachusetts, Amherst.

Wind monitoring equipment was installed at the Blandford Rest Area in January 2008. The base of the 50 meter meteorological tower is installed 446 meters above sea level. Anemometers and wind direction vanes are installed at 35 and 50 m (114.8 and 164 ft) above the tower base. There are redundant anemometers at both heights. There is a temperature sensor installed near the base of the tower.

This report summarizes the wind data collected during the Winter of 2008-2009, between December 2008 and February 2009. The mean recorded wind speed was 5.99 m/s (13.4 mph*) at 50 m and the prevailing wind direction was from the west-northwest. The average wind shear exponent between the two measured heights was 0.286. The average turbulence intensity at 50m for wind speeds between 10 m/s and 11 m/s was 0.2.

The gross data recovery percentage (the actual percentage of expected data received) was 98.89% and the net data recovery percentage (the percentage of expected data which passed all of the quality assurance tests) was 77.86%. Significant icing of all anemometers and both vanes occurred in December 2008 and January 2009. In July 2008 there was a failure of the secondary anemometer at 35, which has since rendered all data collected for this anemometer invalid.

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 RERL 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 Blandford Rest Area monitoring tower is located northeast of the westbound lane of Interstate 90, south of the Blandford Rest Area. The 50 m (164 ft) tower is located at 42°-11'-37.02" North, 72°-55'-51.42" West. The tower base is 446 m (1,462.9 ft) above sea level. The tower is identified with a yellow box in the center of Figure 1 below.

