July 30, 2004

Final Report to Wisconsin Focus on Energy

on

Lake Michigan Offshore Wind Resource Assessment

by

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Executive Summary

This is the final report on SSE's Lake Michigan Offshore Wind Resource Assessment Study for the Wisconsin Focus on Energy Program.

SSE has collected and made available to the public in an accessible Excel format several hundred Mbytes of Southern Lake Michigan Wind Data from 2001 to 2003. To access any of this data, contact Alex DePillis, Renewable Energy Engineer, at the Wisconsin Energy Bureau ((608) 266-1067).

Based on review of available 2001-2003 wind data from Southern Lake Michigan and nearby weather stations, SSE has estimated the offshore wind resource potentially available on the lake at shallow water sites within several miles of shore and further out on the Mid-Lake Plateau east of Milwaukee. We estimate that this wind resource varies from 8.5 m/s (19.0 mph) at typical shallow water sites within a few miles of shore to over 9.0 m/s (20 mph) on the Mid-Lake Plateau 25 miles ENE of Milwaukee.

We estimate that the offshore wind resource is extensive as well as energetic, with a development potential in Wisconsin Waters south of Manitowoc County in excess of 10,000 MW.

In addition, we discuss the progress of SSE's flying anemometer to date and its use in 2003 for lakeshore and offshore wind measurements. Finally, we discuss future improvements SSE plans for the flying anemometer to increase its value as a wind sampling device at a location without a meteorological tower or to sample wind above the height of a tower-mounted anemometer.

Introduction

SSE proposed this project to improve understanding of the offshore wind resource of Lake Michigan in S.E. Wisconsin (Sheboygan County to Kenosha County). Secondarily, we proposed to demonstrate the utility of a new flying anemometer concept for sampling wind speed above the level of an existing tower or at a site without a tower. We envisioned this as a possible future product or as a component of an SSE service for the wind industry, possibly also for other uses.

Our study plan was to gather and use existing, but not necessarily highly accessible, meteorological data and data from SSE's flying anemometer, putting both categories of data into accessible Excel formats and making them publicly available through the Wisconsin Department of Administration. We have already accomplished these tasks. In addition, we planned to use the data, which is not gathered at potential S.E. Wisconsin offshore wind development sites, to characterize the wind resource at such sites. This report completes that task.

As to the flying anemometer, we proposed to use it to sample wind speeds on 18 days in the lakeshore area or offshore within five miles of the lakeshore. We accomplished this, primarily in the lakeshore area, but with one day's data from a moving sailboat off Racine, and have reported the data obtained. This report addresses the sampling data and the utility of the flying anemometer and our plans to improve it further to increase its utility.

Method

As to non-flying anemometer data, we obtained it from two sources: (1) the Midwest Regional Climate Center sold us the 2001-2003 airport meteorological data from eight airports closely surrounding Southern Lake Michigan, and (2) we obtained other NOAA GLERL and NBDC Data for Lake Michigan and Lake Superior Stations for 2001-2003 from the internet websites maintained by GLERL and NDBC.

We put this data into spreadsheet and then database form. We provided the resulting Excel spread sheets to Focus and the Wisconsin Department of Administration Energy Bureau, where they are available to the public. Some of the databases we set up for individual stations reporting five-minute data exceeded 15 Mbytes in size. We developed navigation and non-navigation season databases for each Lake Michigan and Lake Superior Station. We then queried each database extensively to discern annual and seasonal frequency and mean wind speed by 10-degree wind direction slice for each of seven different seasonal periods. For two meteorological buoys, we also queried the data for the mean air-water temperature difference and wave height on a monthly basis.

For each Lake Michigan Station, we summarized the query data obtained in a spreadsheet and used that to produce bar graph wind roses illustrating the station's detailed directional wind pattern. We used differences in these wind roses for different stations to draw conclusions about what factors were accounting for spatial variations in wind speeds across the lake in various seasons.

We also examined seasonal differences in ratios of mean wind speeds between the airport stations (which were some distance back from the lakeshore in every case) and the nearby lakeshore and offshore stations to attempt to identify significant factors driving seasonal changes in the offshore means.

We used data from the two Lake Superior Stations, STDM4, which measured wind at 35.2 meters above lake level, and Buoy 45004, which measured wind at 5 meters, only 42 miles apart and both far from land in the large Eastern Basin of Lake Superior, to provide surrogate or “virtual” monthly wind shear for the navigation season on Lake Superior. We had no other multi-level wind data taken at the same site. We therefore took the analytical leap that STDM4 and Buoy 45004 were “virtually” at the same site if analyzed over a time period of more than a few hours. We analyzed monthly data, putting it in a spreadsheet. We then did a regression analysis on it to determine a functional relationship between the stable season “virtual” wind shear and the mean 5-meter wind speed and mean temperature difference as independent variables.

We then used the functional relationship derived from the Lake Superior “virtual” shear to determine the apparent mean monthly shear at Buoy 45007 in Lake Michigan during stable portions of the navigation season.

We also examined the relationship between wave height and “virtual” shear in Lake Superior to assess whether wave height may limit shear reduction in unstable conditions over mid-lake areas in cold weather and at what level of monthly shear the lower limit would occur at Buoy 45004.

We examined the mean wave heights reported over Northern Lake Michigan, at Buoy 45002, in winter 1990-1991 as a surrogate for winter wave data not collected at the location of Buoy 45007 in winter after the buoy is removed.

We also obtained some wind data samples using SSE’s flying anemometer. As used in July through October 2003, the flying anemometer consisted of an NRG #40C Anemometer in an approximately vertical orientation supported by a lightweight floating framework suspended from the kite line at an elevation considerably below the lifting kite(s). Two lightweight unshielded insulated wires drooping below the flying anemometer carried the anemometer signal to the ground in an approximately vertical manner (it would bow some in strong winds). We marked these at 10-foot intervals to simplify visualization of flying anemometer height. We normally fed the anemometer signal to a calibrated wind odometer (except on October 12, when we fed it to an NRG 9300SA Data Logger). We estimated the height above ground or water level (considering bow in the sensor cable) and the wind direction using a compass or solar means and read the odometer, recording all three parameters at five-minute intervals. At that time, we had unsophisticated means (improved in early 2004) to correct a non-vertical attitude of the anemometer. It would often lean backward (most commonly) or forward to some degree. It would sometimes also lean sideways, especially when the sensor cable would hang up on grass or shrubs at ground level or on rocks or weeds while dangling in the lake and the wind direction would change. While we would attempt to correct lean, side lean in particular was sometimes hard to correct, especially when flying over water (except October 12).

We entered the flying anemometer data from the 18 days of such measurements into separate Excel spreadsheets. This report discusses these measurements and the simultaneous measurements at nearby Lake Michigan Stations. These were qualitative inputs to our analysis of the Lake Michigan Wind Resource, especially the August 16 Harrington Beach and October 12 Offshore (near Racine) Measurements.

We provide more detail on our methods in the ensuing Discussion Section of this report.

Results

SSE has provided more than 200 Megabytes of Lake Michigan wind data from the 2001-2003 period to the Wisconsin DOA/Energy Bureau in an accessible Excel format. This is all available to the public. Contact Renewable Energy Engineer Alex DePillis at the Wisconsin Energy Bureau to obtain an electronic copy ((608) 266-1067).

S.E. Wisconsin's offshore wind resource in Lake Michigan generally exceeds 8.5 m/s (19.0 mph) at reasonable hub heights for large offshore wind turbines three or more miles offshore. The potential offshore wind resource in S.E. Wisconsin exceeds 10,000 MW, including both relatively shallow water near shore and deeper water further out east of Milwaukee which may become usable in a few years as new foundation technology emerges.

SSE's proprietary flying anemometer is already a useful sampling device for both on and offshore wind, but it is not yet a viable commercial product. It would be more useful with further improvements outlined in the Discussion.

Discussion

SSE has previously reported on flying anemometer development and data gathering activities and has submitted its own flying anemometer data as well as regional NOAA and airport data from 2001 to 2003 for the Southern Lake Michigan Region.

This section of SSE's final report to Wisconsin Focus on Energy addresses:

(1) the Lake Michigan wind resource offshore from S.E. Wisconsin;

(2) the information developed by flying anemometer measurements; and

(3) the potential future flying anemometer development and utilization.

I. THE LAKE MICHIGAN OFFSHORE WIND RESOURCE POTENTIALLY AVAILABLE IN S.E. WISCONSIN MOSTLY EXCEEDS 8.5 M/S (19 MPH).

SSE has collected and submitted 2001 to 2003 wind and other meteorological data from eight airport weather stations, five NOAA Great Lakes Environmental Research Laboratory Southern Lake Michigan Network Stations, a NOAA C-MAN station, and an NOAA NDBC data buoy deployed in or around the edges of Southern Lake Michigan.[1] Two of the airport stations, Kenosha and Waukegan, were too far from the lake to be of much value. SSE did not extensively analyze them. Two others, Chicago Meigs and Gary Regional, proved to have non-comparable wind data from human observers. We did not analyze their data at all In addition to the Lake Michigan stations, we examined two Lake Superior stations for comparative purposes. This portion of the report summarizes our data analysis.

Our analysis focused on the area of Southern Lake Michigan shown in Figure 1 below (page 7). Figure 1 depicts lake depths. We depict the Southern Lake Michigan measurement locations on Figure 2 on the following page (page 8). The arrow pointing to each fixed measurement location depicts the height of the wind speed sensor there. These cover a large range, from 16 feet (5 meters) to 80 feet (24 meters). For a station inland from the shore, its callout on Figure 2 shows its elevation above sea level. Where we provide no elevation, the base elevation is lake level, which was about 577 feet during the summer of 2003.

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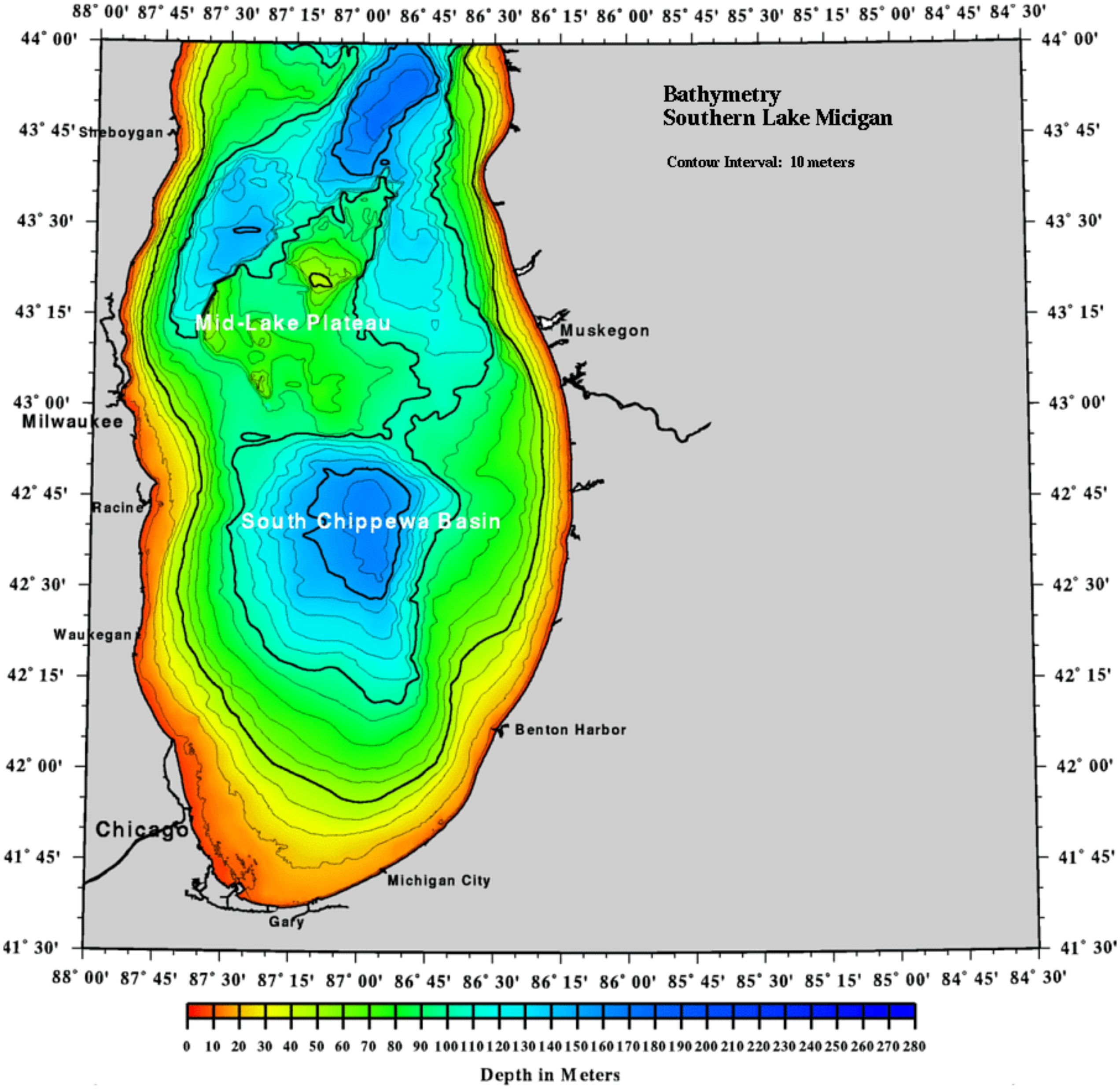
[1] NOAA is the U.S. Department of Commerce's National Oceanic and Atmospheric Administration. C-MAN is the designation for stations in the Coastal-Marine Automated (weather observation) Network. The Sheboygan Harbor Breakwater Lighthouse is a C-MAN Station. The National Data Buoy Center is NDBC. It maintains the Sheboygan Lighthouse (SGNW3) and the Stannard Rock Station (STDM4) in Lake Superior. It also maintains data buoys, including 45007 (S. Lake Michigan Buoy) and 45004 (E. Lake Superior Buoy). SSE is using data from these four NDBC-maintained stations.

