WIND DATA REPORT

Plymouth

May 9 2007 – May 29 2008

Prepared for

Massachusetts Technology Collaborative
75 North Drive
Westborough, MA 01581

by

Thomas Langelier
James F. Manwell
Utama Abdulwahid
Anthony F. Ellis

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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.

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

Wind monitoring equipment was first installed at Plymouth on May 9, 2007. Two sets of anemometers and one wind vane were mounted at 50 m (164 ft) and 38 m (125 ft). The equipment was taken down on May 29, 2009, after completing a calendar year of measurements. For this time period, the gross data recovery percentage (the actual percentage of expected data received) was 97.24% and the net data recovery percentage (the percentage of expected data which passed all of the quality assurance tests) was 95.41%. The lost data was the result of a logger malfunction in September 2007, likely due to vandalism, and the remaining data that didn’t pass QC tests was mostly due to icing events in the winter months.

This final data report summarizes the wind data collected between June 1 2007 and May 29 2008. The mean wind speed at 50 m over this time period was 5.64 m/s (12.62 mph*). The highest monthly mean wind speed during the year at 50 m was in March 2008 at 6.51 m/s (142.56 mph) and the lowest was 4.80 m/s (10.74 mph) in August 2007. The prevailing wind direction in the spring and summer was south-southwest, southwest in the fall, and due west in the winter.

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 Plymouth monitoring tower is located in a cornfield owned by the Plymouth County Sherriff's Office, and is used by the nearby Plymouth County Correctional Facility. The 50 m (164 ft) tower is located at 41°-56'-10.69" North, 70°-39'-02.46" West, shown below in Figure 1. The tower base is 41 m (135 ft) above sea level.

