2013

Lake Michigan Wind Assessment Project Data Summary and Analysis: December 2013

Lake Michigan Offshore Wind Assessment Project

Lake Michigan Wind Assessment Project

Data Summary and Analysis

December 2013

Part I – 2013 Data

This report summarizes the data collected by the Laser Wind Sensor (LWS) #8 with collection information as follows.

Location: Lake Michigan – Near Muskegon (4316.542N, 8630.347W)

Date: December 1 through December 20, 2013 (UTC)

Range Gates 1-6: 75, 90, 105, 125, 150, 175 meters

Cup Anemometer: 3 meters mounted on the buoy

Observations: 10-minute averages

Number of Observations: 20 days at 6 observations per hour = 2880 observations

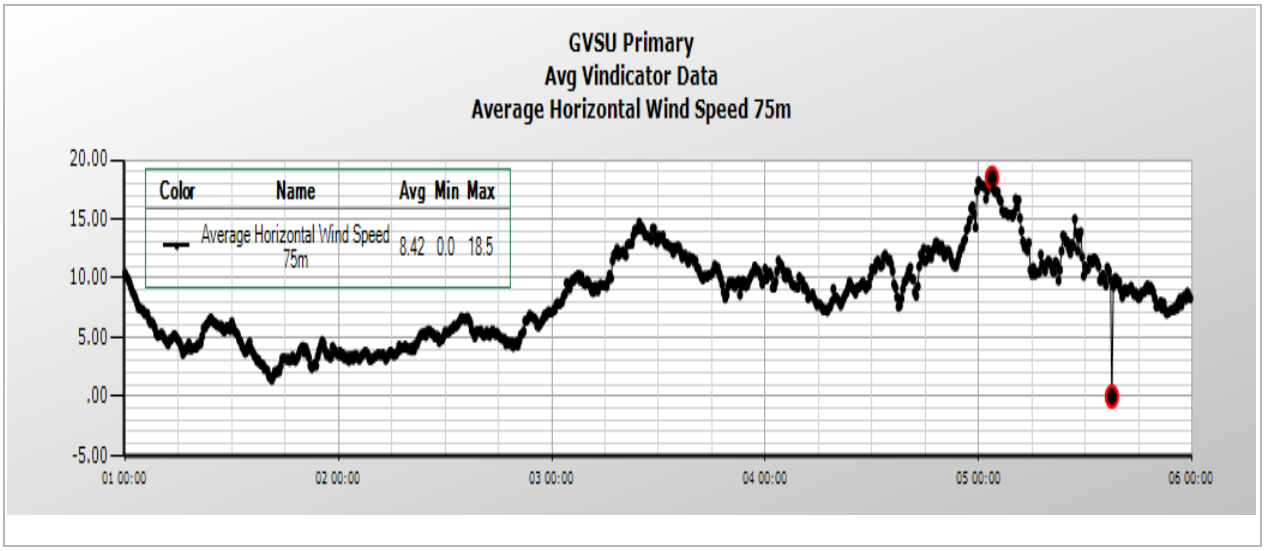
Missing Observations: None

Good Observations: 2880 (100%)

Notes:

- Range Gate 6 (175 meters) is a test range gate to observe the performance of the sensor at the extreme operating height limit for this configuration. Thus, performance degradation was expected.
- All high resolution 1 second data for all wind speeds is stored onboard the buoy and can be used for further detailed post processing as required.