Figure 1: Southern Lake Michigan Depth Contours at 10-meter Intervals[2]



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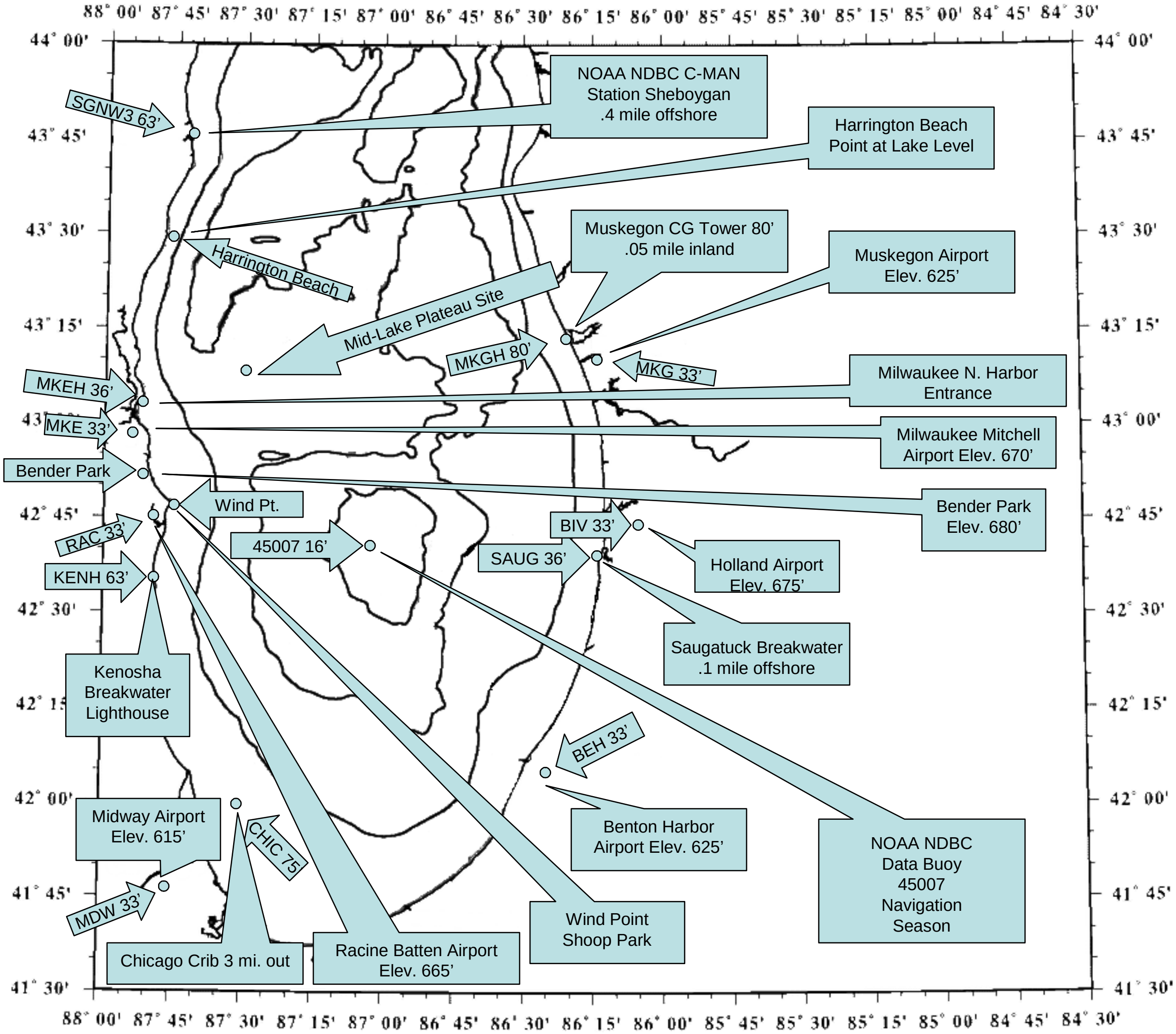
[2] The Great Lakes Environmental Research Laboratory ("GLERL") produced this public domain map available on its website at www.glerl.noaa.gov/data/char/bathymetry.html. SSE just re-sized the map.

Figure 2: Southern Lake Michigan Wind Measurement Sites
50-meter Depth Contour Interval[3]



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[3] Larry Krom created the outline map from Figure 1 above. He also edited the final map. GLERL produced the map in Figure 1. Robert Owen entered the measurement site information.

A. The Averages

SSE put the 2001-2003 data into databases for each station examined and obtained averages. Table 1 below summarizes the averages, showing both mean wind speed (in m/s) and mean temperatures (in degrees C). Table 1 shows only measured data.

Table 1: S. Lake Michigan Seasonal Wind Speeds

Airport Stations	An Hgt m	Ann	Mean Nonnav. DJ	deg C Seas. FM	Below Mean Winte	s r	WS Nav. MA	Seas. MJ	Means JA	SO	ND	Nav. Seas
Milwaukee	10	4.44	4.77	4.85	4.81		5.19	4.12	3.84	4.18	4.56	4.3
Mitchell		9.2	-2.4	-2.1	-2.3		6	15.4	22.6	13.7	4.4	13.6
Racine	10	4.24	4.6	4.71	4.65		4.97	3.99	3.57	3.9	4.43	4.09
Batten		9.1	-2.5	-2.3	-2.3		5.9	15	22.5	13.6	4.4	13.4
Chicago	10	4.5	4.84	5.02	4.92		5.2	4.26	3.86	4.14	4.61	4.34
Midway		11.1	-1.4	-0.1	-0.8		8.8	18	24.4	15.4	5.8	15.7
Benton	10	3.75	4.74	4.58	4.66		4.24	3.11	2.57	3.35	4.43	3.41
Harbor		9.7	-0.9	-0.7	-0.8		7.2	15.9	21.9	13.5	5.4	13.7
Holland	10	4.11	4.86	4.82	4.83		4.81	3.64	3.03	3.58	4.76	3.83
MI		9.5	-1.3	-1.5	-1.4		6.7	15.9	21.9	13.2	4.9	13.6
Muskegon	10	4.36	4.99	4.98	4.91		4.91	3.94	3.41	4	4.94	4.13
MI		9.5	-1	-1.5	-1.2		6.3	15.8	21.9	13.3	4.8	13.5
C-MAN Station												
Sheboygan	19	5.97	6.57	6.78	6.71		6.71	5.37	4.97	5.72	6.32	5.7
Harbor		7.7	-2.5	-3	-2.7		3.5	12.1	20.4	12.5	3.8	11.6
GLERL												
Milwaukee	11	5.02	5.85	5.72			5.74	4.29	4.21	4.61	5.55	4.76
Harbor		8.1					5.5	13.8	21.9	12.1	4.6	11.9
Kenosha	19	5.48	6.01	5.93	5.98		6.43	5.1	4.74	5.31	5.87	5.32
Harbor		9.8	-1.7	-1.9	-1.8		4.8	13.7	21.9	13.7	4.9	13.4
Chicago	23	7.17	7.98	7.79	7.9		7.8	6.42	5.33	7.1	8.03	6.88
Crib		10.1	-1.2	-0.8	-1		7.6	15	22.9	15.2	6.1	14.5
Saugatuck	11	5.64			6.82			4.09	4.21	6.2	7.33	5.54
Breakwtr		13.7			2.1			15.7	20.6	13.5	7	14.8
Muskegon	24	6.09	7.51	6.88	7.2		6.5	5.15	4.51	5.95	7.33	5.73
CG Towr		9.2	-0.5	-1.8	-1.2		4.8	13.8	21	13.5	5.1	12.6
NDBC												
Buoy	5						5.95	4.53	4.81	6.85	7.76	5.83
45007							3.7	9.9	21.2	14.9	6	12.3
Stannard	35	8.94	10.51	9.27	9.94		9.13	7.8	7.31	8.97	10.29	8.53
Rock		4.9	-3	-5.5	-4.2		0.9	9.4	16.4	10.7	1.7	8.5
Buoy	5							4.67	4.35	6.71		
45004								5.1	11.2	9.7		

B. Lake Michigan Station Measured Wind Roses

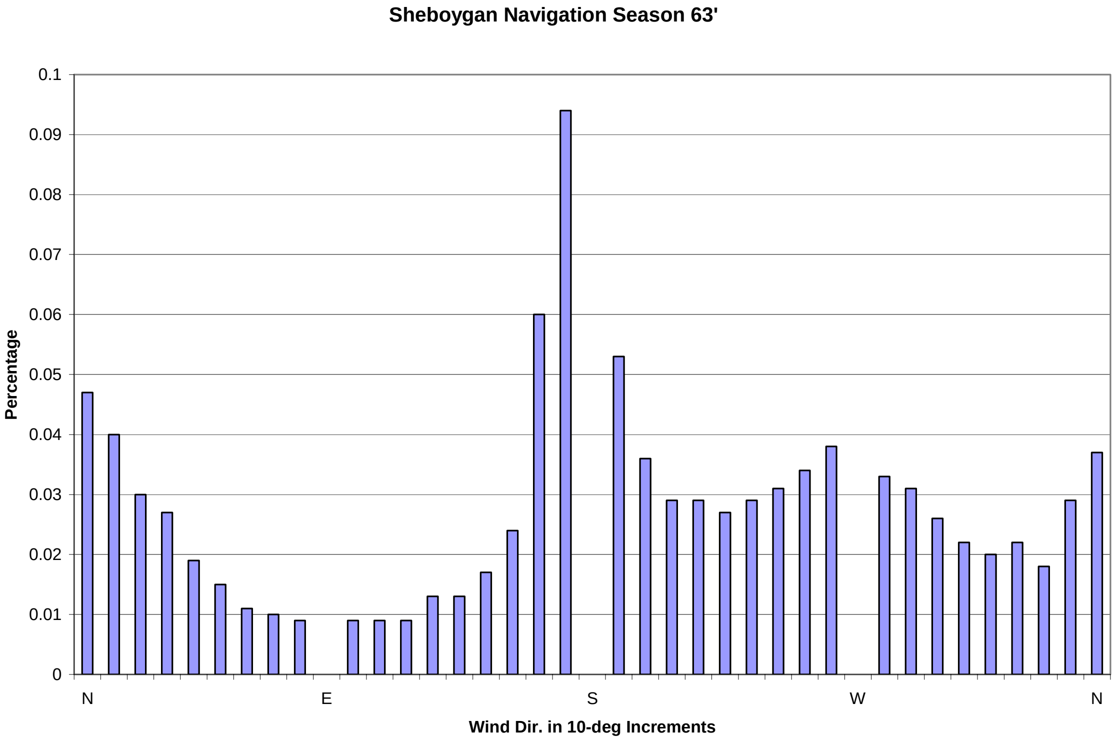
SSE queried databases to obtain detailed wind roses for the following seven Lake Michigan NOAA Measurement Stations, shown in order below, with each station/season on a different page:

Figure 3: Sheboygan Harbor Light 63'/Navigation Season;
Figure 4: Sheboygan Harbor Light 63'/Winter:
Figure 5: Muskegon CG Tower 80'/Navigation Season;
Figure 6: Muskegon CG Tower 80'/Winter;
Figure 7: Saugatuck Breakwater 36'/Navigation Season;
Figure 8: Milwaukee N. Harbor Entrance 36'/Navigation Season;
Figure 9: Milwaukee N. Harbor Entrance 36'/Winter;
Figure 10: Kenosha Breakwater Light 63'/Navigation Season;
Figure 11: Kenosha Breakwater Light 63'/Winter;
Figure 12: Chicago Crib 75'/Navigation Season;
Figure 13: Chicago Crib 75'/Winter; and
Figure 14: Buoy 45007 16'/Navigation Season.

We obtained different wind roses for navigation season (defined as the period, usually March to early December, that Buoy 45007 is deployed and reporting data) and the winter (non-navigation) season. We present both in this report, where possible.

For ease of visualization, we present the wind roses in 10-degree increments in bar graph form, with 0-10 degrees at the left edge and breaks after 80-90, after 170-180, and after 260-270 degrees. In addition to showing mean wind speed versus direction (bottom), the wind roses also show frequencies of winds from different directions (top).

Figure 3: Sheboygan Harbor Lighthouse 63’ Wind Roses
Navigation Season



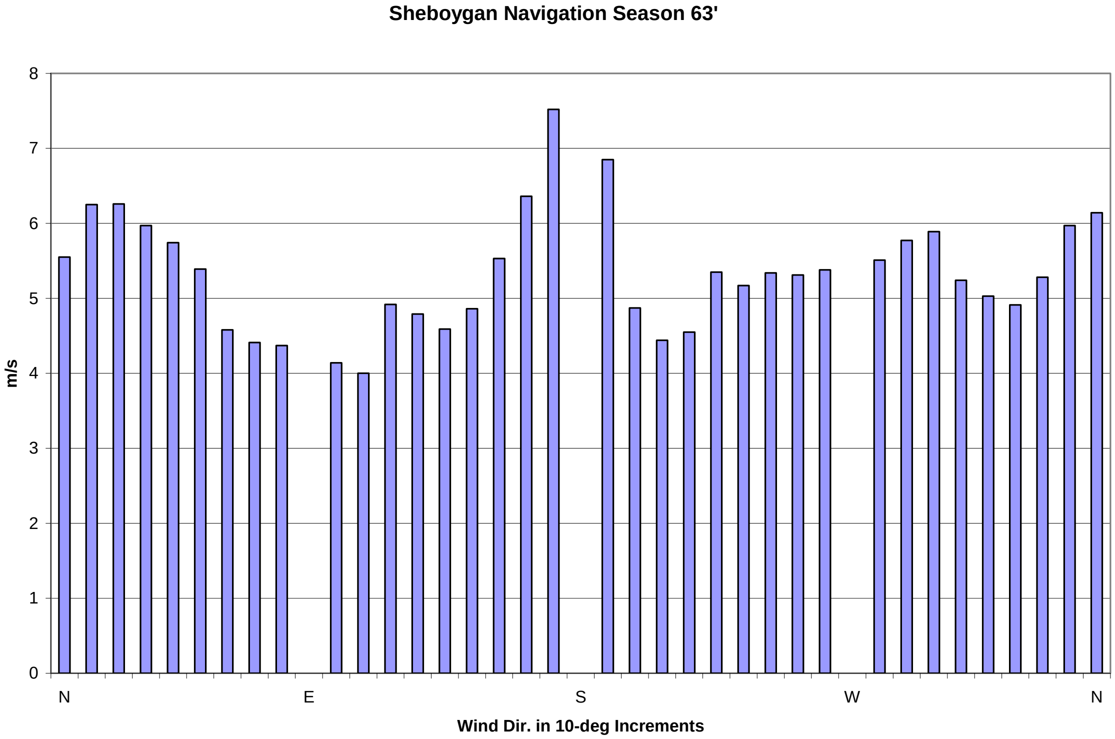
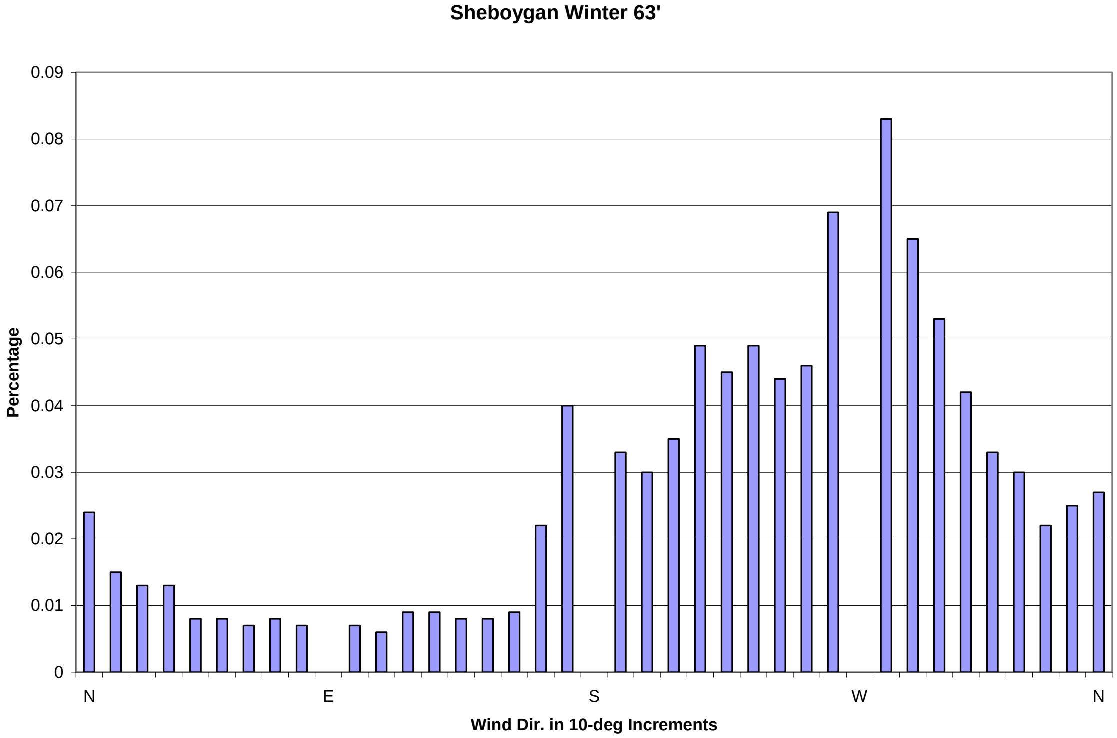