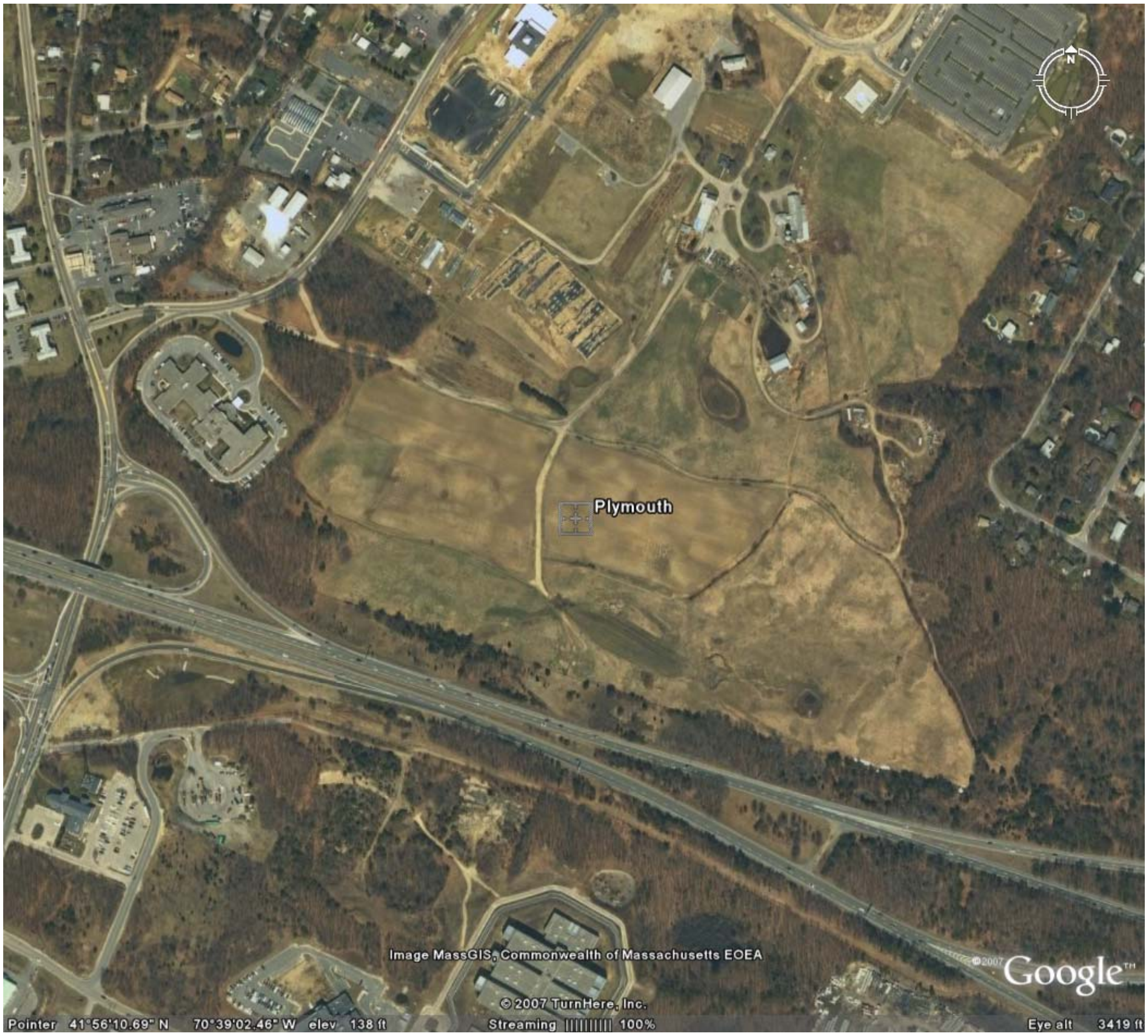

Figure 1 – Site Location

SECTION 2 - Instrumentation and Equipment

The 50 m (164 ft) monitoring tower is supplied by SecondWind, the sensors and logger are supplied by NRG systems. The wind speed and direction were measured at both 38 and 50 m height. The monitoring equipment consists of the following items:

- Symphony Data Logger, serial #3204
- SecondWind 50m tower
- 4-#40 Anemometers, standard calibration (Slope 0.765, Offset 0.350)
- 2-#200P Wind direction vanes (Slope 1.0, Offset 0.0)
- #110S Temperature sensor (Slope 0.138, Offset -86.383)
- 4- Sensor booms for anemometers, 54" length
- 2- Sensor booms for vanes, 44" length
- Lightning rod and grounding cable
- Shielded sensor wire

The logger samples data from the sensors once every two seconds. These samples are combined into 10-minute averages and are put into a binary file along with the standard deviation for each 10-minute interval. These binary files are stored on a data card that is mailed to the University of Massachusetts, Amherst on a regular basis. Using the NRG software BaseStation®, the binary files are converted into ASCII text files.

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 Height Units	Mean Wind Speed 50 m [m/s]	Max Wind Speed 50 m [m/s]	Prevailing Wind Direction 50 m [deg]	Mean Wind Speed 38 m [m/s]	Max Wind Speed 38 m [m/s]	Prevailing Wind Direction 38 m [deg]
Jun 2007	5.48	11.5	SW	5.08	10.90	SW
Jul 2007	4.81	14	SSW	4.43	13.30	SSW
Aug 2007	4.80	14.10	SSW	4.41	13.20	SSW
Sep 2007	-	-	-	-	-	-
Oct 2007	5.35	15.20	SW	4.85	14.20	SW
Nov 2007	6.20	23.10	SSW	5.62	21.30	SSW
Dec 2007	5.77	16.20	W	5.22	15.00	W
Jan 2008	6.16	18.40	SW	5.58	16.80	SW
Feb 2008	6.11	20.50	W	5.67	19.10	W
Mar 2008	6.51	19.50	W	5.97	17.90	W
Apr 2008	5.15	16.70	NE	4.68	15.20	NE
May 2008	5.96	15.20	SSW	5.40	13.90	SSW
Jun 2007 - May 2008	**5.64**	**23.10**	**SSW**	**5.14**	**21.30**	**SSW**

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 are missing, the percent of the available data that are used to determine the data statistics is noted. The statistics for September 2007 are not reported in the table above since the total amount of data recovered in that month was ~70%. This is discussed further in section 7.

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 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	Turbulence Intensity at 10 m/s	Turbulence Intensity at 10 m/s	Mean Wind Shear Coefficient, α
Height Units	50 m [-]	38 m [-]	Between 50 m and 38 m [-]
Jun 2007	0.160	0.170	0.252
Jul 2007	0.171	0.200	0.263
Aug 2007	0.190	0.216	0.129
Sep 2007	-	-	-
Oct 2007	0.176	0.202	0.354
Nov 2007	0.175	0.197	0.368
Dec 2007	0.188	0.210	0.381
Jan 2008	0.175	0.200	0.394
Feb 2008	0.179	0.215	0.387
Mar 2008	0.186	0.209	0.330
Apr 2008	0.183	0.217	0.383
May 2008	0.168	0.186	0.380
Jun 2007 -May 2008	**0.179**	**0.203**	**0.330**