Graphs for wind speed for all ranges as well as the cup anemometer follow. Graphs of the horizontal wind direction at the cup anemometer and range gate 1 are included as well.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02 00:00
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04 00:00
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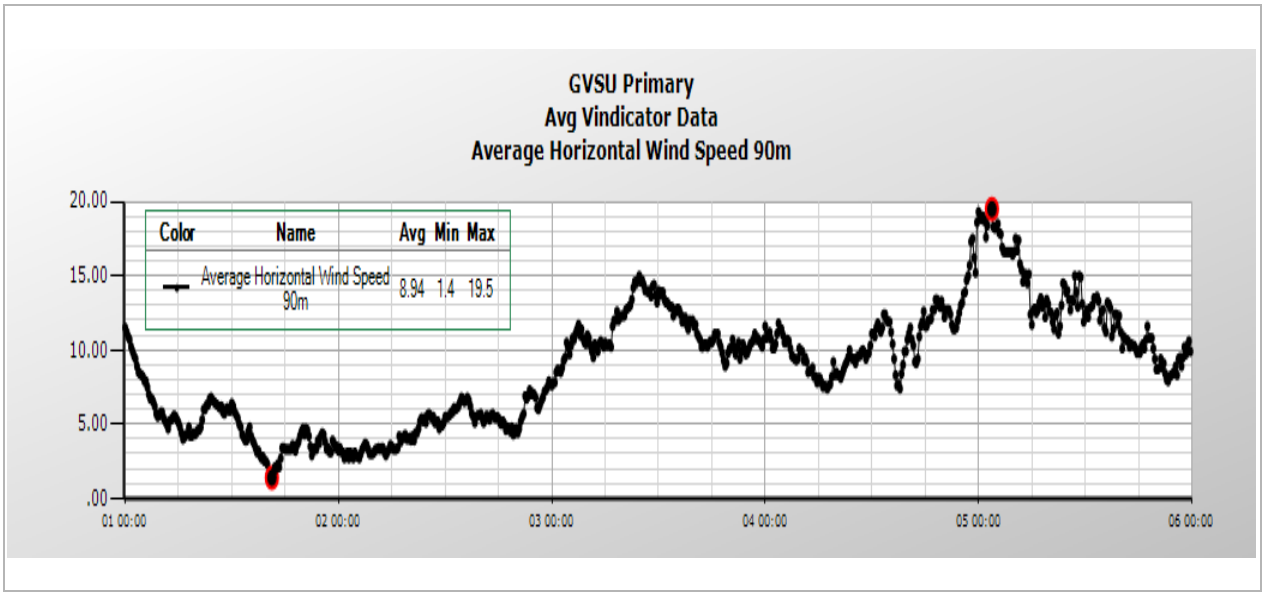
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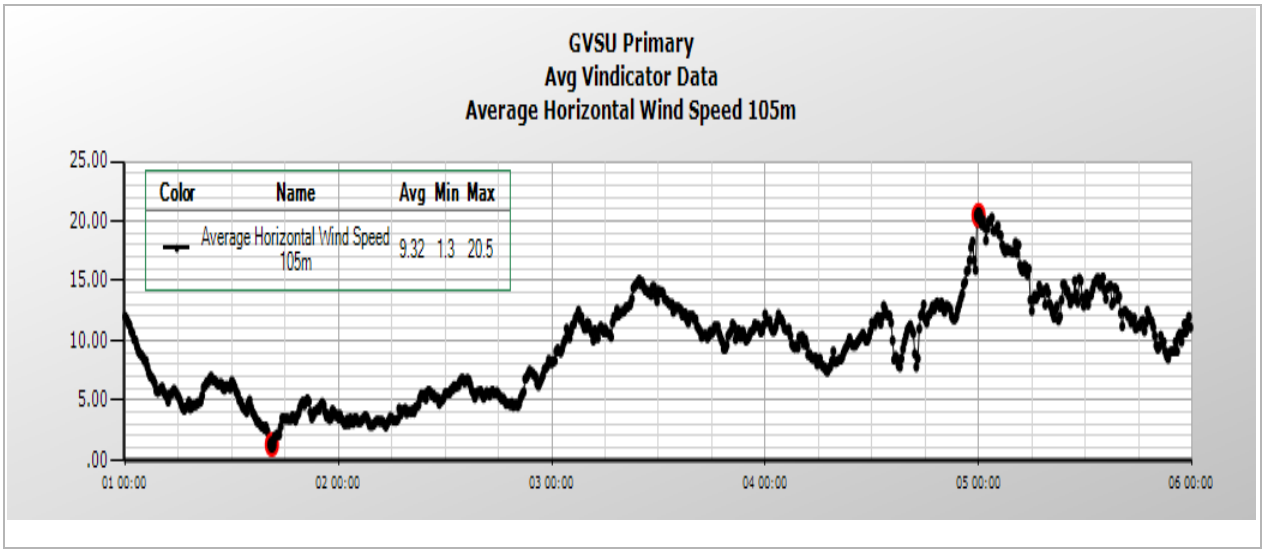
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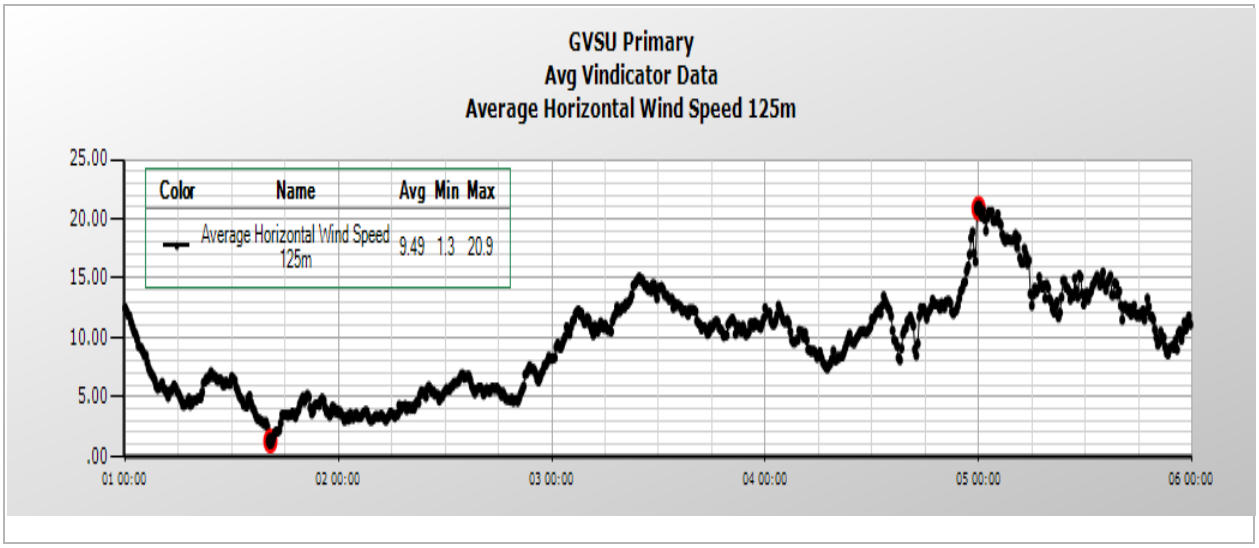