Figure 4: Sheboygan Harbor Lighthouse 63' Wind Roses
Winter Season



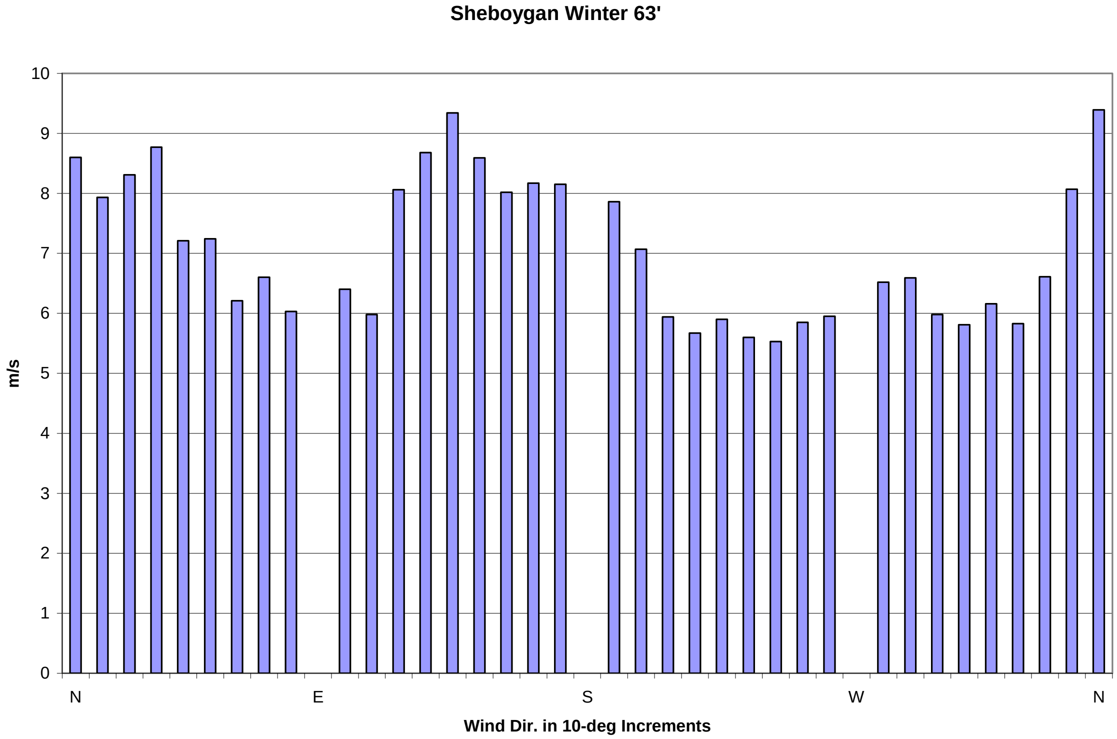
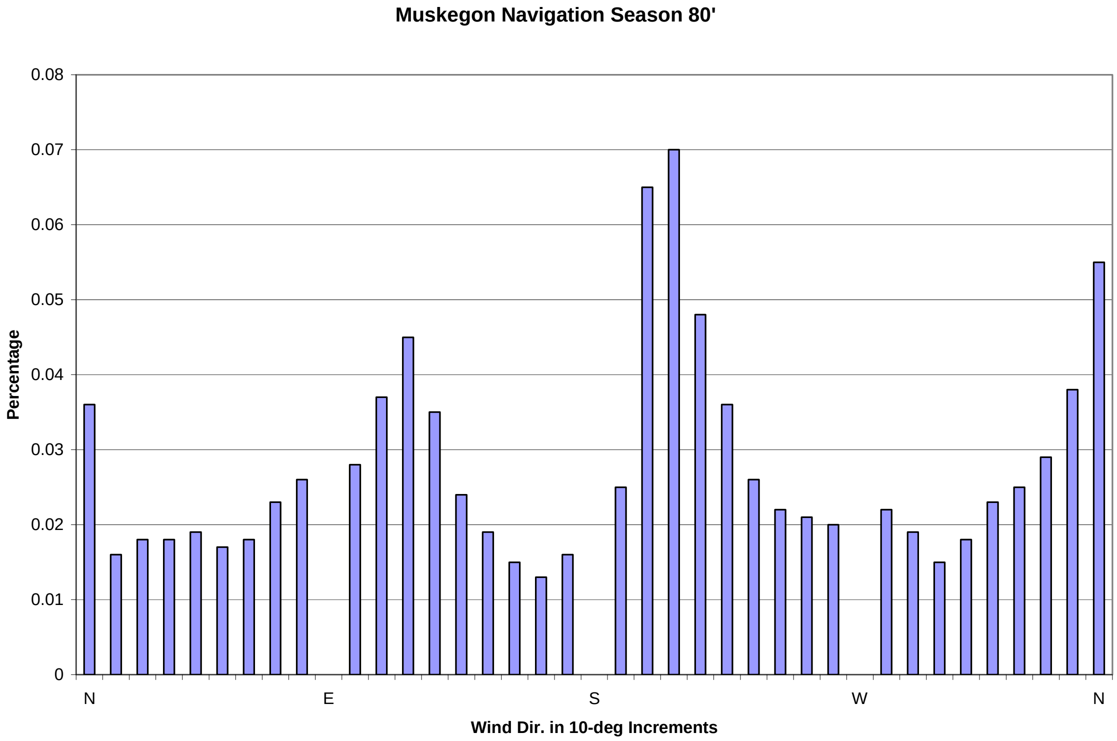


Figure 5: Muskegon CG Tower 80' Wind Roses Navigation Season



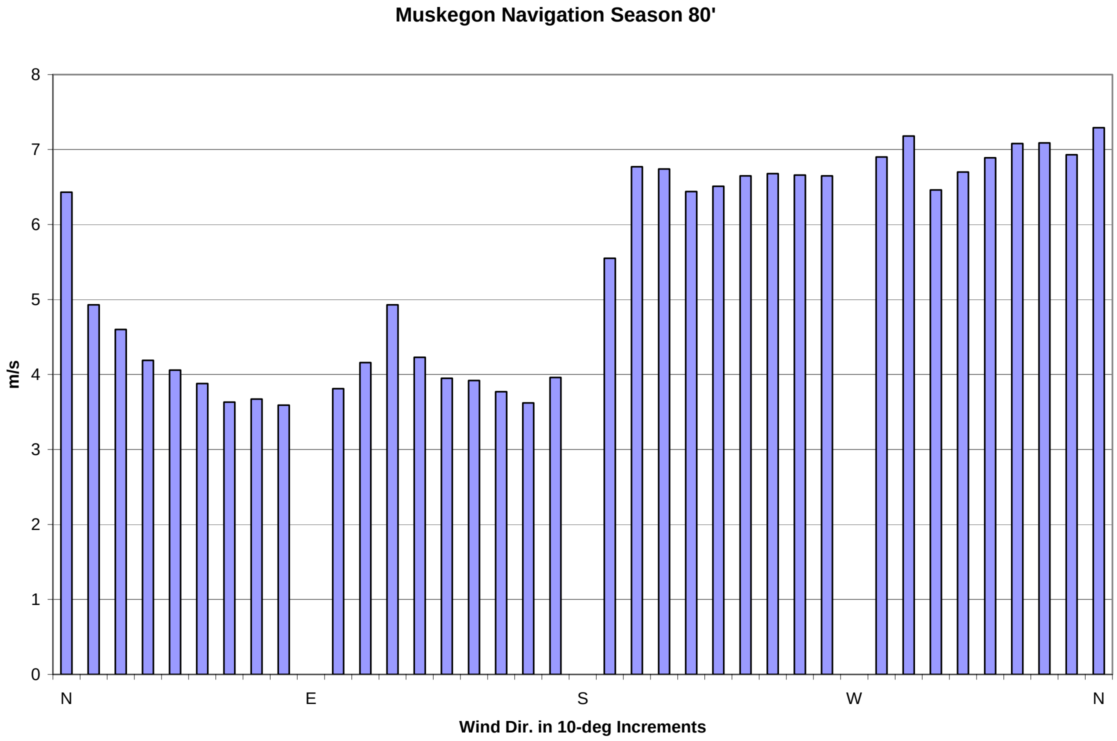
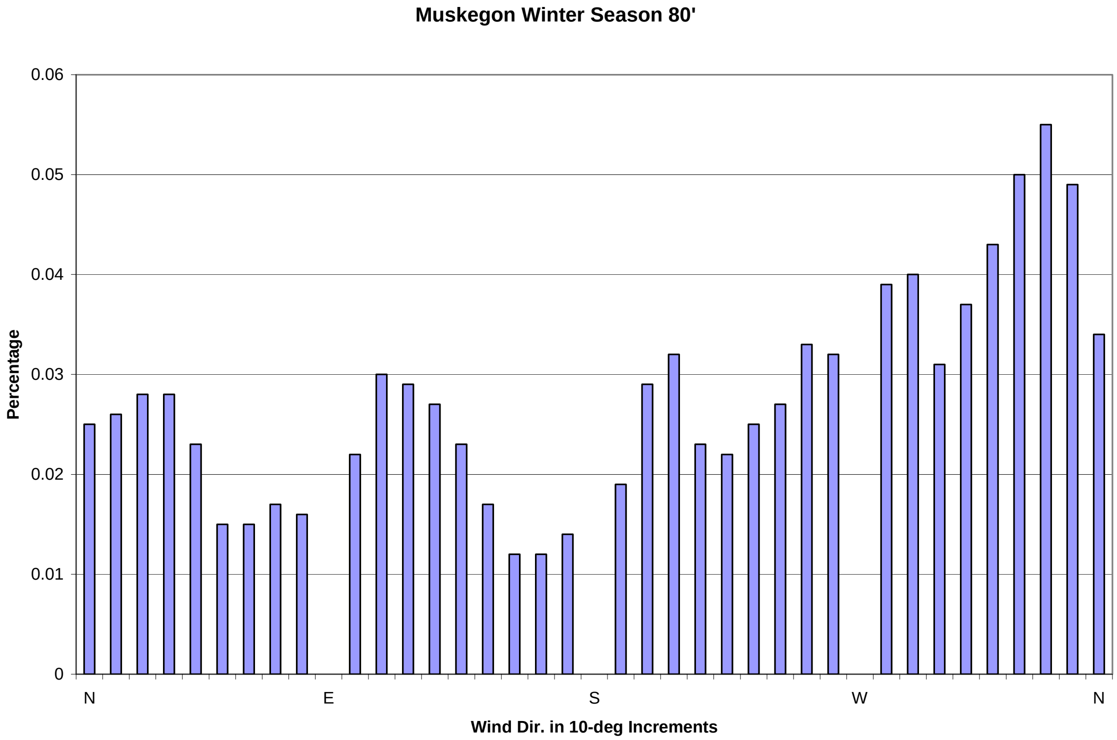