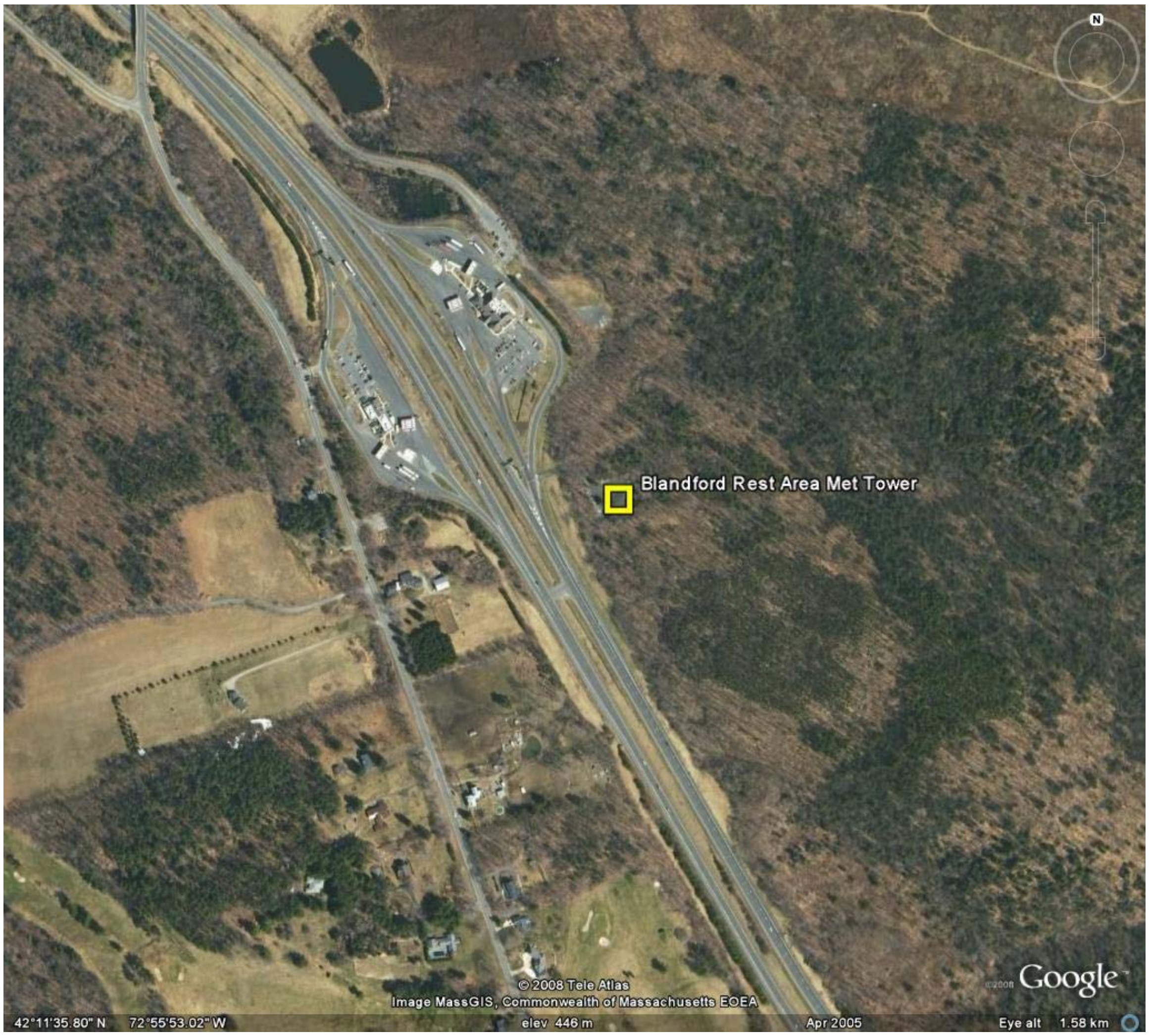

Figure 1 – Site Location

SECTION 2 - Instrumentation and Equipment

The wind monitoring equipment is mounted on a 50 m (164 ft) meteorological tower. The wind monitoring equipment comes from NRG systems and consists of the following items:

- NRG Symphonie data logger with internal temperature.
- 4 – NRG #40 Anemometers, standard calibration (Slope – 0.765 m/s, Offset – 0.350 m/s). Two anemometers are located at 50 m (164 ft) and two anemometers are located at 35 m (114.8 ft)
- 2 – NRG #200P Wind direction vanes. The vanes are located at 50 m (164 ft) and 35 m (114.8 ft).

Data from the Symphonie logger is sent to RERL 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	Mean Wind Speed	Max Wind Speed	Prevailing Wind Direction	Mean Wind Speed	Max Wind Speed	Prevailing Wind Direction
Height Units	**50 m [m/s]**	**50 m [m/s]**	**50 m [m/s]**	**35 m [m/s]**	**35 m [m/s]**	**35 m [m/s]**
Dec 2008	6.44*	18.1*	WNW*	5.78*	16.91*	WNW*
Jan 2009	5.14*	16.58*	WNW*	4.72*	15.63*	WNW*
Feb 2009	6.33	15.5	WNW	5.7	14.39	WNW
Dec 2008 – Feb 2009	**5.99***	**18.1***	**WNW***	**5.41***	**16.91***	**WNW***

*These statistics were determined from data that was less than 90% valid, primarily due to sensor icing.

Unless otherwise noted, wind data statistics in the table are reported when more than 90% of the data during the reporting period are valid. For this period, the total valid data was less than 90% (77.86%). Invalid data during this quarter was almost entirely attributable to two sources: 1.) the failure of the secondary anemometer at 35 meters in July 2008, which rendered all data collected for this anemometer invalid during this quarter, and 2.) significant icing of all anemometers and vanes during December 2008 and January 2009. Other than the secondary anemometer at 35 meters, data from all other sensors were well above the acceptable 90% criterion in February 2009.

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 each measurement height is between 10 and 11 m/s.

Shear coefficients provide a measure of the change in wind speed with height. When data at multiple heights are available, shear coefficients, α, have been determined. They can be used in the following formula to estimate the average wind speed, $U(z)$, at height z, when the average wind speed, $U(z_r)$, at height z_r is known:

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

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 Height Units	Turbulence Intensity at 10 m/s 50 m [-]	Turbulence Intensity at 10 m/s 35 m [-]	Mean Wind Shear Coefficient, α Between 50 m and 35 m [-]
Dec 2008	0.22	0.21	0.303
Jan 2009	0.19	0.2	0.239
Feb 2009	0.18	0.2	0.294
Dec 2008 –Feb 2009	**0.2**	**0.2**	**0.286**