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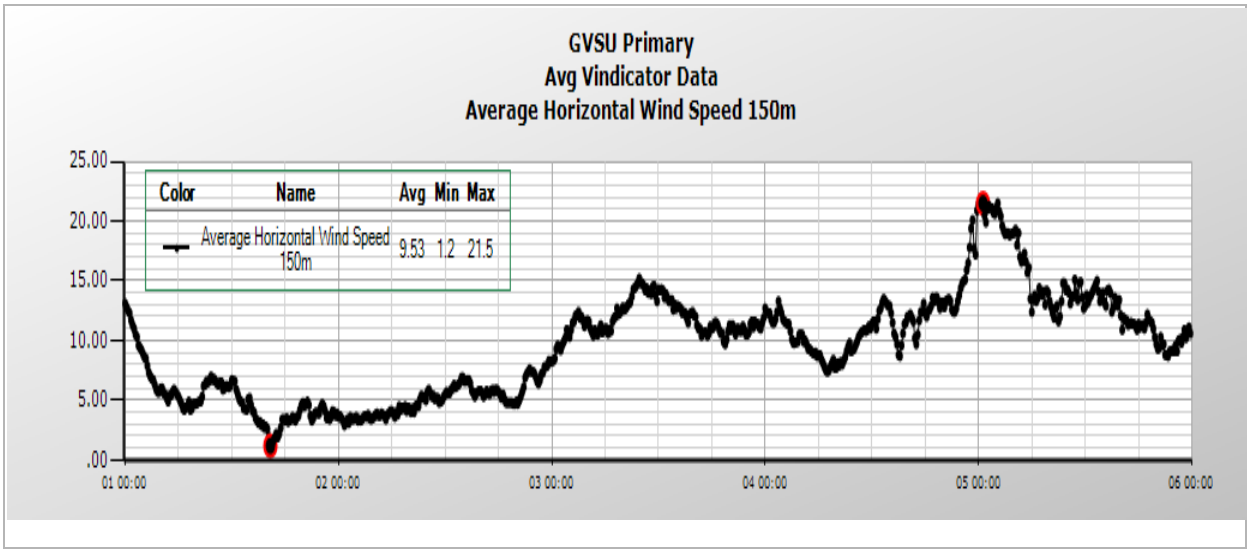
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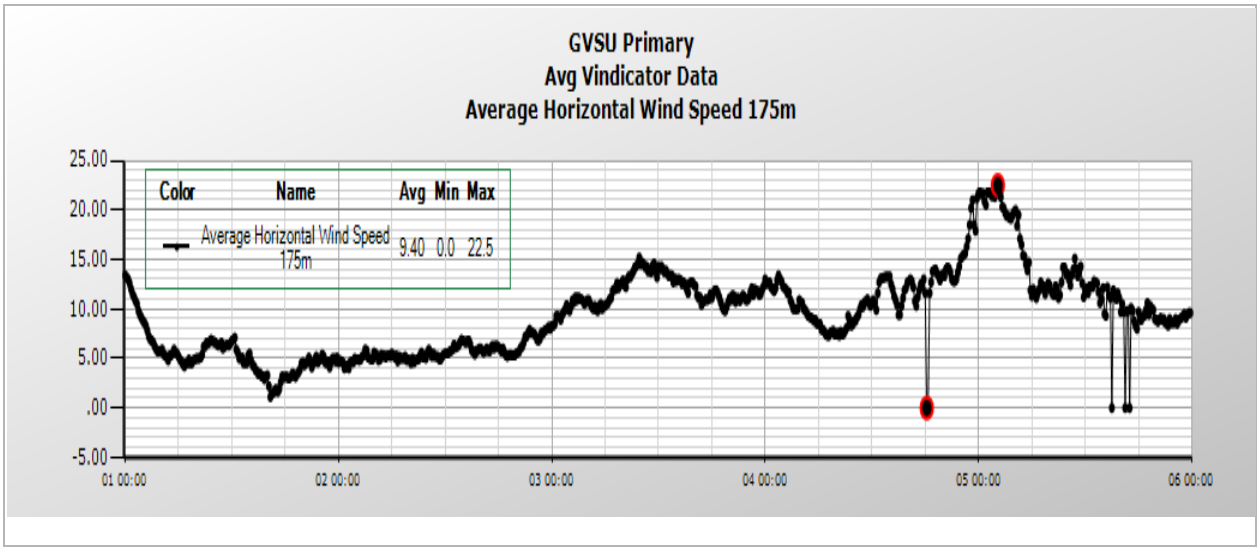
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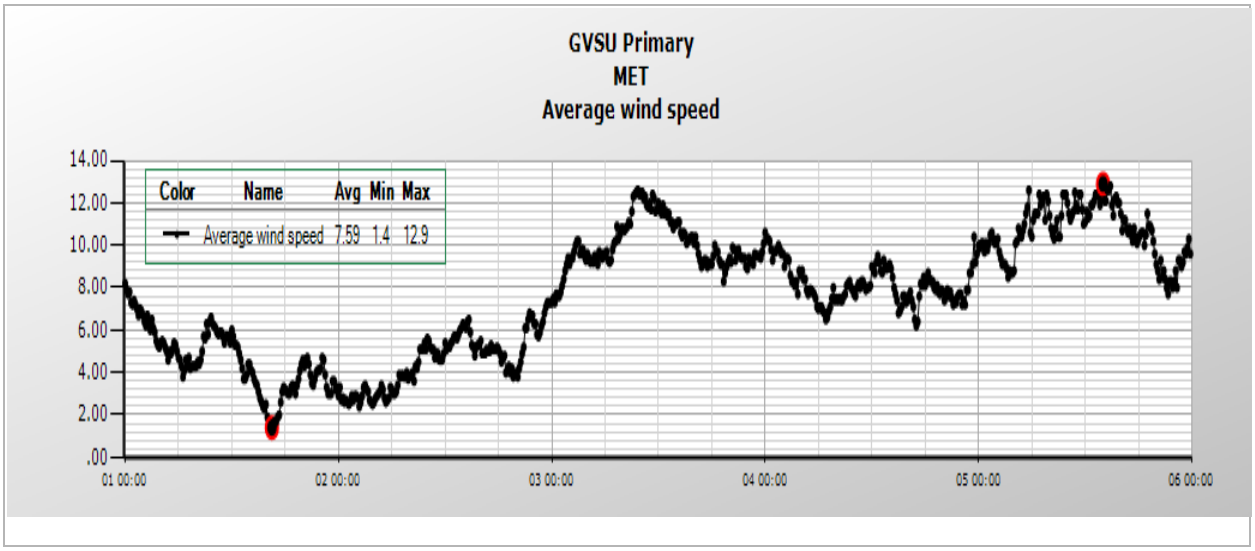
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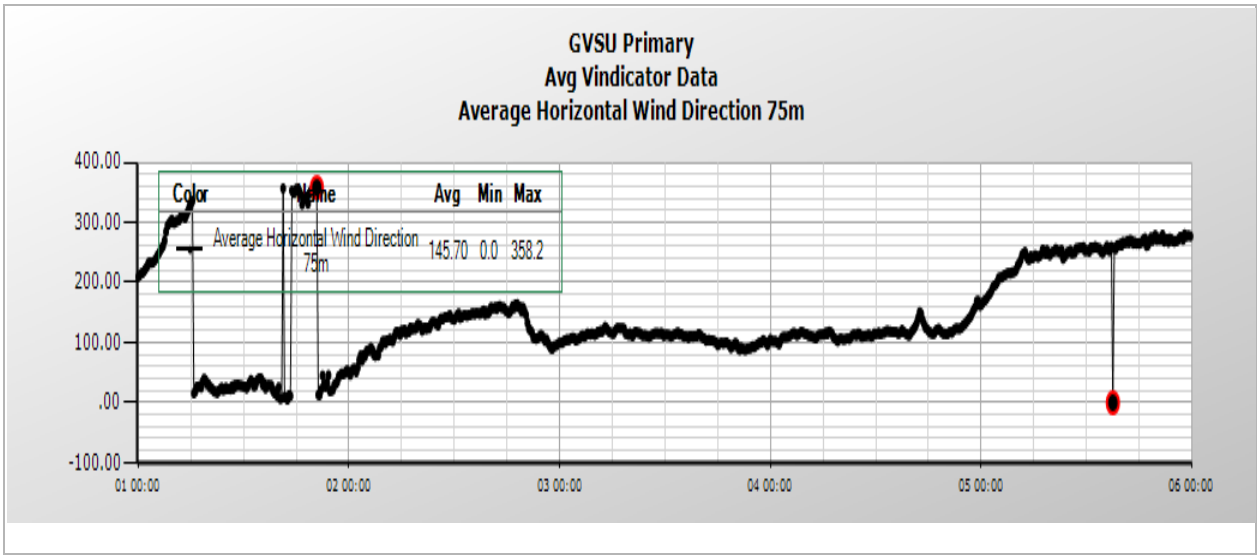
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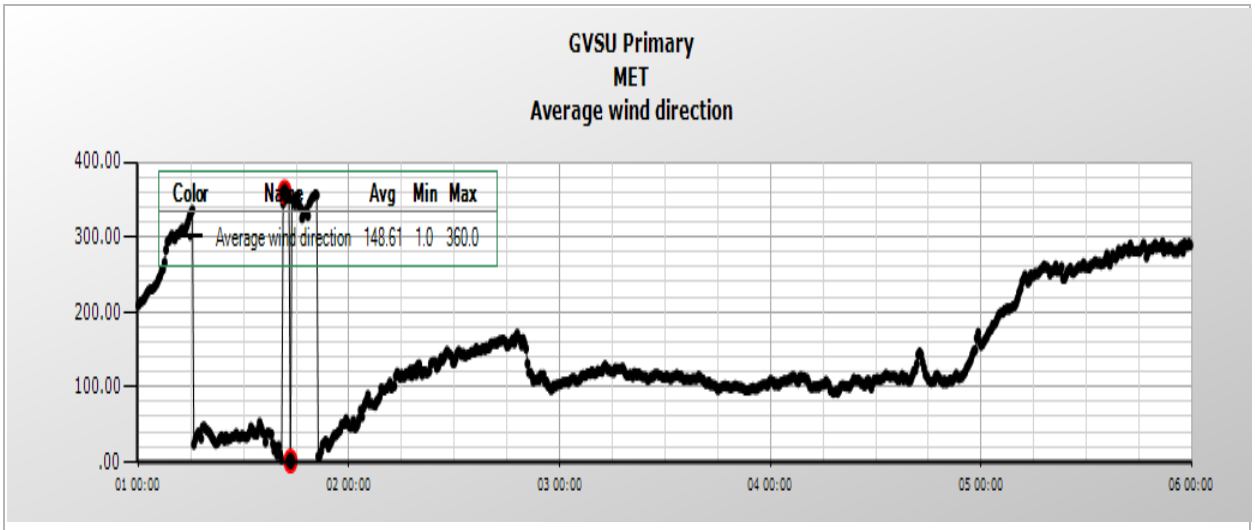
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Average wind direction
Color Name Avg Min Max
Average wind direction 148.61 1.0 360.0
400.00
300.00
200.00
100.00
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03 00:00
04 00:00
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Summary statistics for wind speed by range gate and for the cup anemometer are shown in the following tables. Good observations are 10-minute averages consisting of at least 300 one-second observations. There were 2880 observations of 10-minute averages in total.