Figure 6: Muskegon CG Tower 80’ Wind Roses
Winter Season



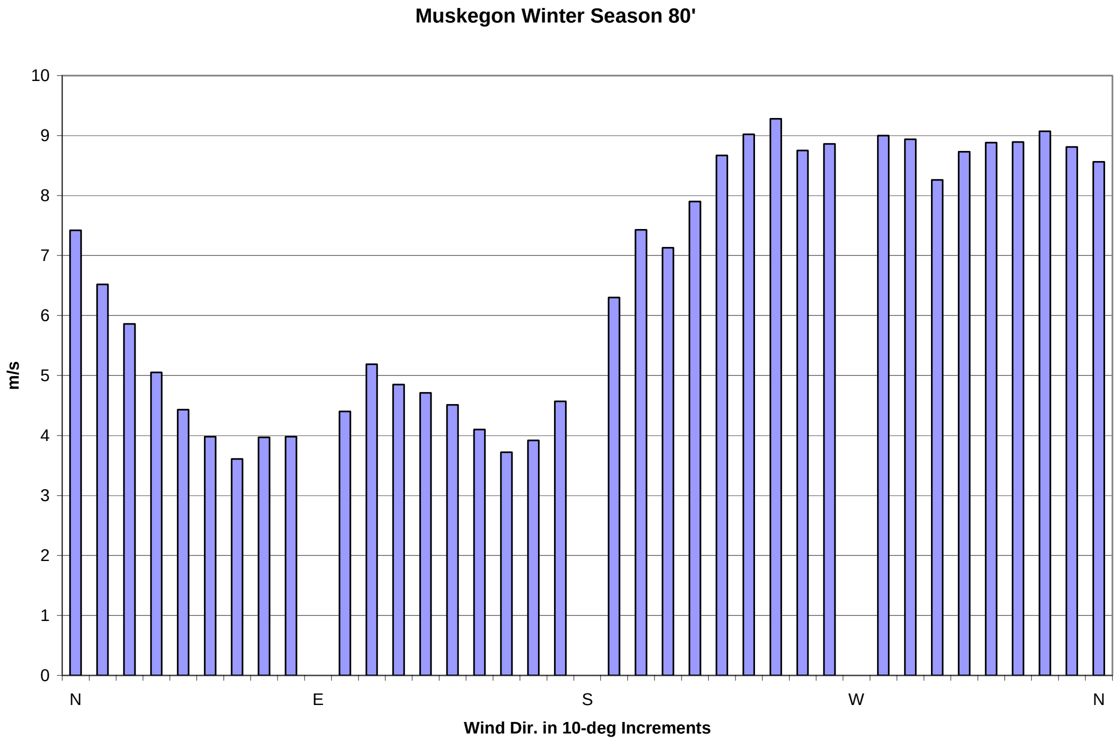
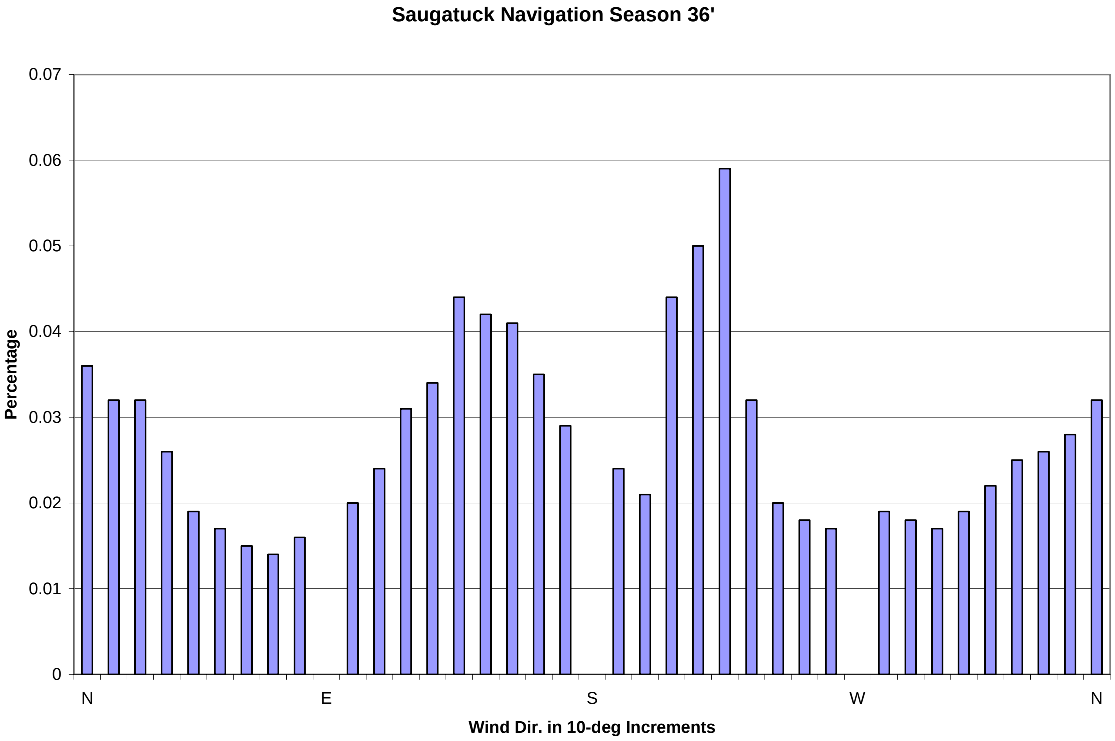


Figure 7: Saugatuck Breakwater 36’ Wind Roses
Navigation Season



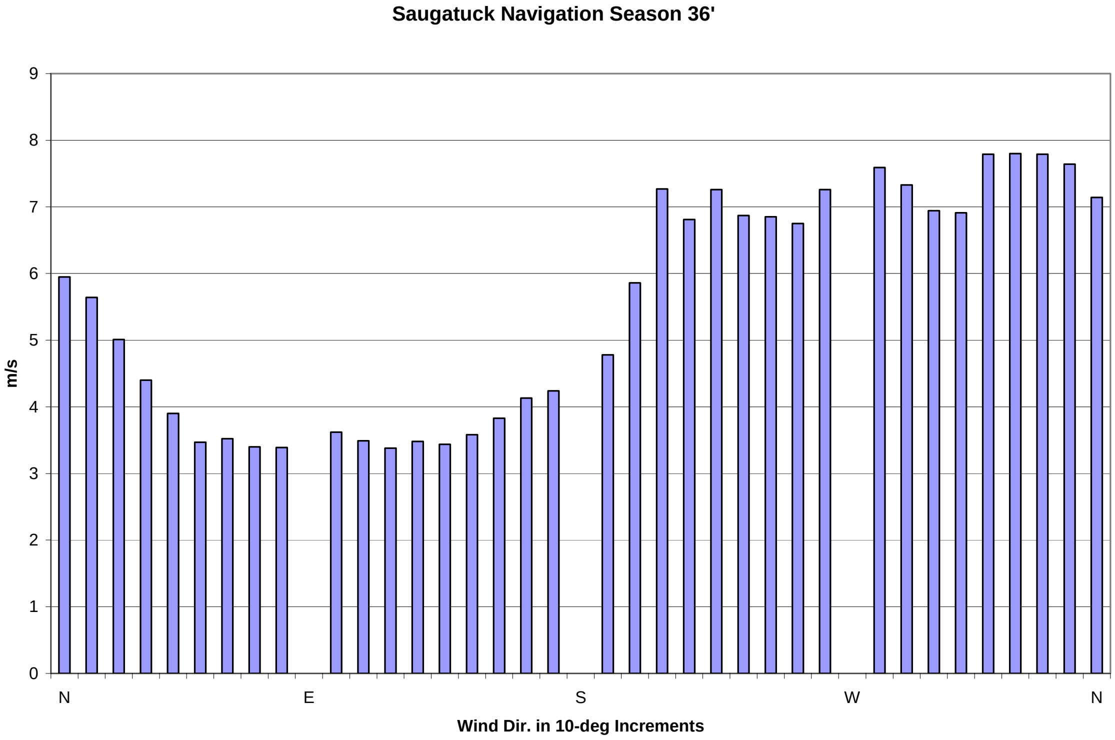
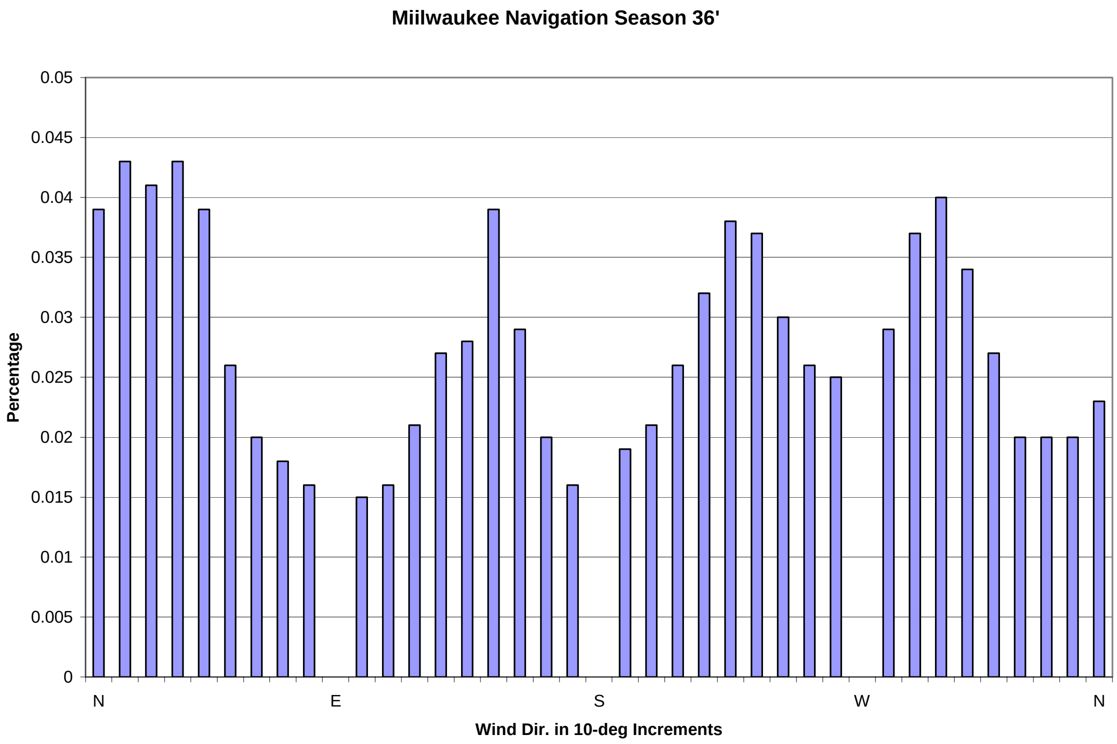


Figure 8: Milwaukee N. Harbor Entrance 36’ Wind Roses
Navigation Season



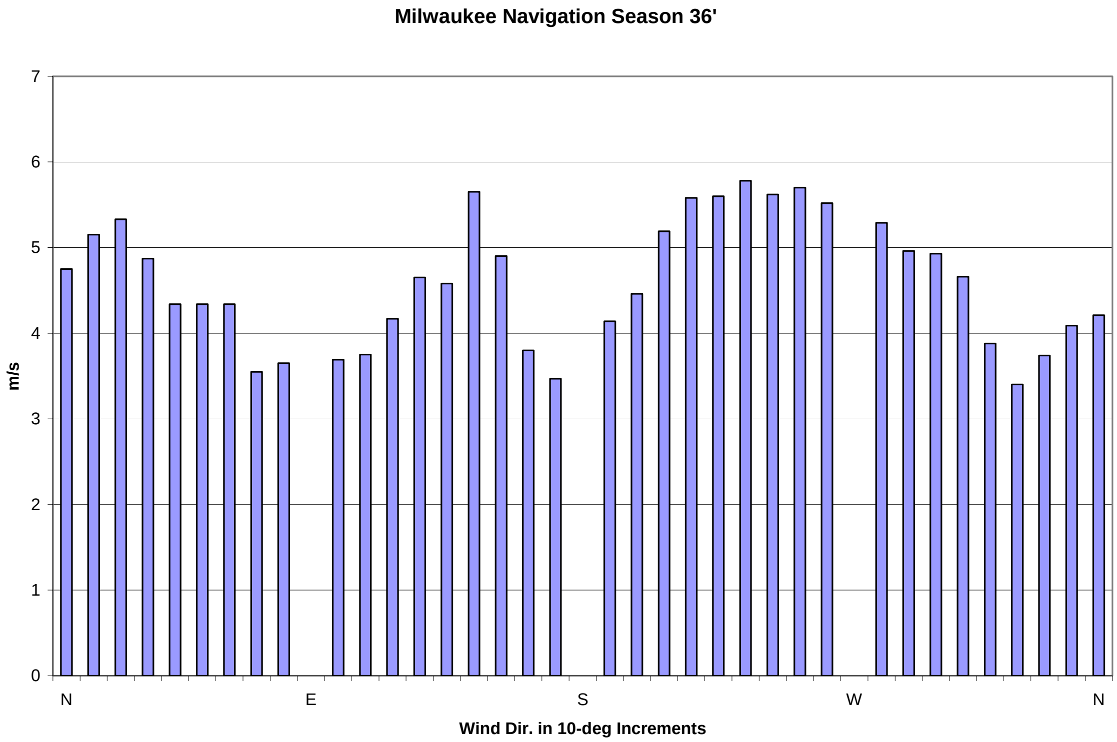
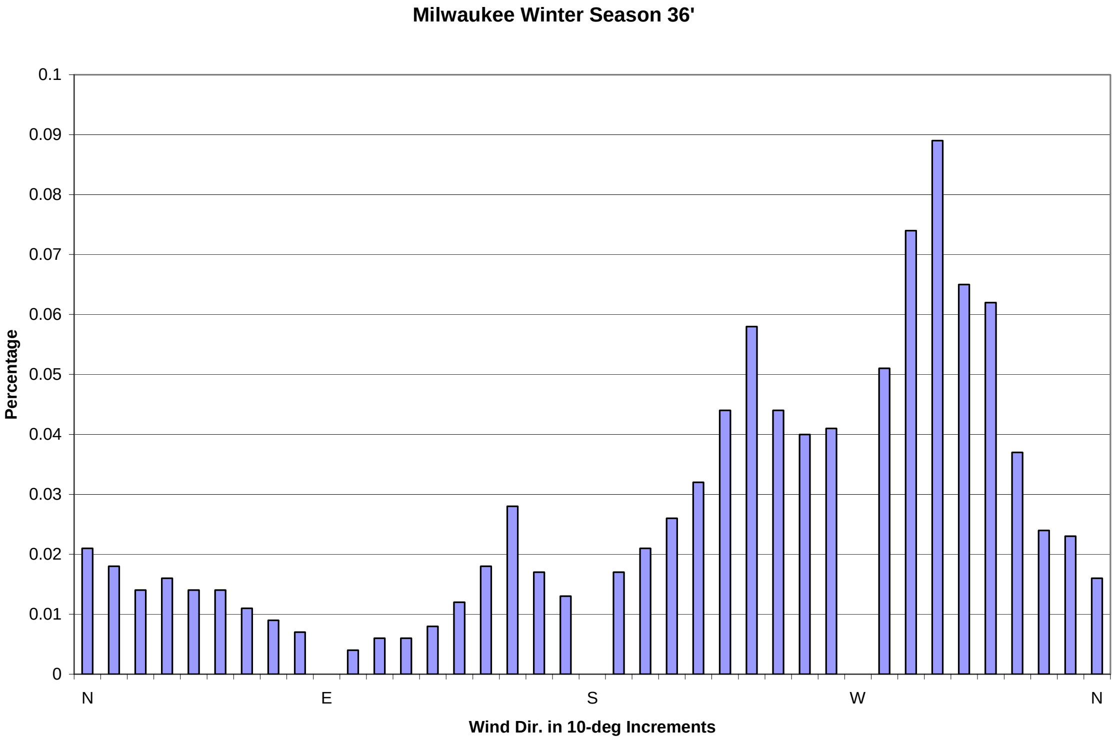