SECTION 4- Capacity Factor

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 hub height of 80 m, a 1.8 MW wind turbine with a rotor diameter of 80 m and the mean wind speed at the highest measurement height and the mean wind shear at the site, in order to determine the mean hub height wind speed. The capacity factor (CF) is then estimated from (see G.M. Masters, Renewable and Efficient Electric Power Systems, Wiley, 2004):

$$CF = (0.087)U_{hub} - \frac{P_{rated}}{D^2}$$

where U_{hub} is the mean annual hub height wind speed in m/s, P_{rated} is the rated power of the wind turbine in kW and D is the diameter of the rotor in meters. Based on this equation, the estimated capacity factor of a wind turbine at this site would be about 0.292.

SECTION 5- Graphs

This report contains several types of wind data graphs. Unless otherwise noted, each graph represents data at a height of 50 m (161.4 ft) for the year of measurement (June 2007 through May 2008). The following graphs are included:

- Time Series – In Figure 2, 10-minute average wind speeds are plotted against time for data starting in May 2007 through May 2008. This graph includes all of the collected data. During this time, the highest measured wind speed of 23.1 m/s was recorded in early November 2007, and can be clearly seen on the graph.

- Wind Speed Distribution – A histogram plot giving the percentage of time that the wind is at a given wind speed is shown in Figure 3. This plot shows that the wind speeds ranged between 5 and 6 m/s (11.2 and 13.4 mph) 18.67% of the time.

- Monthly Average – A plot of the monthly average wind speed over the 12-month period from June 2007 to May 2008 is shown in Figure 4. Less than 90% of the data from September 2007 was recovered, so the average from this month is not reported. This graph shows that for Plymouth, the highest average monthly wind speed was 6.51 m/s (14.56 mph) in March 2008. The lowest speed was 4.80 m/s (10.74 mph) in August 2007.

- Diurnal – Figure 5 is a plot of the average wind speed for each hour of the day. The hourly average varied between 5.39 and 5.98 m/s (12.06 and 13.38 mph) with the highest average speeds between 1 PM and 3 PM. The lowest average speeds were between 6 AM and 8 AM

- Turbulence Intensity – A plot of turbulence intensity as a function of wind speed is shown in Figure 6. 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. In general, turbulence intensities range from 0.1 to 0.4; for Plymouth, the average turbulence intensity over the entire year at 10 m/s was 0.179.

- Wind Rose – Figure 7 is 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. The wind rose shows that the prevailing direction was from the