Table 1: Horizontal Wind Speed (meters per second) Statistics by Range Gate

Statistic	N001S007 P006 Cup Anemometer	N001S009 P083 75m	N001S009 P084 90m	N001S009 P085 105m	N001S009 P086 125m	N001S009 P087 150m	N001S009 P088 175m
Good Obs.	2880	2587	2791	2851	2842	2790	2452
% of Total (2880)	100	89.8	96.9	99.0	98.7	96.9	85.1
Average	8.0	9.0	9.3	9.6	9.7	9.7	9.8
Std. Dev.	3.2	3.4	3.6	3.6	3.6	3.6	3.5
Coeff. of Variation	0.40	0.38	0.39	0.38	0.37	0.37	0.36
Minimum	0	1.2	1.3	1.3	1.3	1.2	1.1
Quartile 1	6.0	6.7	6.9	7.1	7.2	7.3	7.6
Median	8.2	8.9	9.3	9.5	9.6	9.6	9.7
Quartile 3	10.3	11.3	11.7	12.1	12.2	12.2	12.1
Maximum	16.9	19.7	23.0	21.0	20.9	23.0	22.5
99% CI– Lower Bound	7.8	8.8	9.1	9.4	9.5	9.5	9.6
99% CI Upper Bound	8.2	9.2	9.5	9.8	9.9	9.9	10

Table 2: Wind Speed Frequencies by Range Gate – Percent of Time in Each Wind Speed Range

Wind Speed Range (m/s)	N001S007 P006 Cup Anemometer	N001S009 P083 75m	N001S009 P084 90m	N001S009 P085 105m	N001S009 P086 125m	N001S009 P087 150m	N001S009 P088 175m
0-4	11.1	8.1	7.5	6.6	6.4	5.9	4.1
4-8	34.4	29.9	27.7	26.4	25.2	24.8	24.8
8-12	45.4	42.3	41.3	41.0	40.9	42.8	44.9
12-16	8.9	17.7	20.0	22.4	23.6	22.3	23.1
16-20	0.1	2.0	3.2	3.3	3.3	3.2	2.2
20-24	0	0	0.3	0.4	0.6	0.9	1.0
24-28	0	0	0	0	0	0	0
28-32	0	0	0	0	0	0	0
>32	0	0	0	0	0	0	0

Table 3: Wind Direction Frequencies by Range Gate – Percent of Time in Each Wind Direction Range

Wind Direction Range (Degrees)	N001S009P089 Average Horizontal Wind Direction RG#1	N001S009P083 Average Horizontal Wind Speed RG#1
0 – 45 (NNE)	5.3	4.8
45 – 90 (NE)	17.9	8.2
90 – 135 (SE)	16.2	9.0
135 – 180 (SSE)	5.2	8.4
180 – 225 (SSW)	2.2	12.6
225 – 270 (SW)	13.3	10.6
270 – 315 (NW)	30.0	9.9
315 – 360 (NNW)	10.0	7.3

Table 4 contains the summary statistics shown in table 1 for the subset of times when every range gate had a good observation that is there were 300 one-second observations for each range gate.