Figure 9: Milwaukee N. Harbor Entrance 36’ Wind Roses
Winter Season



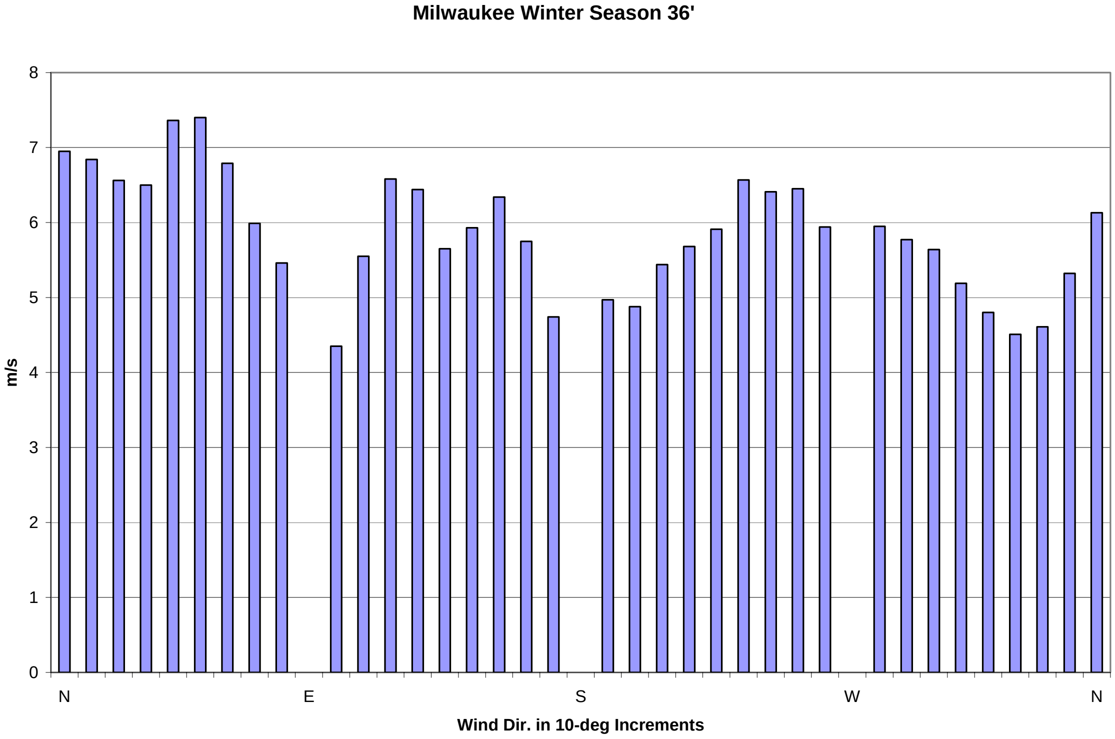
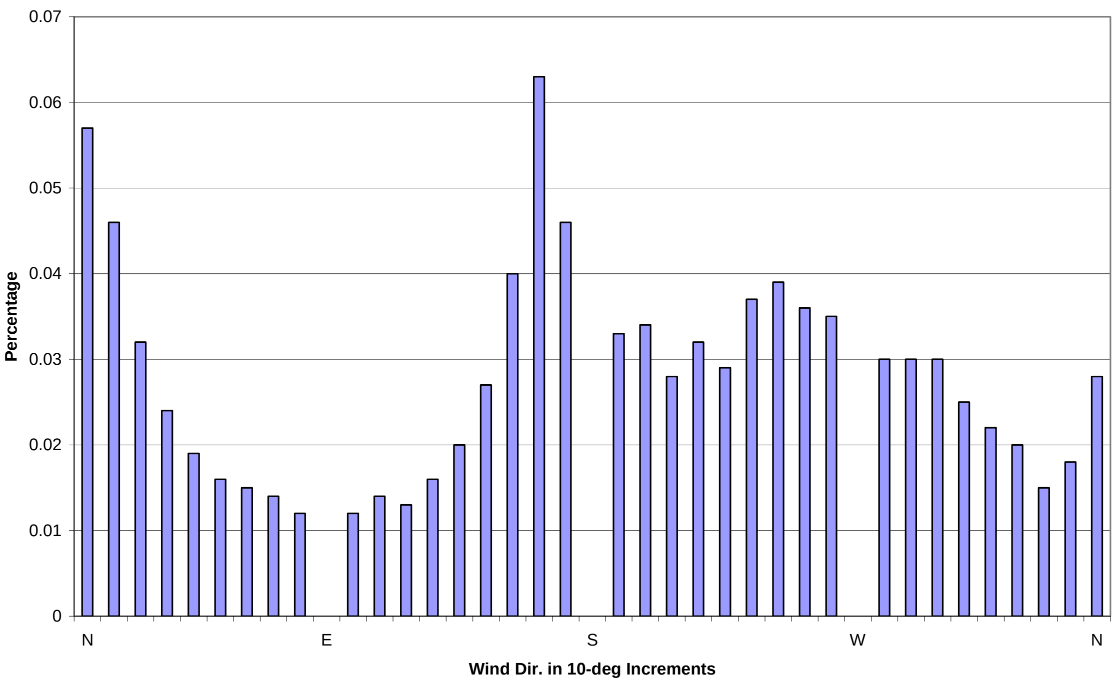


Figure 10: Kenosha Harbor Lighthouse 63' Wind Roses
Navigation Season

Kenosha Navigation Season 63'



Kenosha Navigation Season 63'

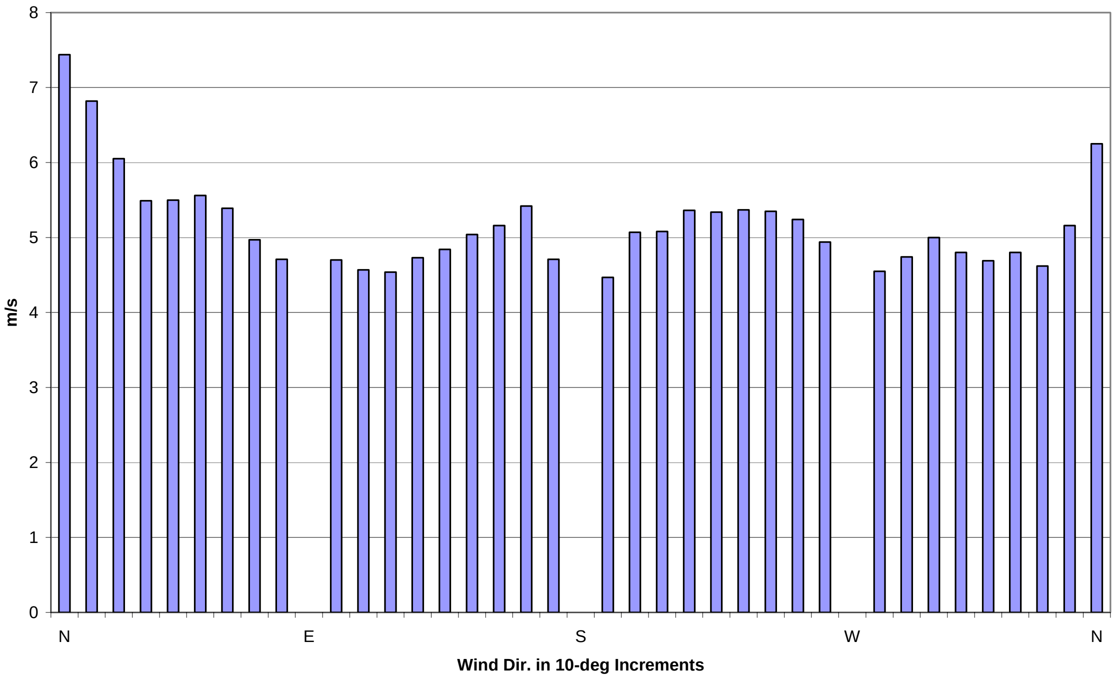
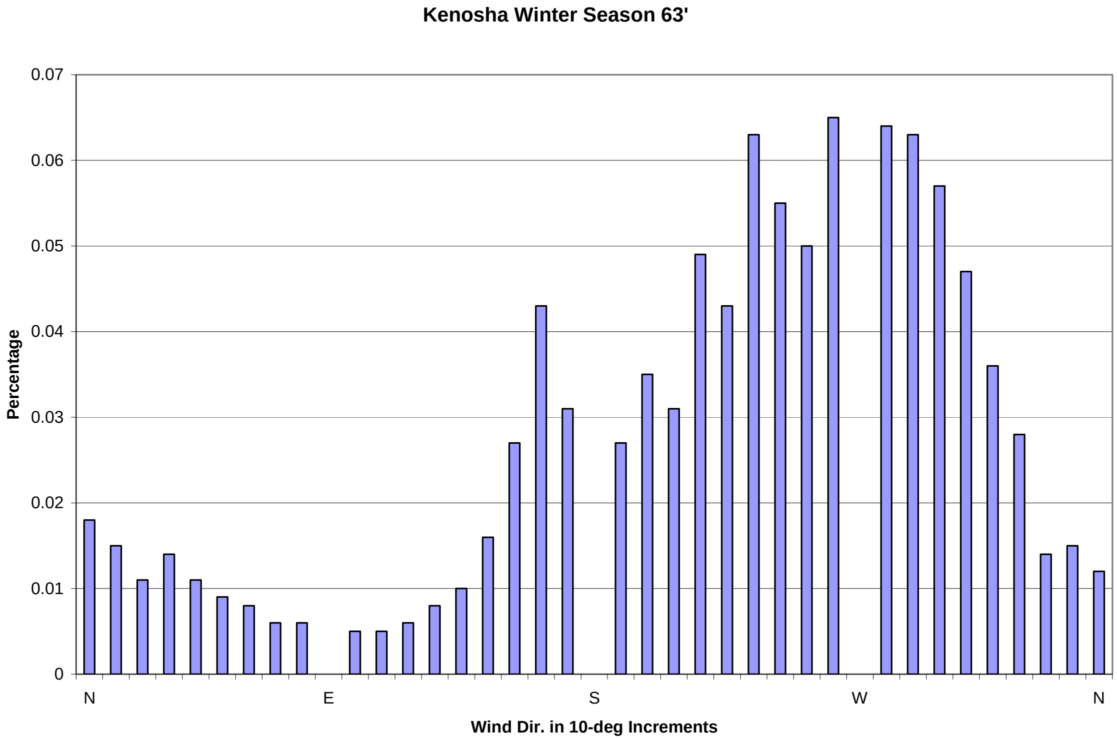


Figure 11: Kenosha Harbor Lighthouse 63’ Wind Roses
Winter Season



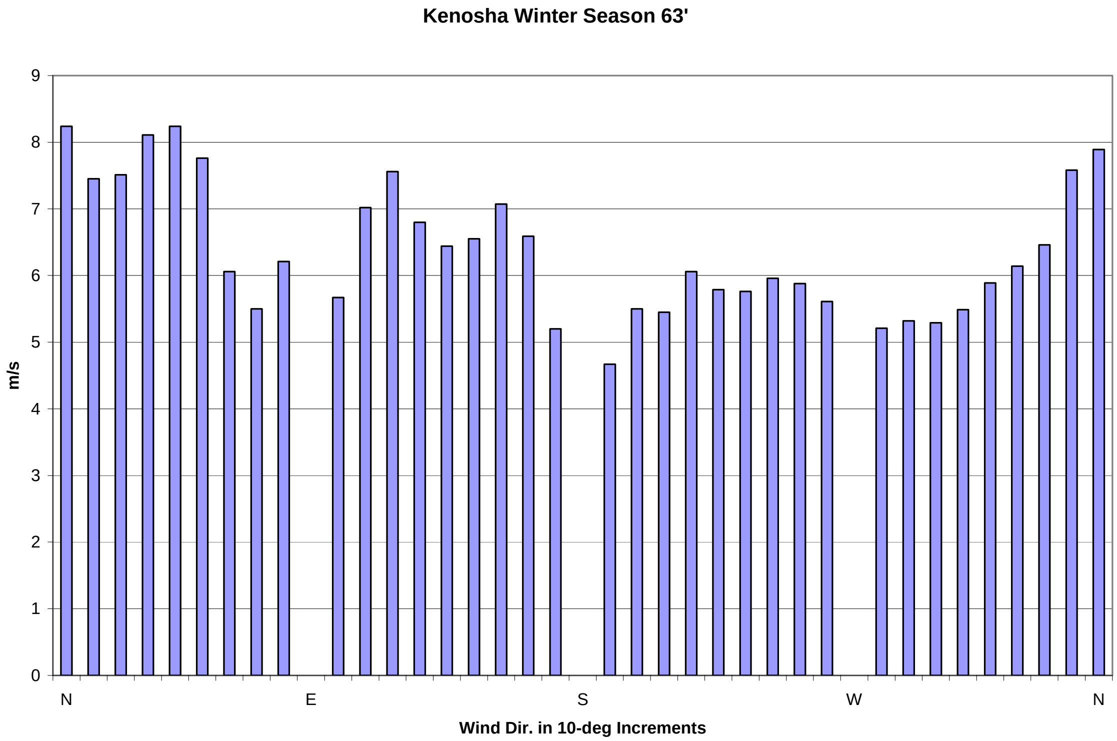
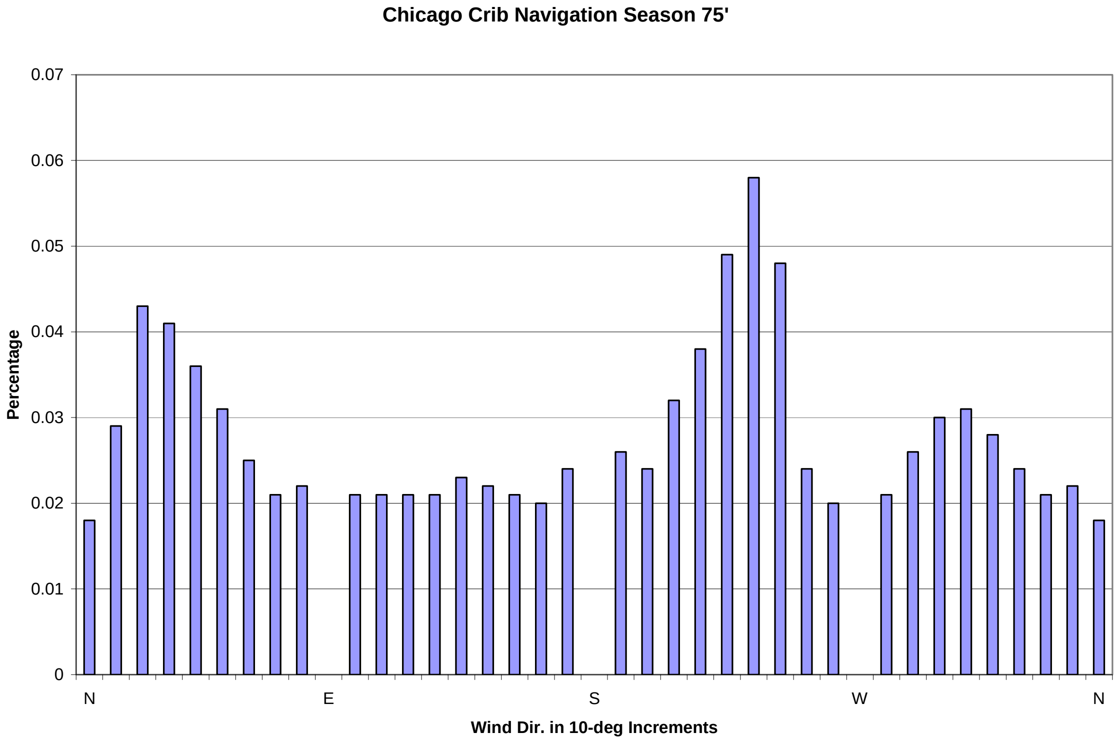