SECTION 4- Graphs

This report contains several types of wind data graphs. Unless otherwise noted, each graph represents data from 1 quarter (3 months). The following graphs are included:

- Time Series – 10-minute average wind speeds are plotted against time.
- 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 year.
- 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 Blandford Rest Area site, the following observations are noted:

- Time Series, Figure 2: wind speeds seldom exceeded 15 m/s at the site during the winter months.
- Wind Speed Distribution, Figure 3: we can see in Figure 3 that wind speeds are mostly between 3 and 6 m/s during the winter months
- Monthly Average, Figure 4: we show the average for 12 months, March 2008 through February 2009.
- Diurnal, Figure 5: we can see in Figure 5 a relatively consistent wind speed trend throughout the day during winter months.
- Turbulence Intensity, Figure 6: we can see that turbulence numbers roughly cluster between 0.1 and 0.3 for most wind speeds.
- Wind Rose, Figure 7: a west-northwesterly wind direction bias is clear, possibly due to a channeling effect of the I-90 corridor.

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

Wind Speed Time Series

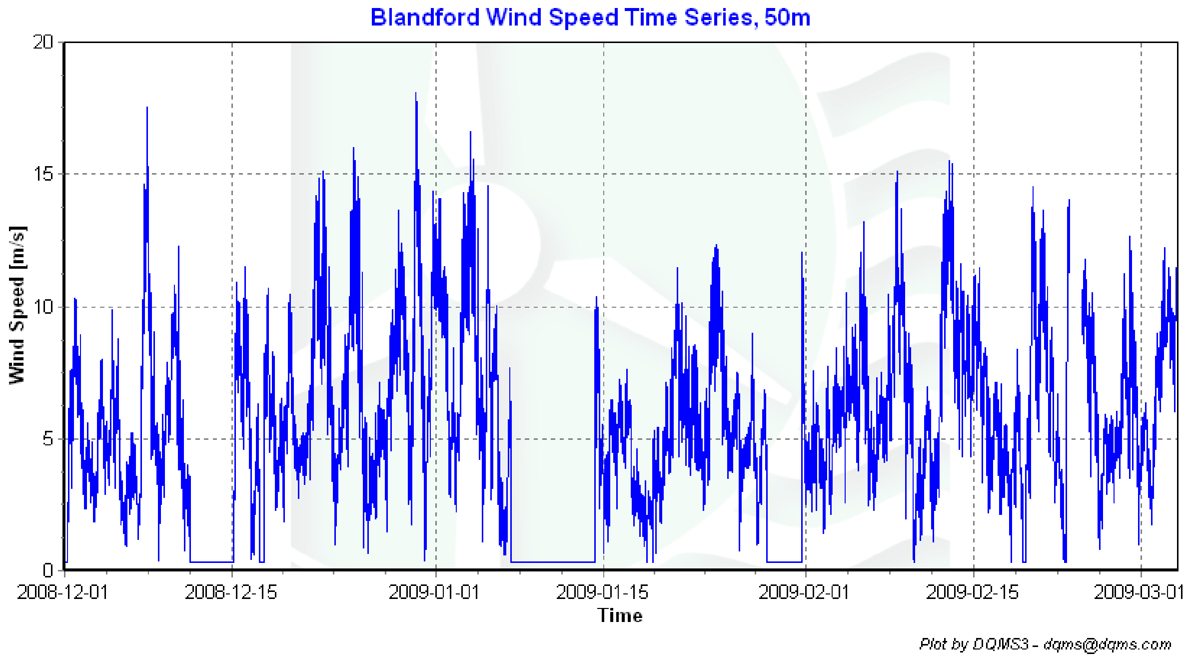

Figure 2 – Wind Speed Time Series, December 1, 2008 – February 28, 2009

Wind Speed Distributions

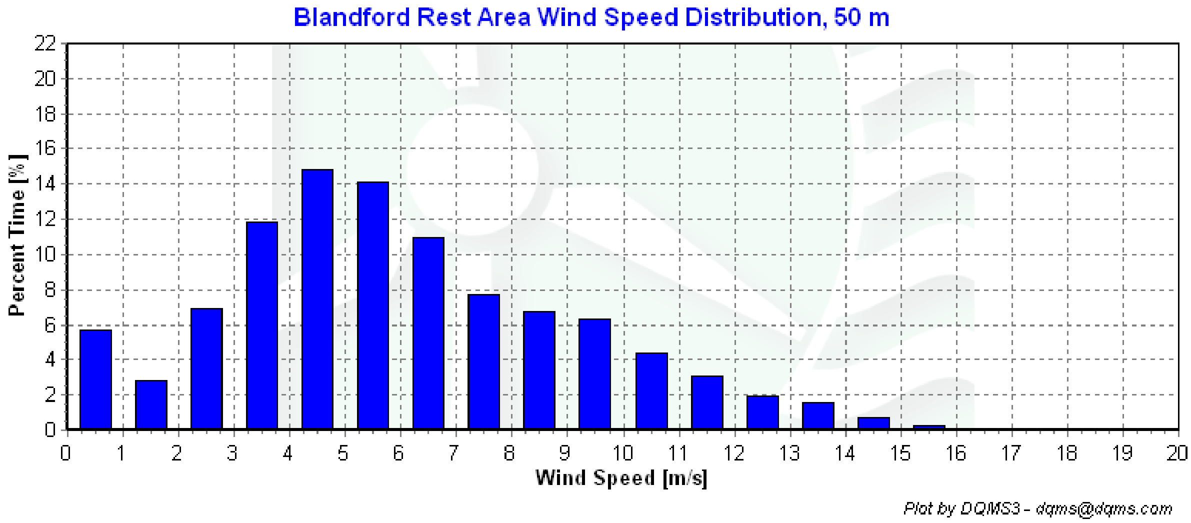

Figure 3 – Wind Speed Distribution, December 1, 2008 – February 28, 2009

Monthly Average Wind Speeds

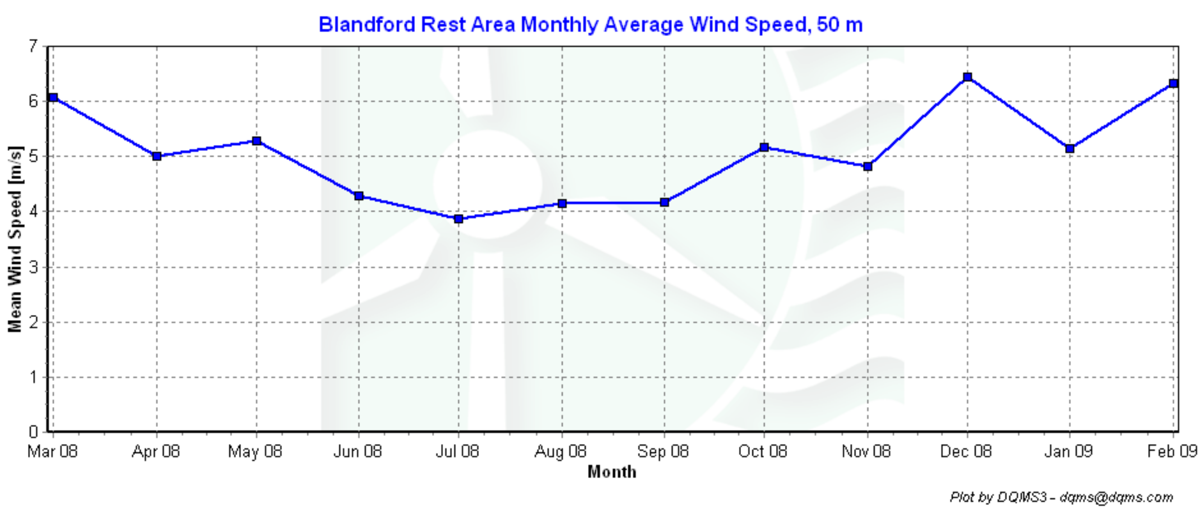

Figure 4 – Monthly Average Wind Speed, March 2008 – February 2009

Diurnal Average Wind Speeds