Table 4: Horizontal Wind Speed (meters per second) Statistics by Range Gate – All Range Gates with Good Observations (2425/2880= 84.2%)

Statistic	N001S009 P083 75m	N001S009 P084 90m	N001S009 P085 105m	N001S009 P086 125m	N001S009 P087 150m	N001S009 P088 175m
Average	9.1	9.4	9.5	9.6	9.7	9.8
Std. Dev.	3.4	3.5	3.5	3.6	3.6	3.5
Coeff. of Variation	0.37	0.37	0.37	0.38	0.37	0.36
Minimum	1.2	1.3	1.3	1.3	1.2	1.1
Quartile 1	6.9	7.1	7.2	7.3	7.4	7.6
Median	9.0	9.4	9.5	9.6	9.6	9.7
Quartile 3	11.4	11.8	12.0	12.1	12.2	12.1
Maximum	19.7	19.9	20.5	20.9	21.5	22.5
99% CI– Lower Bound	8.9	9.2	9.3	9.4	9.5	9.6
99% CI Upper Bound	9.3	9.6	9.7	9.8	9.9	10

Table 5 shows the 99% confidence intervals for the mean difference in average wind speed between adjacent range gates for example between the range gates centered at 175 meters and 150 meters. The difference is higher range gate – lower range gate. The confidence intervals are computed using the paired t method. An observation time is included in the difference if the number of observations for each of the two range gates was at least 300.

Table 5: Horizontal Wind Speed – Average Difference by Pairs of Adjacent Range Gates

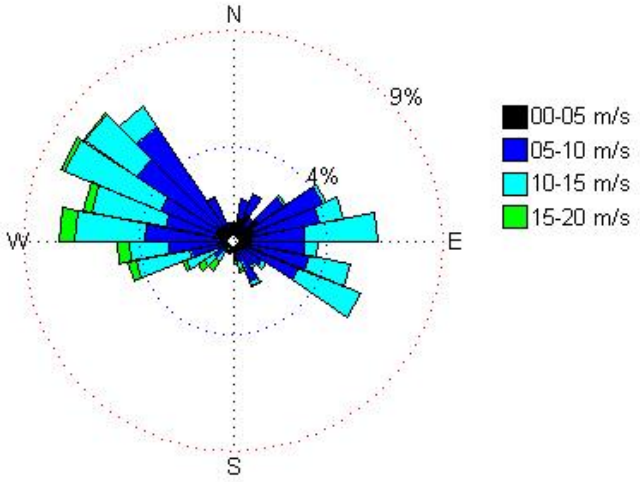
Statistic	175m – 150m	150m-125m	125m-105m	105m-90m	90m-75m
Good Obs.	2451	2787	2832	2781	2577
% of Total (2880)	85.1	96.8	98.3	96.6	89.5
Average	0.072	0.081	0.11	0.20	0.29
99% CI– Lower Bound	0.040	0.070	0.10	0.18	0.27
99% CI Upper Bound	0.10	0.10	0.12	0.22	0.31

Table 6 shows the energy generated for each range gate both when all data are considered as in Table 1 and the subset of times when every range gate had a good observation as in Table 4. The amount of energy generated depends on the turbine employed in this case the Gamesa Elioca G58 850kW. The energy estimate was computed assuming that the turbine will always face the wind.

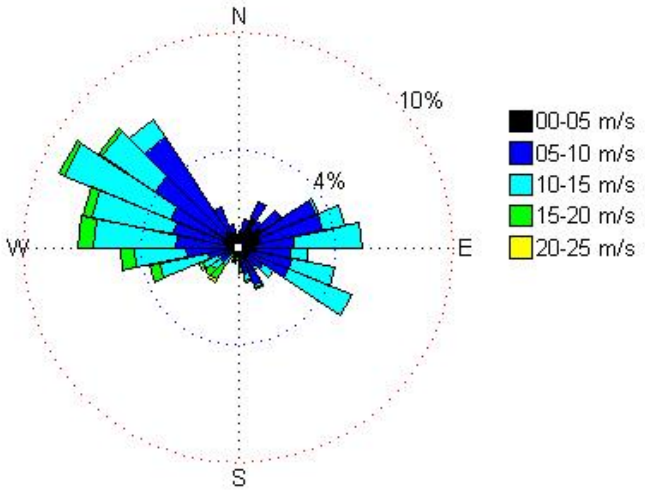
Table 6: Energy (kWh/time unit) by Range Gate

	All data		Every Range Gate with Good Obs.	
Range Gate	**Average Power (MW)**	**Average Daily Energy (MWh)**	**Average Power (MW)**	**Average Daily Energy (MWh)**
1	0.491	11.8	0.501	12.0
2	0.514	12.3	0.523	12.6
3	0.535	12.9	0.536	12.9
4	0.545	13.1	0.542	13.0
5	0.545	13.1	0.546	13.1
6	0.549	13.2	0.549	13.2
Buoy Cup	0.429	10.3	0.501	12.0

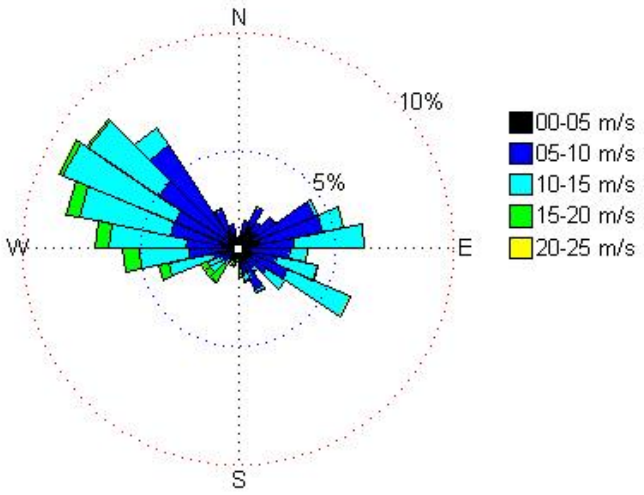
The wind rose graphs show the wind speed by direction as well as the percent of time the wind was blowing in each direction.