Figure 12: Chicago Crib 75’ Wind Roses
Navigation Season



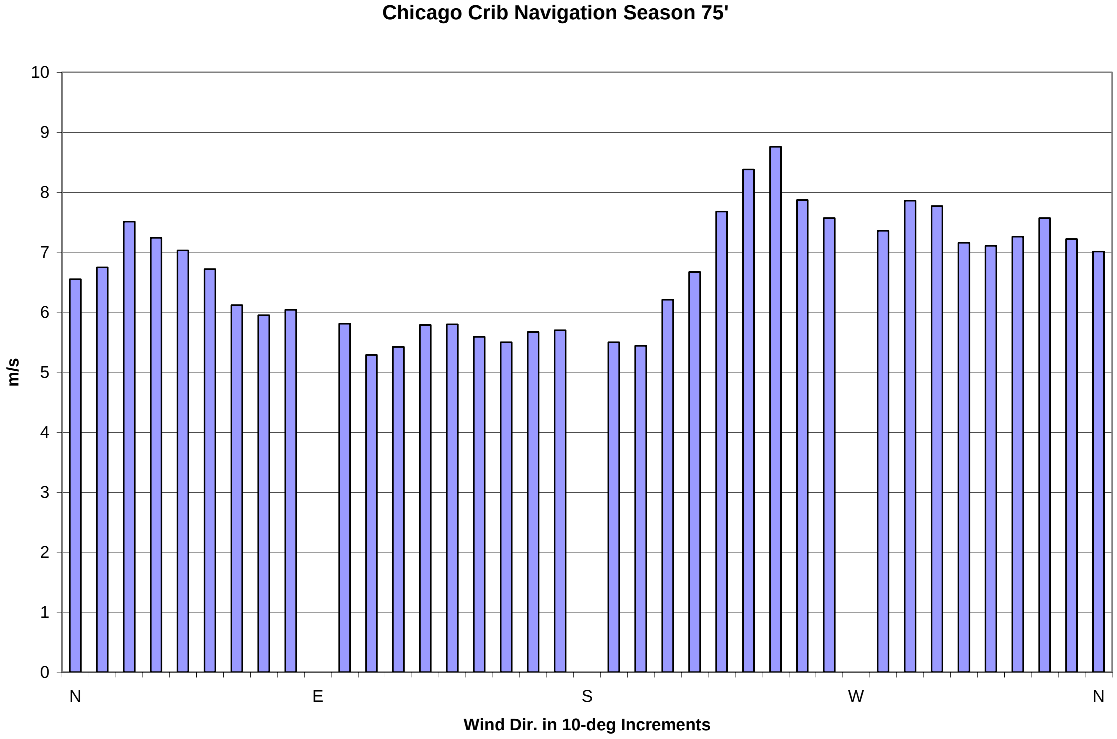
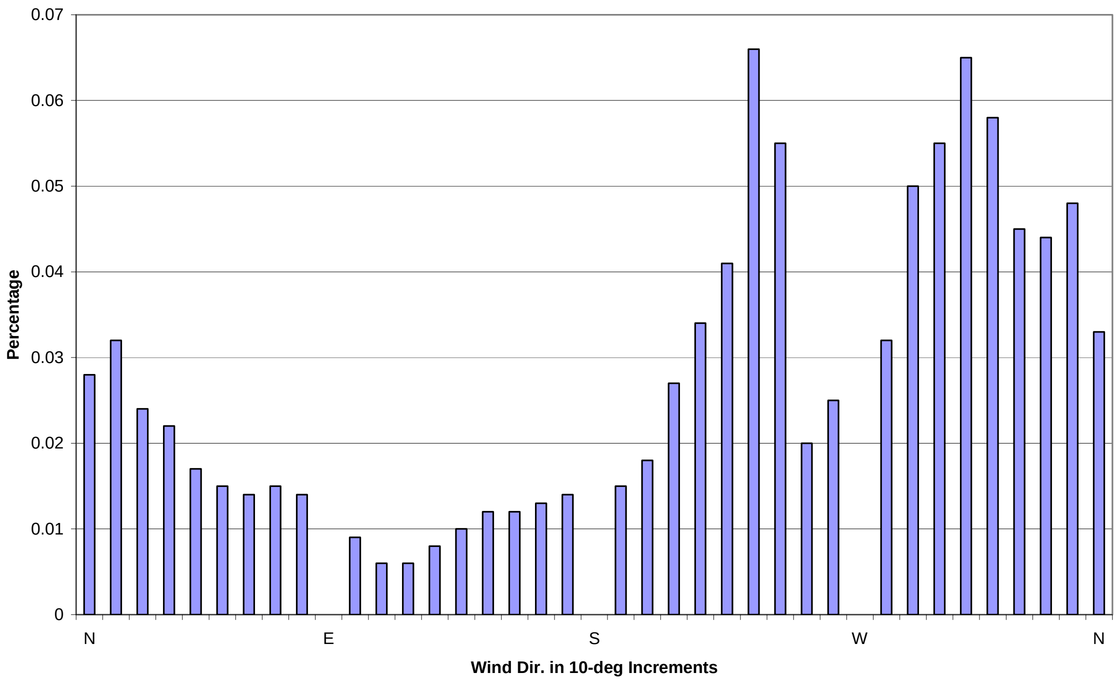


Figure 13: Chicago Crib 75' Wind Roses
Winter Season


Chicago Crib Winter Season 75'

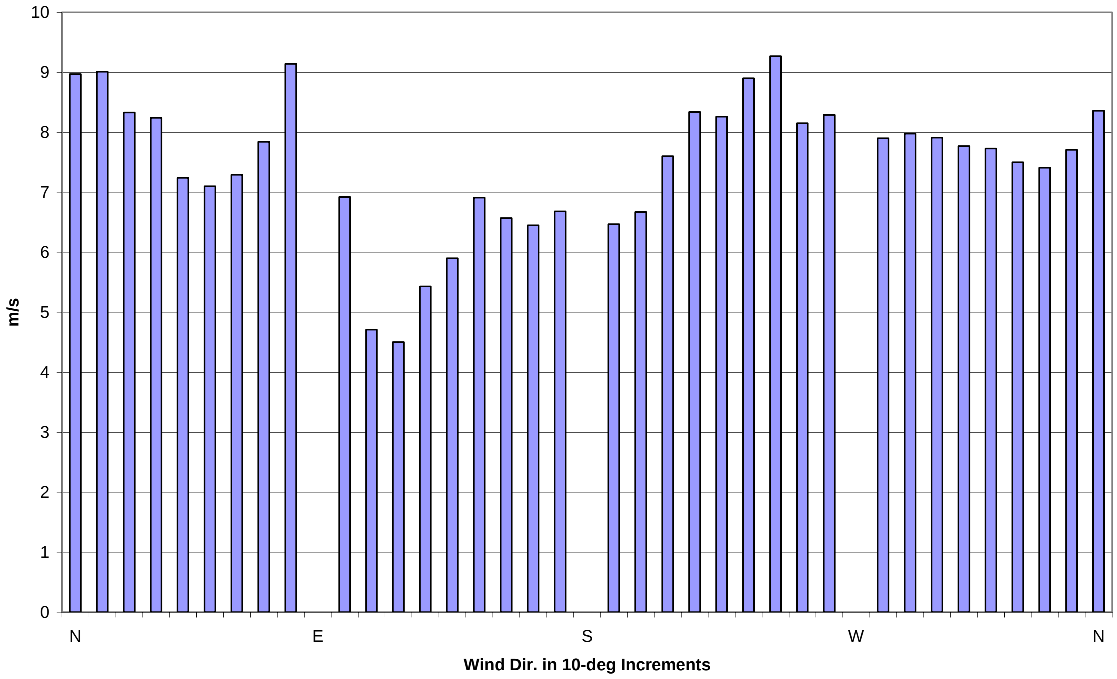
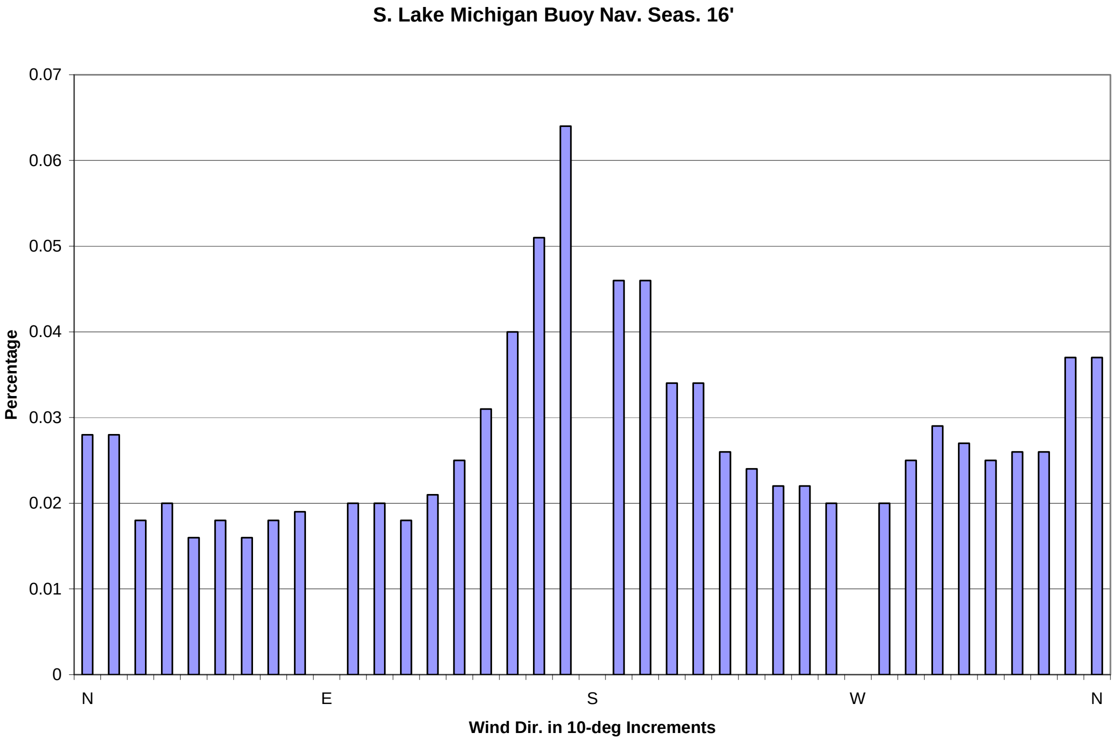
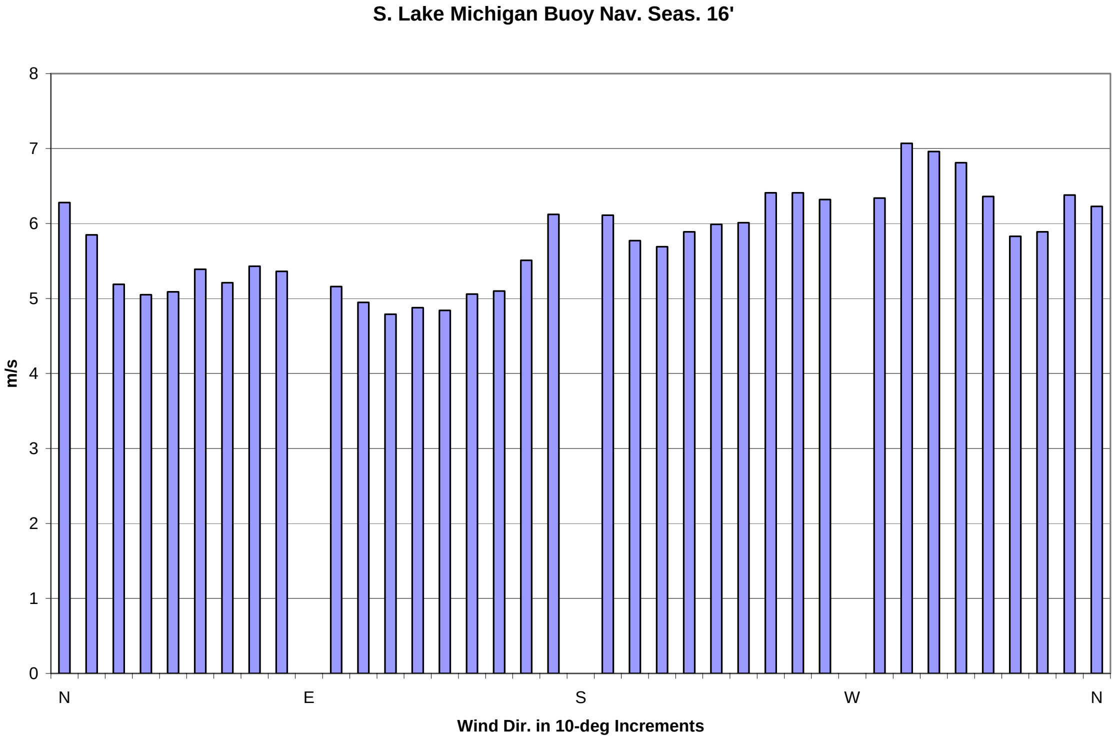

Chicago Crib Winter Season 75'

Figure 14: Buoy 45007 16' Wind Roses
Navigation Season





The depicted wind roses show such things as how N and S winds tend to increase in strength and frequency near points on the Lake Michigan Western Shore (see Sheboygan wind roses, Figs. 3-4, pp. 11-12), how strongly the winds vary seasonally on the Lake Michigan Eastern Shore (see Muskegon, Figs. 5-6, pp. 13-14), and how strongly the winds fall off for wind directions from nearby land at coastal locations (see Figs. 3-11, pp. 11-19). On the other hand, there is much less sensitivity to wind direction at Buoy 45007 (Fig. 14, p. 22) which is quite distant from land in all directions, and there is also less sensitivity at the Chicago Crib (Figs. 12 & 13, pp. 20-21), about three miles offshore, than at shore locations.