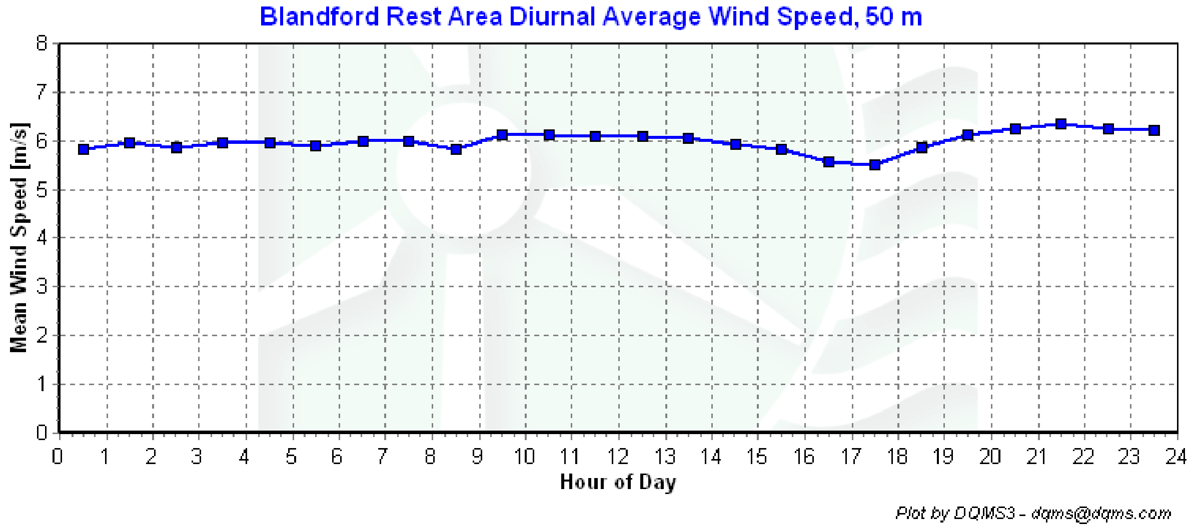

Figure 5 – Diurnal Average Wind Speeds, December 1, 2008 – February 28, 2009

Turbulence Intensities

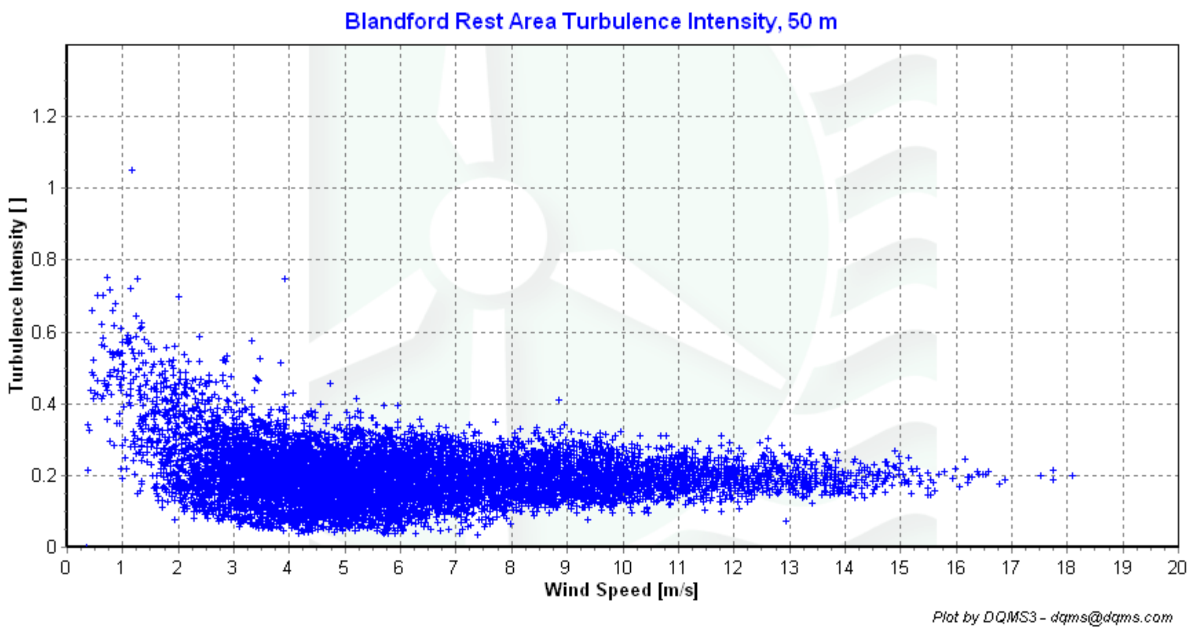

Figure 6 – Turbulence Intensity vs. Wind Speed, December 1, 2008 – February 28, 2009

Wind Rose

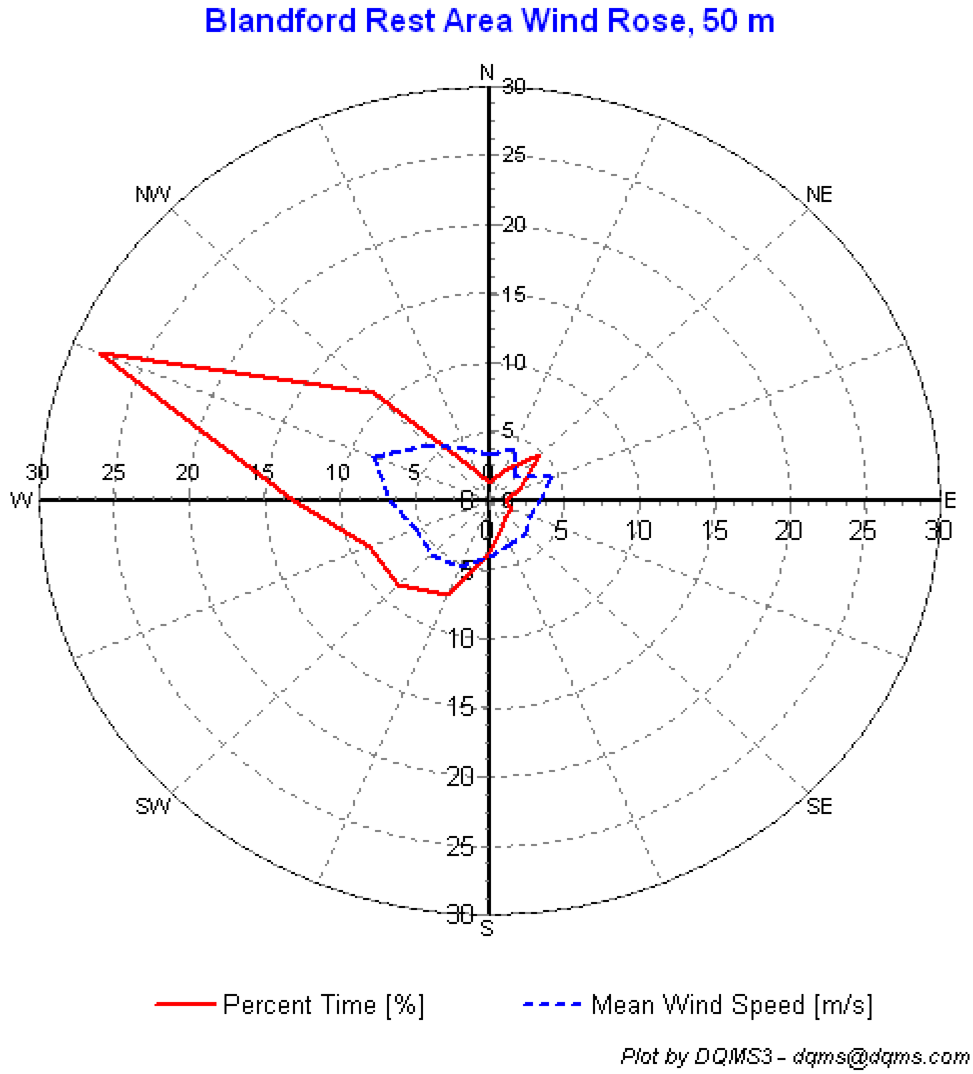

Figure 7 – Wind Rose, December 1, 2008 – February 28, 2009

SECTION 5 - Significant Meteorological Events

There were no extreme metrological events during this data collection period. The highest recorded wind speed was 18.1 m/s (40.5 mph).