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

Wind Speed Time Series

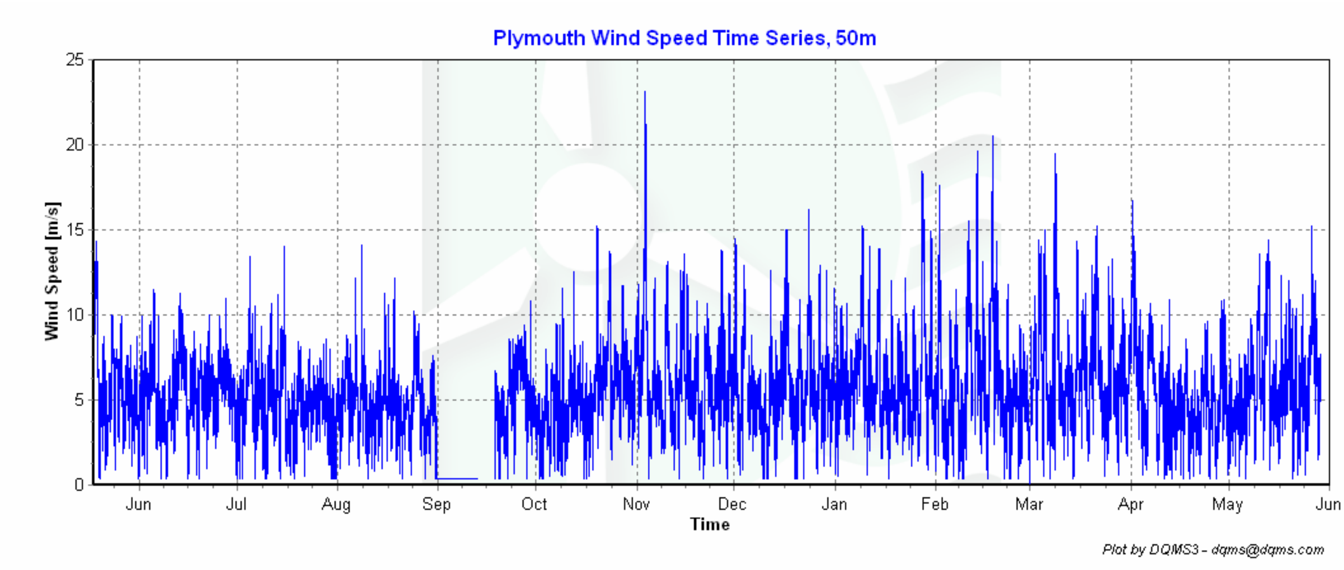

Figure 2 – Wind Speed Time Series, May 18 2007 – May 29 2008

Wind Speed Distributions

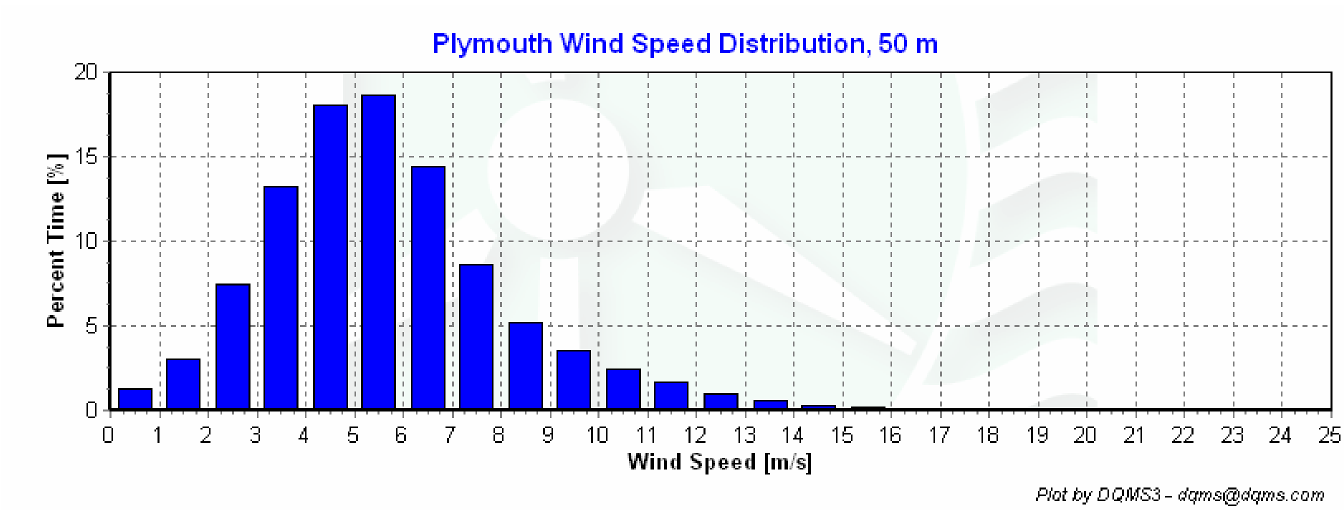

Figure 3 – Wind Speed Distribution, June 2007 – May 2008

Monthly Average Wind Speeds

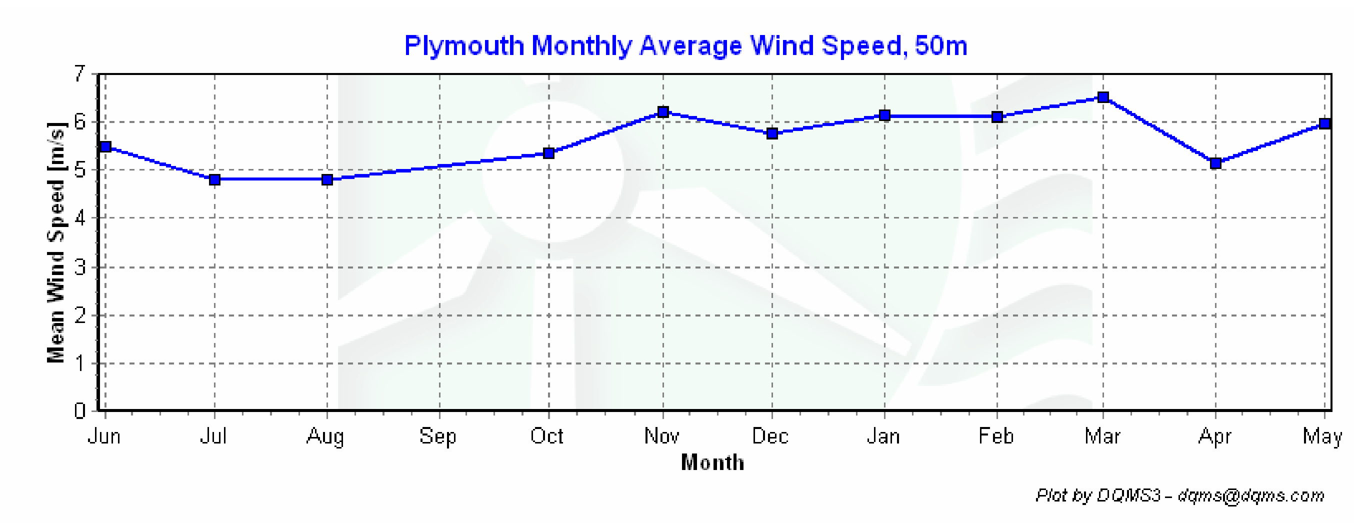

Figure 4 – Monthly Averages, June 2007 – May 2008

Diurnal Average Wind Speeds

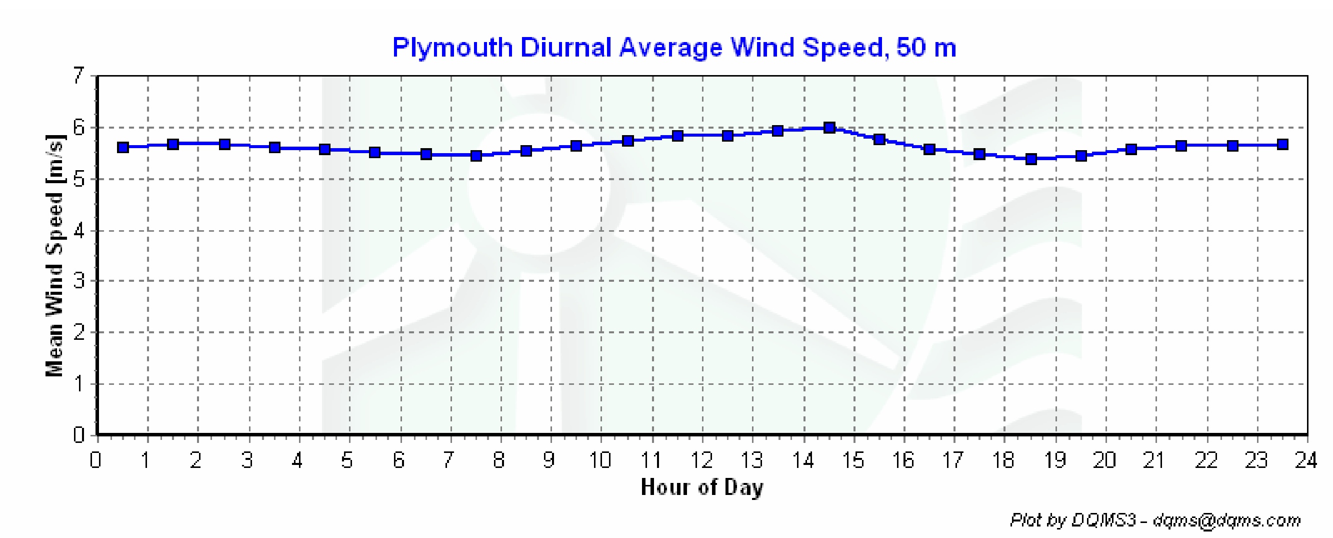

Figure 5 – Diurnal Average Wind Speed, June 2007 – May 2008

Turbulence Intensities

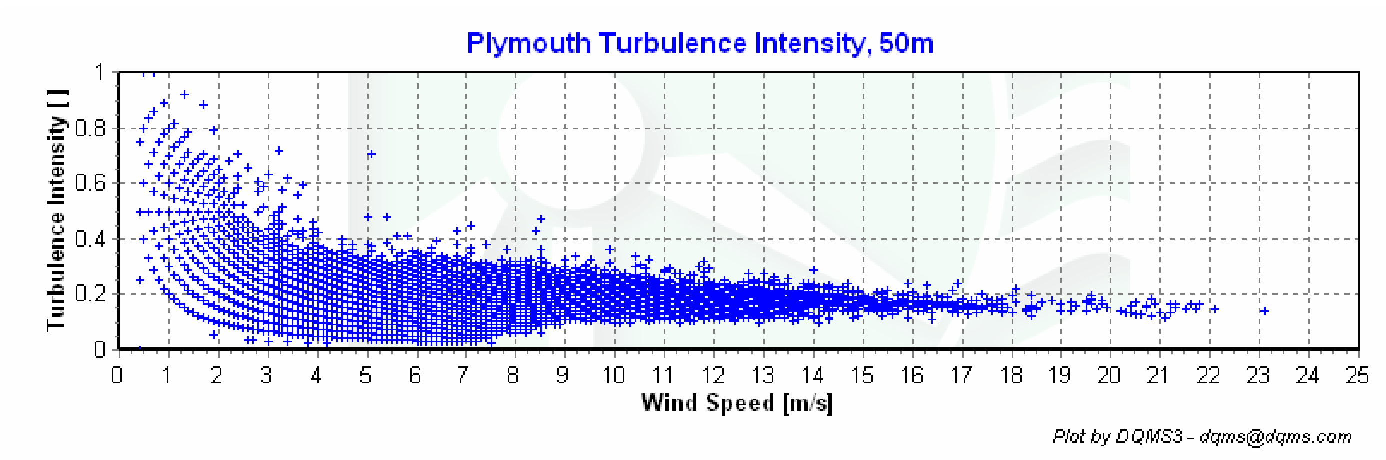

Figure 6 – Turbulence Intensity vs. Wind Speed, June 2007 – May 2008

Wind Roses

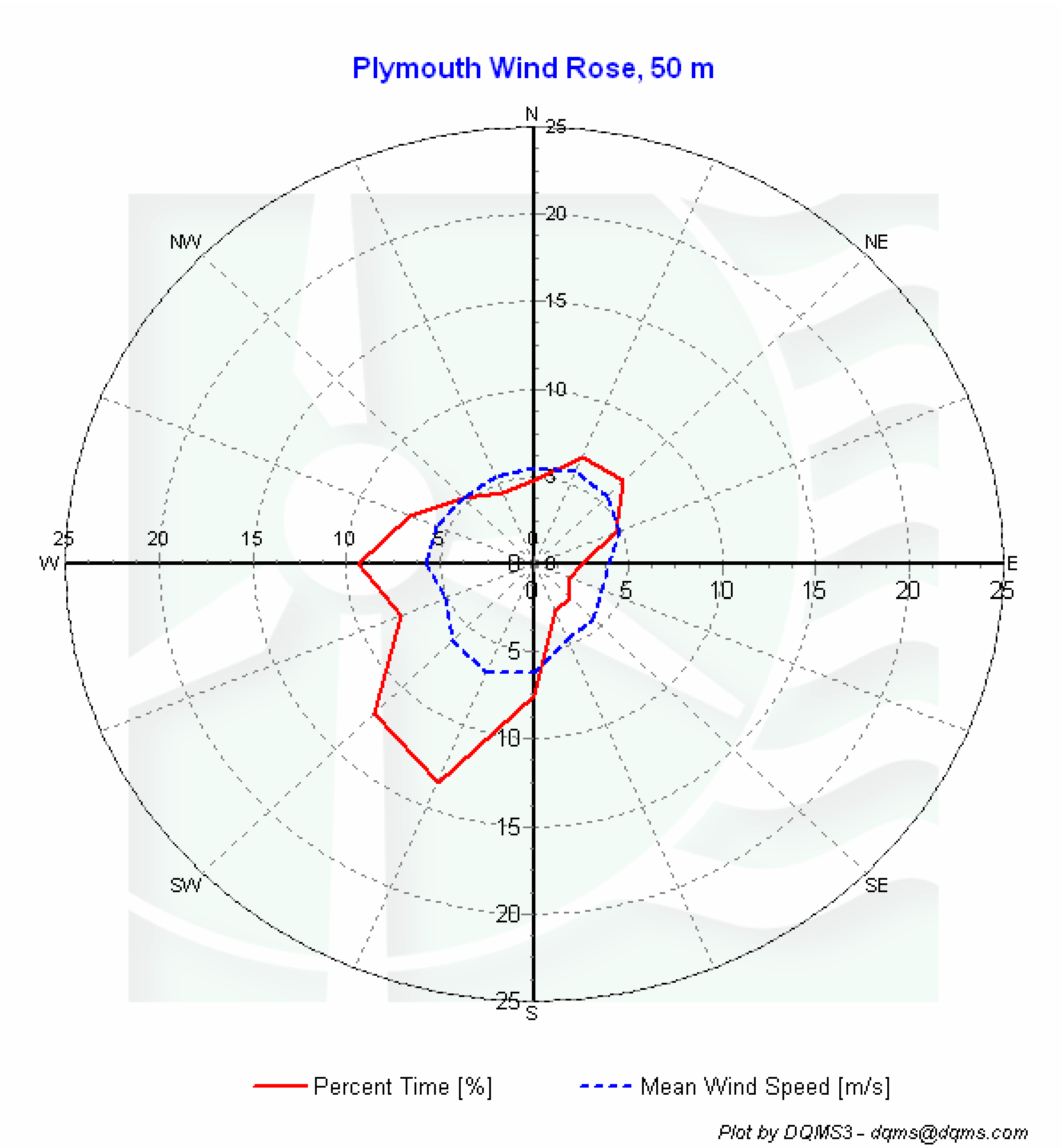

Figure 7 – Wind Rose, June 2007 – May 2008

SECTION 6 - Significant Meteorological Events

The following significant meteorological events occurred during the measurement period:

- 11/03/2007 – Winter Storm, High Winds
- 12/23/2007 – Winter Storm, High Winds