C. The Dramatic Seasonal Variation of Wind Shear

Wind shear varies dramatically over Lake Michigan, depending primarily on the air-water temperature difference, the wind speed, and wave height (see Liu and Schwab, 1987). However, no one directly measures wind shear over Southern Lake Michigan currently (all measurement locations measure at one height, often not the same height at which other nearby locations measure), and NDBC only measures wave height during an eight or nine-month-long navigation season when Buoy 45007 is deployed. The determination of wind shear at any single location above the lake is thus a complicated exercise, subject to significant risk of error, until measurements are improved, hopefully ultimately including multi-level measurements. Nonetheless, the measurements we do have show that the variation in shear over the lake surface must be quite large.

1. Land vs. Offshore Stations

Comparing the average of seasonal mean wind speeds at inland sites just west of the lake (Milwaukee Mitchell and Racine Batten Airports) to Buoy 45007 mean wind speeds during the navigation season, we find a ratio that varies sharply on a seasonal basis. Table 2 shows the ratio as a function of season.

Table 2: Seasonal Ratios of Wind Speeds Over Water & Land in S.E. Wisconsin (Wind Speeds in m/s)

	March-April	May-June	July-Aug.	Sept.-Oct.	Nov.-Dec.
Buoy 45007 5-m mean	5.95	4.53	4.81	6.85	7.76
MKE-RAC 10-m mean	5.08	4.055	3.705	4.04	4.495
Ratio (buoy/land)	1.17	1.12	1.30	1.70	1.73

Table 2 suggests that mean wind speeds are more depressed relative to the annual average over the lake surface in late spring and early summer than they are over land in the same time frame. In another season, fall, mid-lake winds appear to be higher relative to the annual average over the lake than they are over land. The ratio increases 48% from 1.17 in March-April to 1.73 in November-December.

We know that in late spring and early summer, the lake surface is usually considerably colder than the nearby land, while in the fall the opposite is often the case. These temperature differences tend to produce temperature inversions over the lake in the first case and unstable atmospheric conditions over the lake in the second case. On land, inversion conditions tend to be associated with lower 5-meter wind speeds and higher shear, while unstable conditions produce higher 5-meter wind speeds and reduced shear. So the hypothesis that the ratio changes are related to seasonal stability changes over the lake is on its face reasonable. And there is other evidence supporting the hypothesis.

2. Near-shore vs. Mid-lake Stations

If the seasonal ratio changes are related to stability, we might expect similar ratios involving stations on or just offshore of the west shoreline to exhibit lesser changes, because these near-shore locations are thermally distinct, somewhat more lake influenced, than their inland counterparts a few miles inland. The ratios do change in the direction expected if the hypothesis is correct. The highest increase of the two from March-April to November-December is 39%. See Table 3.

Table 3: Seasonal Ratios of Wind Speeds Over Water & Near-shore & Shoreline Locales in S.E. Wisconsin (wind speeds in m/s)

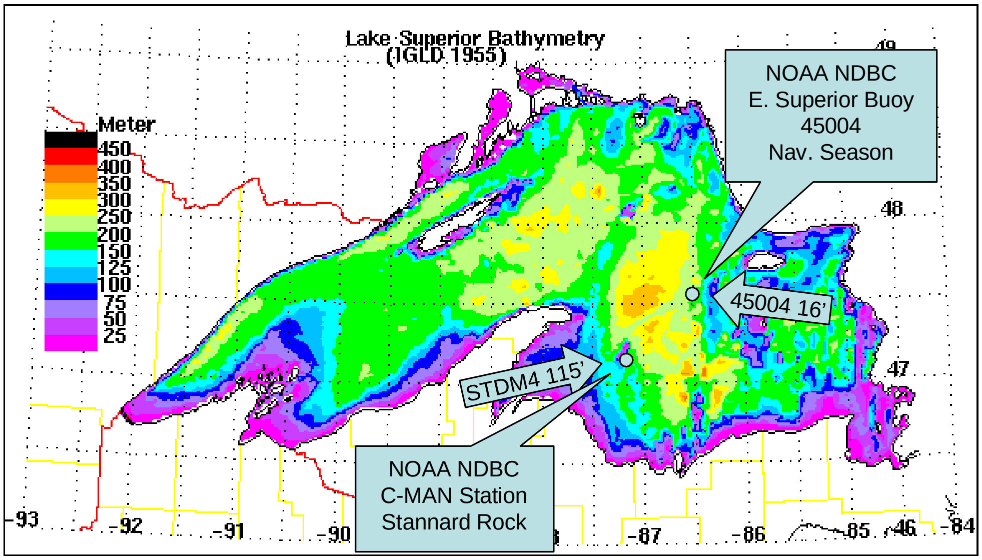
	March-April	May-June	July-Aug.	Sept.-Oct.	Nov.-Dec.
Buoy 45007	5.95	4.53	4.81	6.85	7.76
Sheboygan (SGNW3)	6.71	5.37	4.97	5.72	6.32
MKEH-KENH	6.085	4.695	4.475	4.96	5.71
Ratio: 45007/SGNW3	.89	.84	.97	1.20	1.23
Ratio: 45007/MKEH-KENH	.98	.96	1.07	1.38	1.36

Unfortunately, we do not have any direct shear measurements over Lake Michigan itself to verify the stability hypothesis. But we do have an instructive analogy to the north.

3. The Close Lake Superior Analogy

Fortunately, NDBC instruments two sites in the Eastern Basin of Lake Superior which do, together, provide considerable insight into how stability influences wind shear above that colder and larger lake. The first of these sites is Stannard Rock, an instrumented lighthouse on a rock in open Lake Superior about 40 miles N of Marquette. Stannard Rock is a C-MAN Station, measuring wind at 35.2 meters above lake level and temperature and dew point at the same height year round. The second site is Buoy 45004, which measures wind at 5 meters, air temperature at 4 meters, water temperature at -.6 meters, and wave statistics during the navigation season, roughly from April to November. Both sites are shown on Figure 15 below.

Figure 15: Lake Superior Virtual Shear Stations[4]



Buoy 45004 is about 42 miles NE of STDM4. Both locations are more than

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[4] GLERL makes this public domain map available at www.glerl.noaa.gov/char.bathymetry.html. Robert Owen re-sized the map and added the information about the virtual shear measurement sites.

20 miles from land. They probably have very similar wind climates. If one site is a little windier, it is probably Buoy 45004, and the difference is probably very small except during the winter season when the buoy is not deployed and we have no on-site data. For purposes of this study, focusing on periods the buoy is deployed, SSE has assumed that over time frames longer than a few hours STDM4 and Buoy 45004 are effectively co-located in the horizontal but vertically stacked. This assumption gives SSE a "virtual" direct wind-shear measurement for Eastern Lake Superior during periods when the buoy is deployed.[5]

Although beyond the original scope of the current research effort, SSE downloaded 2001-2003 data for STDM4 and Buoy 45004 to delve into the stability and wave factors bearing on issues in this study. "Virtual" shear measurements are not as useful as actual multi-level measurements, but they are better than no multi-level measurements at all. SSE combined the STDM4 and Buoy 45004 data for the period of Buoy 45004 deployment into the same database file to examine apparent vertical wind shear.

Table 4 summarizes the monthly mean wind, temperature, and wave statistics generated in this "virtual" shear study for Eastern Lake Superior. The highlight of this aspect of the study may be the extreme stability and consequent very high wind shear prevailing during June and July. Please note in this connection that Lake Superior is so cold and deep at the location of Buoy 45004 that it is sometimes still in an "overturning" mode at about 4 degrees C into August. Lake Michigan finishes overturning much earlier and its water temperature approaches air temperature significantly earlier in the summer. It probably also experiences a less intense inversion in early summer. However, notwith-

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[5] Both the NDBC buoys and C-MAN stations use the same prop-vane anemometer, the RM Young Wind Monitor, as do the GLERL Southern Lake Michigan Network stations, so there is no anemometer incompatibility issue here.

standing some differences in timing and intensity, both lakes experience highly stable atmospheric conditions for extended periods of time in spring and early summer.

Table 4: East Lake Superior Monthly Means During Navigation Season
(mean wind speed in m/s, temperature in degrees C)

	Stannard Rock		Buoy 45004				
	35.2 m		5 m	4 m	-.6 m	Atmp-	WvHgt
	WS	Atmp	WS	Atmp	Wtmp	Wtmp	m
May	8.51	7.19	5.95	3.68	2.42	1.27	.69
June	7.30	11.70	4.13	5.75	2.93	2.82	.28
July	7.56	14.75	4.14	8.43	5.25	3.17	.26
Aug.	7.06	17.61	4.55	14.04	12.28	1.76	.42
Sept.	8.64	14.43	6.20	13.02	12.39	.63	.78
Oct.	9.29	7.13	7.20	6.56	8.05	-1.49	1.08

We also compared the monthly mean air-water temperature and wave height differences of Buoys 45004 and 45007. This comparison is in Table 5.

Table 5: Buoy 45007 and 45004 Comparison of Mean Air-Water
Temperature Differences (deg C) and Wave Heights (m)

	Buoy 45007		Buoy 45004	
	Atmp-Wtmp	WvHgt	Atmp-Wtmp	WvHgt
May	2.27	.50	1.27	.69
June	2.23	.23	2.82	.28
July	.41	.37	3.17	.26
Aug.	-.48	.52	1.76	.42
Sept.	-1.89	.80	.63	.78
Oct.	-2.64	1.02	-1.49	1.08

We examined the relationship from the STDM4/Buoy 45004 comparison between the buoy 5-meter mean wind speed and the 35.2-meter/5-meter wind speed ratio. This is in Table 6.

Table 6: Comparison of Buoy 45004 Wind Speed and STDM4/Bouy 45004 Wind Speed Ratio

	STDM4 WS	Buoy 45004 WS	STDM4/Buoy 45004 WS Ratio
	------	------	------
May	8.51	5.95	1.43
June	7.30	4.13	1.77
July	7.56	4.14	1.83
Aug.	7.06	4.55	1.55
Sept.	8.64	6.20	1.39
Oct.	9.29	7.20	1.29

Table 6 shows that lower wind speeds at the buoy are associated with higher lighthouse/ buoy wind speed ratios (see Liu and Schwab, 1987).

In Table 7, we compare the buoy air-water temperature difference and the lighthouse/buoy wind speed ratio.

Table 7: Comparison of Buoy 45004 Air-Water Temperature Difference and STDM4/Buoy 45004 Wind Speed Ratio

	Buoy 45004 Atmp-Wtmp	STDM4/Buoy 45004 WS Ratio
	-----	-----
May	1.27	1.43
June	2.82	1.77
July	3.17	1.83
Aug.	1.76	1.55
Sept.	.63	1.39
Oct.	-1.49	1.29

Table 7 shows that the higher positive air-water temperature differences of stable conditions are associated with higher lighthouse/buoy wind speed ratios (see *ibid.*).

It appears that over Lake Superior light winds and high stability at the buoy (e.g., positive air-to-water temperature difference exceeding 1 degree C) are both associated with relatively high wind shear.

4. Waves and Seasonal Variation of Surface Roughness

In addition to obtaining the information already depicted relating to stability and shear and wind speed and shear, we also investigated whether wave height might be a limiting factor on the low end for shear under unstable atmospheric conditions over the lake. These conditions are common in fall and winter when cold winds blow over the warmer lake surface. But often these winds are accompanied by big waves, somewhat more so over the middle and eastern portion of the lake. Bigger waves could mean increased surface roughness and higher shear. Thus, it is conceivable that the increased wave height may limit further thermally-driven decreases in shear at some point. We queried the data and discovered the information shown in Table 8, which does suggest that there may be a limit for shear in cold weather established by the prevailing wave height. One of the implications of this is that shear may be higher over the central and eastern part of the lake surface than the western part when cold winds blow from the west. Another implication is that there may be an effective lower limit to mean monthly wind shear in the colder months. The Buoy 45004 wave-vs.-shear relationship suggests this lower limit may be an unstable month power-law exponent of about .12 for a mid-lake location.

Table 8: STDM4/Buoy 45004 Wind Speed Ratio Versus Wave Height
(wave heights in m)

Wave Height	0-.49	.50-.99	1.00-1.49	1.50-1.99	2.00-2.49	2.50-3.00	>3.0
STDM4/45004 WS Ratio	2.00	1.61	1.36	1.26	1.27	1.25	1.32

Table 8 suggests that for waves of around 1.5 meter height and up, ratios below about 1.25 do not occur over long time scales such as a month or more. Rather, it appears that the ratio "plateaus" around 1.25 to 1.27, then actually increases a little for waves over 3 meters. With a height difference of 35.2 meters versus 5 meters, a ratio of 1.25 corresponds to a shear exponent of about .114.