SECTION 6 - Data Collection and Maintenance

The secondary 35 meter anemometer failed in the last week of July at which point it gave readings of exclusively 0.35 m/s. The data from the primary 35 m anemometer shows consistent wind speeds relative to the 50 meter data after the secondary 35 m anemometer failed. No maintenance was performed during this quarter.

SECTION 7 - 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.

Gross Data Recovered [%]	98.89
Net Data Recovered [%]	77.86

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.

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

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.

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

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

Test Definitions

Test Order	Test Field 1	Test Field 2	Test Field 3	Calc Field 1	Calc Field 2	Test Type	Factor 1	Factor 2	Factor 3	Factor 4
1						TimeTest Insert	0	0	0	0
4	Etmp2aDEGC					MinMax	-30	60	0	0
5	EtmpSD2aDEGC					MinMax	-30	60	0	0
6	Batt2aVDC					MinMax	10.5	15	0	0
10	Anem50aMS					MinMax	0	90	0	0
11	Anem50bMS					MinMax	0	90	0	0
12	Anem30aMS					MinMax	0	90	0	0
13	Anem30bMS					MinMax	0	90	0	0
14	Anem50yMS					MinMax	0	90	0	0
15	Anem30yMS					MinMax	0	90	0	0
20	AnemSD50aMS					MinMax	0	4	0	0
21	AnemSD50bMS					MinMax	0	4	0	0
22	AnemSD30aMS					MinMax	0	4	0	0
23	AnemSD30bMS					MinMax	0	4	0	0
24	AnemSD50yMS					MinMax	0	4	0	0
25	AnemSD30yMS					MinMax	0	4	0	0
30	Vane50aDEG					MinMax	0	359.9	0	0
31	Vane30aDEG					MinMax	0	359.9	0	0
50	Turb50zNONE					MinMax	0	2	0	0
51	Turb30zNONE					MinMax	0	2	0	0
200	VaneSD50aDEG	Anem50yMS				MinMaxT	0	100	100	10
201	VaneSD30aDEG	Anem30yMS				MinMaxT	0	100	100	10
300	Anem50aMS	AnemSD50aMS	Vane50aDEG	VaneSD50aDEG	Etmp2aDEGC	Icing	0.5	1	2	4
301	Anem50bMS	AnemSD50bMS	Vane50aDEG	VaneSD50aDEG	Etmp2aDEGC	Icing	0.5	1	2	4
302	Anem30aMS	AnemSD30aMS	Vane30aDEG	VaneSD30aDEG	Etmp2aDEGC	Icing	0.5	1	2	4
303	Anem30bMS	AnemSD30bMS	Vane30aDEG	VaneSD30aDEG	Etmp2aDEGC	Icing	0.5	1	2	4
304	Anem50yMS	AnemSD50yMS	Vane50aDEG	VaneSD50aDEG	Etmp2aDEGC	Icing	0.5	1	2	4
305	Anem30yMS	AnemSD30yMS	Vane30aDEG	VaneSD30aDEG	Etmp2aDEGC	Icing	0.5	1	2	4
400	Anem50aMS	Anem50bMS				CompareSensors	1	0.25	3	0
401	Anem30aMS	Anem30bMS				CompareSensors	1	0.25	3	0
500	Amax50aMS					MinMax	0	90	0	0
501	Amin50aMS					MinMax	0	90	0	0
502	Amax50bMS					MinMax	0	90	0	0
503	Amin50bMS					MinMax	0	90	0	0
504	Amax30aMS					MinMax	0	90	0	0
505	Amin30aMS					MinMax	0	90	0	0
506	Amax30bMS					MinMax	0	90	0	0
507	Amin30bMS					MinMax	0	90	0	0
508	Vmax50aDEG					MinMax	0	359.9	0	0
509	Vmin50aDEG					MinMax	0	359.9	0	0
510	Vmax30aDEG					MinMax	0	359.9	0	0
511	Vmin30aDEG					MinMax	0	359.9	0	0
512	Etmx2aDEGC					MinMax	-30	60	0	0
513	Etmn2aDEGC					MinMax	-30	60	0	0