- 02/18/2008 – Winter Storm, High Winds

The wind and precipitation conditions were close to average for the rest of the year.

Sources:

http://www.erh.noaa.gov/box/MonthlyClimate2.shtml

http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwevent~storms

SECTION 7 - Data Collection and Maintenance

Data collection began on May 9, 2007 and ended when the measurement tower was taken down on May 29, 2008. Data cards were manually removed from the logger and mailed to staff at RERL approximately once a month, except for the last month when the card was removed by RERL staff. In September 2007 more than 10% of the data was out of range or simply not reported, likely due to vandalism of the logger and/or sensor cables. No statistics are reported for the month of September. No other problems with the data were encountered during the yearlong measurement campaign and no other maintenance operations were needed or performed on the equipment.

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.

Gross Data Recovered [%]	97.24
Net Data Recovered [%]	95.41

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.

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

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

Test Definitions

TestOrder	TestField1	TestField2	TestField3	CalcField1	CalcField2	CalcField3	TestType	Relation	Factor1	Factor2	Factor3	Factor4
1							TimeTest Insert					
4	Etmp2aDEGC						MinMax		-30	60		
5	EtmpSD2aDEGC						MinMax		-30	60		
10	Anem50aMS						MinMax		0	90		
11	Anem50bMS						MinMax		0	90		
12	Anem38aMS						MinMax		0	90		
13	Anem38bMS						MinMax		0	90		
14	Anem50yMS						MinMax		0	90		
15	Anem38yMS						MinMax		0	90		
20	AnemSD50aMS						MinMax		0	4		
21	AnemSD50bMS						MinMax		0	4		
22	AnemSD38aMS						MinMax		0	4		
23	AnemSD38bMS						MinMax		0	4		
24	AnemSD50yMS						MinMax		0	4		
25	AnemSD38yMS						MinMax		0	4		
30	Vane50aDEG						MinMax		0	359.9		
31	Vane38aDEG						MinMax		0	359.9		
50	Turb50zNONE						MinMax		0	2		