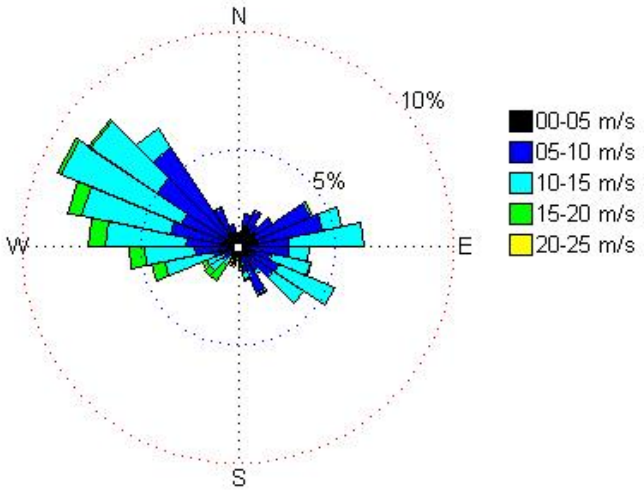
Range Gate 1: Average Wind Speed and Percent Time by Direction



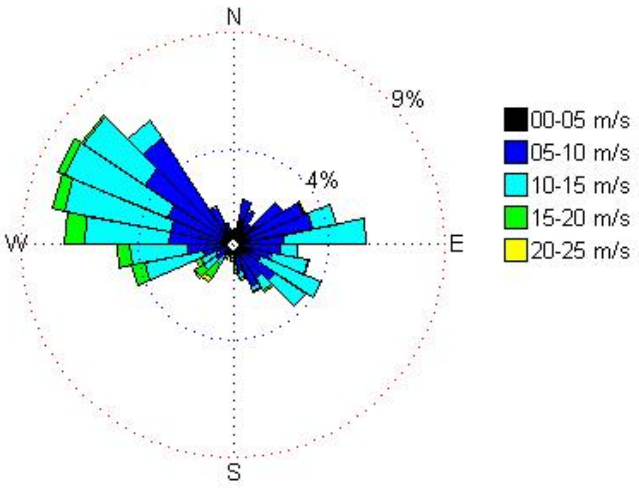
Range Gate 2: Average Wind Speed and Percent Time by Direction



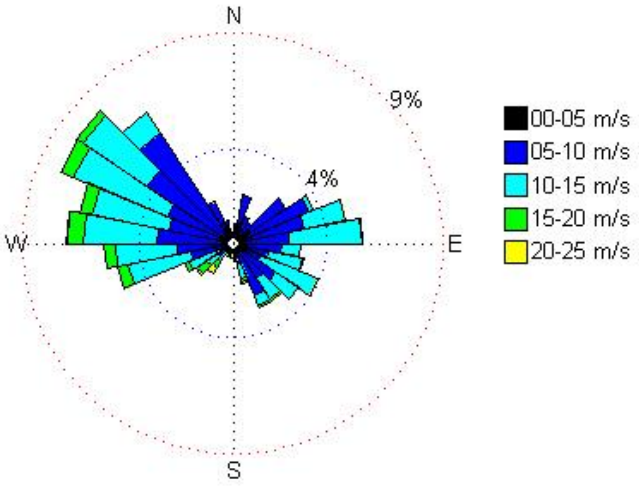
Range Gate 3: Average Wind Speed and Percent Time by Direction



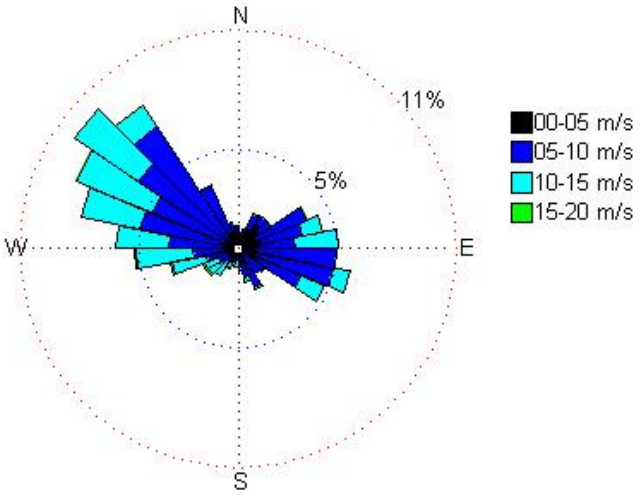
Range Gate 4: Average Wind Speed and Percent Time by Direction