Sensor Statistics

Sensor	Expected Data Points	Actual Data Points	% Data Recovered	Hours Out of Range	Hours of Icing	Hours of Fault	% Data Good
Etmp2aDEGC	12960	12816	98.889	0	0	0	98.889
EtmpSD2aDEGC	12960	12816	98.889	0	0	0	98.889
Batt2aVDC	12960	12816	98.889	0	0	0	98.889
Anem30aMS	12960	12816	98.889	0.333	332	0	83.503
AnemSD30aMS	12960	12816	98.889	0.333	332	0	83.503
Anem30bMS	12960	12816	98.889	0	0	1737.833	18.434
AnemSD30bMS	12960	12816	98.889	0	0	1737.833	18.434
Anem50aMS	12960	12816	98.889	0.333	325.167	22.5	82.778
AnemSD50aMS	12960	12816	98.889	0.333	325.167	22.5	82.778
Anem50bMS	12960	12816	98.889	0.167	326.167	3.5	83.619
AnemSD50bMS	12960	12816	98.889	0.167	326.167	3.5	83.619
Vane30aDEG	12960	12816	98.889	0.167	332	0	83.511
VaneSD30aDEG	12960	12816	98.889	0.167	332	0	83.511
Vane50aDEG	12960	12816	98.889	0	326.167	0	83.789
VaneSD50aDEG	12960	12816	98.889	0	326.167	0	83.789
Total	194400	192240	98.889	2	3283	3527.667	77.862

APPENDIX B - Plot Data

Wind Speed Distribution Data

Bin Center Wind Speed [m/s]	December 2008 - February 2009 [%]
0.5	5.72
1.5	2.77
2.5	6.95
3.5	11.83
4.5	14.84
5.5	14.14
6.5	10.92
7.5	7.68
8.5	6.78
9.5	6.34
10.5	4.34
11.5	3.08
12.5	1.96
13.5	1.56
14.5	0.7
15.5	0.24
16.5	0.12
17.5	0.03
18.5	0.01
19.5	0
20.5	0
21.5	0
22.5	0
23.5	0
24.5	0

Monthly Average Wind Speed Data

Date	50m Mean 10 min [m/s]
February 2008	
March	6.06
April	5
May	5.28
June	4.29
July	3.86
August	4.16
September	4.17
October	5.18
November	4.82
December	6.44
January	5.14
February 2009	6.33
Winter: Dec 2008 - Feb 2009	**5.99**

Diurnal Average Wind Speed Data

Hour of Day	December 2008 - February 2009 Mean Wind Speed [m/s]
0	5.84
1	5.96
2	5.87
3	5.95
4	5.96
5	5.88

6	5.98
7	6
8	5.83
9	6.13
10	6.11
11	6.08
12	6.09
13	6.06
14	5.92
15	5.82
16	5.56
17	5.51
18	5.88
19	6.13
20	6.25
21	6.36
22	6.26
23	6.23

Wind Rose Data

	December 2008 - February 2009	
Direction	Percent Time [%]	Mean Wind Speed [m/s]
N	1.34	3.32
NNE	2.43	4.06
NE	4.64	2.51
ENE	2.13	4.47
E	1.11	3.36
ESE	1.58	2.94
SE	1.55	3.31
SSE	2.22	3.52
S	3.78	4.01
SSW	7.35	5.15

SW	8.63	5.52
WSW	8.68	5.36
W	13.12	6.7
WNW	28.13	8.37
NW	11.01	5.65
NNW	2.27	4.06