51	Turb38zNONE						MinMax		0	2		
60	Wshr0zNONE						MinMax		-100	100		
70	Pwrd50zWMC						MinMax		0	5000		
71	Pwrd38zWMC						MinMax		0	5000		
200	VaneSD50aDEG	Anem50yMS					MinMaxT		0	100	100	10
201	VaneSD38aDEG	Anem38yMS					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	Anem38aMS	AnemSD38aMS	Vane38aDEG	VaneSD38aDEG	Etmp2aDEGC		Icing		0.5	1	2	4
303	Anem38bMS	AnemSD38bMS	Vane38aDEG	VaneSD38aDEG	Etmp2aDEGC		Icing		0.5	1	2	4
400	Anem50aMS	Anem50bMS					CompareSensors		1	0.25	3	0
401	Anem38aMS	Anem38bMS					CompareSensors		1	0.25	3	0
500	Amax50aMS						MinMax		0	90		
501	Amin50aMS						MinMax		0	90		
502	Amax50bMS						MinMax		0	90		
503	Amin50bMS						MinMax		0	90		
504	Amax38aMS						MinMax		0	90		
505	Amin38aMS						MinMax		0	90		
506	Amax38bMS						MinMax		0	90		
507	Amin38bMS						MinMax		0	90		
508	Vmax50aDEG						MinMax		0	359.9		
509	Vmin50aDEG						MinMax		0	359.9		
510	Vmax38aDEG						MinMax		0	359.9		
511	Vmin38aDEG						MinMax		0	359.9		
512	Etmx2aDEGC						MinMax		-30	60		