Range Gate 5: Average Wind Speed and Percent Time by Direction



Range Gate 6: Average Wind Speed and Percent Time by Direction



Buoy Cup Anemometer: Average Wind Speed and Percent Time by Direction

Notes:

1. The average wind speed at 75m and above is notably more than the average wind speed on the buoy deck. This conclusion is supported by the statistics in table 1, particularly the average and the median. Further, the data in table 2 show that about 90% of the time the wind speed on the buoy deck is 12m/s or less. For heights 75m and above, this is true about 76%-83% of the time.
2. The average wind speed increases as the range gate height increases. Each difference between adjacent range gate height pairs is statistically significant (α = 0.01). This is consistent with the average daily energy values shown in table 6.
3. The highest frequency of wind speed is SSW through SW, about 15% of the time as shown in table 3. The highest frequency of wind direction is NW and NNW about 40% of the time. In addition, the wind is from the NE or SE about 34% of the time.

Part II – Comparison of 2013 Data and 2012 Data

In this section, the data collected from December 1 through December 17, 2012 at the mid-lake plateau (4320.510N, 8707.206W) are compared to data from December 1 through December 20 in 2013 as described above. The results are shown in table 7. Homogeneity of variance is assumed. Note that two variables are confounded regarding the comparison:

- Location (mid-lake plateau versus near Muskegon)
- Year (2012 versus 2013)

Table 7: Comparison of 2012 and 2013 Data

Statistic	N001S007 P006 Cup Anemometer	N001S009 P083 75m	N001S009 P084 90m	N001S009 P085 105m	N001S009 P086 125m	N001S009 P087 150m	N001S009 P088 175m
2012							
Good Obs.	2448	2382	2417	2389	2297	1854	1382
% of Total (2448)	100	97.3	98.7	97.6	93.8	75.7	56.5
Average	7.8	9.7	9.9	10.1	10.0	9.9	9.3
2013							
Good Obs.	2880	2587	2791	2851	2842	2790	2452
% of Total (2880)	100	89.8	96.9	99	98.7	96.9	85.1
Average	8.0	9.0	9.3	9.6	9.7	9.7	9.8
Compare							
Average Difference	-0.2	0.7	0.6	0.5	0.3	0.2	-0.5
Pooled Std. Dev.	2.9	3.7	3.8	3.8	3.8	3.8	3.8
99% CI– Lower Bound	-0.41	0.43	0.33	0.23	0.02	-0.09	-0.83
99% CI Upper Bound	0.0082	1.0	0.87	0.77	0.58	0.49	-0.17

Notes:

1. The November 2013 average wind speeds are high due to the effects of storms, which impacts the items in notes 2 and 3.
2. The average wind speed at heights 75m through 150m is higher at the mid-lake plateau in 2012 than near to the shore in 2013. At height 175m, the wind speed is lower. The difference is statistically significant for all heights except 150m. For all results $\alpha = 0.01$.
3. The average wind speed is lower at the mid-lake plateau in 2012 than near to shore in 2013 on the buoy deck. This result is not statistically significant ($\alpha = 0.01$).

Part III – Comparison of November 2013 Data and December 2013 Data

In this section, the data collected from November 1 through November 30 are compared with the data collected from December 1 through December 20. The results are shown in table 8. Homogeneity of variance is assumed.

Table 8: Comparison of Monthly Data: November versus December

Statistic	N001S007 P006 Cup Anemometer	N001S009 P083 75m	N001S009 P084 90m	N001S009 P085 105m	N001S009 P086 125m	N001S009 P087 150m	N001S009 P088 175m
November							
Good Obs.	4264	3068	3689	4153	4206	3959	3001
% of Total (4320)	98.7	71.0	85.4	96.1	97.4	91.6	69.5
Average	9.7	10.9	11.2	11.3	11.6	11.7	11.9
December							
Good Obs.	2880	2587	2791	2851	2842	2790	2452
% of Total (2880)	100	89.8	96.9	99.0	98.7	96.9	85.1
Average	8.0	9.0	9.3	9.6	9.7	9.7	9.8
Compare							
Average Difference	1.7	1.9	1.9	1.7	1.9	2.0	2.1
Pooled Std. Dev.	3.2	3.6	3.9	4.1	4.1	4.0	3.9
99% CI– Lower Bound	1.5	1.7	1.6	1.4	1.6	1.7	1.8
99% CI Upper Bound	1.9	2.1	2.2	2.0	2.2	2.3	2.4

Notes:

1. The November 2013 average wind speeds are high due to the effects of storms, which impacts the items in notes 2, 3 and 4.
2. The average wind speed at all heights is greater in November than in December. All results are statistically significant ($\alpha = 0.01$).
3. The average wind speed is greater in November than in December on the buoy deck. This result is statistically significant ($\alpha = 0.01$).
4. In addition, there appears to be a notable shift of wind direction from November to December. In November, the wind was from the SSE through SW about 66% of the time. In December, the wind was from this direction about 21% of the time. The wind was from the NW or NNW about 40% of the time and from the NE or SE about 34% of the time.