Sensor Statistics

Sensor	Expected Data Points	Actual Data Points	% Data Recovered	Hours Out of Range	Hours of Icing	Hours of Fault	% Data Good
Etmp2aDEGC	52704	51353	97.437	0	0	0	97.437
EtmpSD2aDEGC	52704	51353	97.437	0	0	0	97.437
Anem50aMS	52704	51349	97.429	0.667	87.5	317.5	92.811
AnemSD50aMS	52704	51353	97.437	0.667	87.5	5.667	96.368
Anem50bMS	52704	51349	97.429	0.5	91.5	312.333	92.826
AnemSD50bMS	52704	51353	97.437	0.5	91.5	0.5	96.384
Anem38aMS	52704	51349	97.429	0.5	101.5	355.5	92.221
AnemSD38aMS	52704	51353	97.437	0.5	101.5	348.167	92.312
Anem38bMS	52704	51353	97.437	0.333	102.167	5	96.213
AnemSD38bMS	52704	51353	97.437	0.333	102.167	5	96.213
Vane50aDEG	52704	51353	97.437	0.833	93.333	0	96.365
VaneSD50aDEG	52704	51353	97.437	0.833	93.333	0	96.365
Vane38aDEG	52704	51353	97.437	1	107.167	0	96.205
VaneSD38aDEG	52704	51353	97.437	1	107.167	0	96.205
Total	948672	922471	97.238	8.5	1530.667	1349.667	95.411

APPENDIX B - Plot Data

Wind Speed Distribution Data

Bin Center Wind Speed [m/s]	Percent of Time [%]
0.5	1.27
1.5	3.07
2.5	7.46
3.5	13.27
4.5	18.06
5.5	18.67
6.5	14.37
7.5	8.64
8.5	5.15
9.5	3.48
10.5	2.47
11.5	1.68
12.5	1.01
13.5	0.57
14.5	0.31
15.5	0.20
16.5	0.13
17.5	0.08
18.5	0.03
19.5	0.03
20.5	0.03
21.5	0.02
22.5	0.00
23.5	0.00
24.5	0.00

Monthly Average Wind Speed Data

Month	Average Wind Speed [m/s]
Jun	5.48
Jul	4.8
Aug	4.8
Sep	-
Oct	5.35
Nov	6.18
Dec	5.58
Jan	6.14
Feb	6.06
Mar	6.51
Apr	5.15
May	5.96

Diurnal Average Wind Speed Data

Bin Center Hour	Average Wind Speed [m/s]
0.5	5.61
1.5	5.67
2.5	5.67
3.5	5.59
4.5	5.57
5.5	5.51
6.5	5.48
7.5	5.46
8.5	5.55
9.5	5.64
10.5	5.75
11.5	5.85
12.5	5.85
13.5	5.93
14.5	5.98
15.5	5.77
16.5	5.56
17.5	5.47
18.5	5.39
19.5	5.45
20.5	5.56
21.5	5.63
22.5	5.65
23.5	5.66

Wind Rose Data

Direction	Percent Time [%]	Mean Wind Speed [m/s]
N	4.78	5.46
NNE	6.58	5.76
NE	6.75	5.47
ENE	4.74	4.87
E	2.56	3.99
ESE	2.09	3.86
SE	2.70	4.47
SSE	2.91	4.66
S	7.48	6.16
SSW	13.50	6.73
SW	12.03	6.14
WSW	7.64	5.16
W	9.37	5.76
WNW	7.16	5.61
NW	5.36	5.38
NNW	4.37	5.42