We know from 1990-1991 when the North Lake Michigan Buoy (Buoy 45002 between Washington and Beaver Islands) was left out all winter, and its wave gage continued to function, that mid-lake areas experience wave heights averaging over one meter in late fall and winter months. We know from buoy data obtained in the fall before buoy removal that wave heights commonly exceed one meter in fall on Lake Michigan. We also know from shoreline wind data (see, e.g., Fig. 6, p. 14 above) in that season that strong west-to-northwest winds dominate. In that season, such winds are normally associated with cold air blowing over the lake, producing highly unstable conditions, strong downward momentum transfer from higher-level (e.g., 850-millibar) westerly winds toward the lake surface from mid levels of the atmosphere, and significant wave development. Also, in most winters, there is little ice development in the central and eastern areas of the lake between Muskegon and Milwaukee to dampen wave development.

Mean monthly wave height measurements from Buoys 45004 and 45007 during the navigation season are similar (see Table 5, p. 28 above).

Considering these factors, we are assuming that the mean monthly wind shear exponent during the late fall-early winter months at the Buoy 45007 location when Buoy 45007 is removed is .12, tending to increase slightly to .13 in February and more substantially to .15 in March, as longer episodes of stable conditions begin to develop over mid lake on warmer days.

5. “Constructing” the Buoy 45007 Navigation Season Shear

In attempting to figure out the navigation season shear, we have used the “virtual” shear figures from Eastern Lake Superior as a guide, but have not used exactly the same monthly shear values due to the differences between the two lakes, including the slower warming of Lake Superior and the more extreme inversions which appear to develop over that larger lake in late spring and summer. Instead, we have used a shear function predicting monthly mean shear for April through July from the mean monthly air-water temperature difference and the mean monthly 5-meter wind speed measured at Buoy 45007. We derived this function from regression analysis of May to September “virtual” shear data from Lake Superior.[6] During this period, wave height is seldom a significant factor. It becomes more significant mainly toward the end of the navigation season, e.g., in October and November.[7]

For the stable months we are looking at here, the functional relationship neglects wave height, which averages .52 meter (August) or less at Buoy 45007 for these months in any event. It just uses mean monthly 5-meter wind speed and buoy air-water temperature difference to predict mean monthly shear as shown in Table 9.[8]

Table 9: Calculated Buoy 45007 Wind Shear for Stable Months

	WS	Atmp-Wtmp	Shear Exponent
April	5.81	1.41	.21
May	5.12	2.27	.26
June	3.90	2.23	.26
July	4.42	.41	.16

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[6] To derive this function, we plotted “virtual” monthly shear exponent versus air-water temperature difference and mean monthly wind speed.

[7] For October, SSE is assuming a shear exponent of .13, the same as the “virtual” shear value for Lake Superior for that month. For November, we assume.12, the same as the assumption for December and January. For August and September, we assume .15 and .13, respectively.

[8] The relationship is: $\text{Exp} = .139 - .001(\text{WS5}) + .055\,(\text{AT} - \text{WT})$, where

Exp is power law shear exponent for month
WS5 is monthly mean buoy 5-m wind speed in m/s
AT is mean monthly air and WT is mean monthly water temperature at buoy in degrees C

For near-neutral-stability months, we also pay attention to the "virtual" shear from Lake Superior to a significant degree (.17 in September), but we have assumed that the shear would be slightly lower for a slightly negative air-water temperature difference. We are assuming .15 for August and the same for March.

For fall months with unstable conditions, we use the October "virtual" shear on Lake Superior, .13, as guidance. We assume that this also applies to September on Lake Michigan, and that it drops to .12 for October and November.

For the non-navigation season months, we have no direct guidance, but we assume that .12 applies for December and January based on the tendency of these months to feature fairly high waves in mid lake, tending to prevent shear exponents from dropping below .12 despite a frequently highly unstable atmosphere. As previously noted, we estimate that the shear increases slightly in February to .13 and to .15 in March.

D. Constructing Annual Mid-lake Winds from Part-year Data

Once again, the paucity of year-round data from the middle of Lake Michigan forces us to look elsewhere to fill the data hole. In this case, we use STDM4 and other data (see Fig. 15, p. 26) to estimate the 24-meter winter winds during the period the buoy is removed and use previously described shear values to adjust the data up and down in elevation.

At STDM4, the mean annual wind speed for 2001-2003 at 35.2 meters was 8.94 m/s (20.0 mph), and the wind speed averaged 9.94 m/s (22.2 mph) during the winter period when Buoy 45007 was removed, an 11% increase. At Stannard Rock, way out in Lake Superior, the strongest near-surface winds occur in winter, not in either November or March as is typical of inland stations in Wisconsin. Presumably, this is because the offshore winds are driven in part by strong vertical mixing associated with deep instability over the relatively warm water surface. The deep instability is associated with lake-effect snow showers over the Upper Peninsula and Western Lower Peninsula of Michigan. It is also associated with mixing of stronger winds down from 850-millibars (5000’) or higher to the vicinity of the lake surface. This mixing undoubtedly contributes to the apparent early winter maximum of mean wind speeds over Lake Superior. If we had winter measurements in the middle of Lake Michigan, we would undoubtedly see a winter maximum.

We do have GLERL data from a Chicago water intake crib three miles east of the lakeshore. That shows a 10% increase in the winter period wind speeds at 23 meters above the lake surface with Buoy 45007 removed and a winter maximum.

We also have GLERL data from the 24-meter level of a Muskegon CG tower a short distance east of the lakeshore. That shows an early winter maximum and an 18% increase in the winter period wind speeds.

Since winter winds are overwhelmingly westerly, the greater increase at Muskegon than Chicago relative to the annual average is consistent with the hypothesis of mixing down of stronger winds above the relatively warm lake surface. Mixing would occur to a greater depth, allowing stronger winds to reach the surface, the further east we go on a west-to-east trajectory across the lake, at least until we run into the ice cover sometimes lining the immediate eastern shore of the lake starting in January.

Since both the Chicago and Muskegon CG Tower anemometers are located at approximately 24 meters and are both about the same distance from the Buoy 45007 Site and on opposite ends of a line from the Chicago Crib to Muskegon, we are assuming that at the 24 meter level above the Buoy 45007, the winter wind speed increases 14% from the annual average, midway between the measured increases at the Chicago Crib and Muskegon Tower. The annual average is, of course, significantly higher than the navigation season average since the winter season is the windiest season offshore.

Table 10 shows the calculated mean monthly 5 and 24-meter wind speeds based on the 14% increase assumption. Within the December to March period, we assumed that the monthly means were in the same ratio as measured for that period at Stannard Rock.

Table 10: Estimates of S. Lake Michigan Buoy Wind Speeds to 24 m
(wind speeds in m/s)

	Buoy	45007	
Period	Shear	WS5	WS24
Jan	0.12	7.53	9.09
Feb	0.13	7.48	9.17
Mar	0.15	6.62	8.38
Apr	0.21	5.81	8.08
May	0.26	5.12	7.7
Jun	0.26	3.9	5.86
Jul	0.16	4.42	5.68
Aug	0.15	5.19	6.57
Sep	0.13	6.4	7.85
Oct	0.12	7.28	8.79
Nov	0.12	7.67	9.26
Dec	0.12	8.25	9.96
Wgtd Ann.	0.155	6.3	8.03

SSE’s estimated annual average wind speed at the Buoy 45007 Site in mid lake is 8.03 m/s (18.0 mph) at 24 meters.

With both shear and monthly means determined, it is possible to estimate the wind resource at this site for any reasonable hub height.[9] Considering that wind turbines

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[9] One concern, however, which is difficult to address in the absence of more data about the depth of the spring-summer inversion over the lake, is whether, for example, an 80-meter hub height would exceed the

used offshore are likely to be at least 3 MW in size with rotor diameters of at least 100 meters and it will be desirable to keep the rotors above freezing spray generated by breaking waves occasionally reaching the 6-meter (20') and rarely reaching the 9-meter (30') range,[10] we estimate that initial offshore turbines will have 80-meter (262') turbine hub heights.

E. Buoy 45007 Location 80-m Monthly Mean Wind Resource

Table 11 below shows our estimated mean wind speeds on a monthly basis for an 80-meter hub height at the Buoy 45007 Site assuming the shear exponent determined for the 5-to-24-meter level applies. The annual average at this location at 80 meters would be approximately 9.7 m/s (21.7 mph).

Buoy 45007 is located approximately 40 miles east of the point where the Racine-Kenosha County Line intersects the Western Shore of Lake Michigan. It is anchored in a deep portion of the South Chippewa Basin of the lake SE to S of the Mid-Lake Plateau between Milwaukee and Muskegon (see Figs. 1-2, pp. 7-8).

Buoy 45007 is representative of the windiest mid-lake sites which could be utilized in the deepest parts of Lake Michigan within the State of Wisconsin. It is a substantially

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depth of the inversion, and whether the use of a high shear exponent above the inversion height would exaggerate the wind resource. This is a possibility. Wind and temperature sampling measurements near hub height would be desirable to explore it. While SSE's experience flying its flying anemometer often in lake breeze conditions on the shore of Lake Michigan last summer suggests that lake breeze inversions in S.E. Wisconsin are generally in excess of 60 meters deep near the shoreline, we have no good information on inversion heights over the mid lake region. The STDM4 temperature measurements do suggest that the inversion above Lake Superior usually extends above 35.2 meters. They do not tell us by how much.

[10] In 2001-2003, the highest mean significant wave height reported by Buoy 45007 was 5.16 m. Buoy 45004 in Lake Superior reported a highest mean significant height of 5.39 m. In neither case was this an absolute maximum. Neither buoy measured winter waves. The mean significant wave height is the average of the highest one third of the waves in the observation period. This period is 20 minutes for waves. The absolute highest wave is somewhat higher than the mean significant wave height. For very high waves, wave periods are typically around 10 seconds. The wave observation may be reporting on the highest 40 of a sample of 120 waves in the observation period closest to the top of the hour. Higher waves may occur in another period between the hours. It is conceivable that the absolute highest wave may be 50-100% higher than the mean significant wave height reported by a buoy.

Table 11: Estimated S. Lake Michigan Buoy Wind Speeds to 80 m
(wind speeds in m/s)

	Buoy	45007	
Period	Shear	WS5	WS80
Jan	0.12	7.53	10.5
Feb	0.13	7.48	10.72
Mar	0.15	6.62	10.04
Apr	0.21	5.81	10.4
May	0.26	5.12	10.53
Jun	0.26	3.9	8.01
Jul	0.16	4.42	6.89
Aug	0.15	5.19	7.87
Sep	0.13	6.4	9.18
Oct	0.12	7.28	10.16
Nov	0.12	7.67	10.7
Dec	0.12	8.25	11.51
Wgtd Ann.	0.155	6.3	9.7

windier location than a typical potential site located in relatively shallow water closer to shore, and it is significantly windier than a more probable large-scale offshore development area of "moderate" depth east of the Milwaukee Area. Since the moderate-depth and near-shore shallows areas are distinct in location and wind resource, we will discuss them separately, starting with the moderate-depth area.

F. Resources in Mid-Lake Plateau Area East of Milwaukee

1. General Considerations

While moderate in depth compared to the Buoy 45007 Location, the potential large-scale, far-offshore, wind development area east of Milwaukee is in waters considerably deeper than waters developed offshore in Europe in recent years (see Figs. 1-2, pp. 7-8 above). With depths of around 40 to 80 meters, no one would consider it shallow.

However, it is in a depth range which could be considered for new foundation concepts beginning to be proposed in both the U.S. and Europe. A proposed submerged horizontal foundation supported on four pilings driven into the bottom was suggested by a west coast firm in a poster paper at Global Windpower 2004 in Chicago this past March.[11] Undoubtedly, there will be new foundation technologies developed for such sites in the next five years. Some European offshore projects are already proposed for depths exceeding 30 meters. Other designers have proposed floating foundations for even deeper waters. These concepts would theoretically permit utilization of the deepest parts of the lake for wind energy production, but moderate depth locations would be less expensive to develop so would presumably be developed before the mid-lake depths.

The general area we have in mind is on the Mid-Lake Plateau located roughly between Milwaukee and Muskegon. See Fig. 1, p. 7 above. Approximately 250 square miles in this area have depths of less than 80 meters and about 20 square miles are between 40 and 60 meters deep. The areas of greatest interest are shaded in light green. Within Wisconsin waters relatively close to Milwaukee are a roughly 100-square mile area of less than 80 meter depth centered near 43◦09’ N, 87◦27’ W and a smaller area further to the southeast. There are other areas closer to mid lake. The wind estimate developed in this report is for the larger site closer to Milwaukee which is shown on Fig. 2, p. 8 above. This site is centered about 25 miles ENE of the mouth of the Milwaukee River, about 22 miles E of where the Milwaukee County-Ozaukee County Line intersects the shoreline.

Advantages of a potential large-scale far-offshore site east of Milwaukee are that

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[11] Gordon Fulton, Concept Marine Associates, Inc., “Modular Sub-Surface Support Platform and Refloatable Anchoring Systems.” While this paper was not ultimately published in the GWP 2004 Proceedings, as posted it appeared to offer an interesting concept for an affordable moderate-depth offshore foundation.

it is near a potential underwater EHV power line corridor between S.E. Wisconsin's Oak Creek Power Plant and W. Michigan's Campbell Power Plant (a GW-scale wind farm would likely require EHV grid hookup), it is big enough to potentially support thousands of MW of wind capacity, it is far enough offshore that it would be unlikely to give rise to the same esthetic and recreational boating concerns as a near-shore wind farm in the lake, and it is likely to be significantly windier than such a closer-in site. Disadvantages include higher grid connection, foundation, and maintenance costs as compared to a shallower site closer in to shore. One question would be whether the increased wind resource would outweigh the negatives.

2. Wind Resource

There have been no wind measurements above the Mid-Lake Plateau in general. Buoy 45007 is in deeper water to the south. One possibility for getting some wind information on this area in the future would be to take wind speed measurements from the new high-speed Milwaukee-Muskegon ferry by measuring and simultaneously logging boat position and resultant wind speed and direction during ferry lake crossings.[12] The new ferry crosses the Mid-Lake Plateau several times daily during the navigation season.

It is possible to use the existing data to estimate how the Mid-Lake Plateau differs from Buoy 45007 in its wind characteristics. To do this, we treated much of the navigation season differently than the winter.

For the navigation season, we have information from mid lake which we can compare with data from the eastern and western shores and the Chicago Crib. We looked

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[12] By means of vector computations similar to those SSE performed when it used its flying anemometer to measure wind speed from a moving sailboat last October, it would be possible to glean some wind speed information over the lake from an anemometer installed on the ferry.

at this data, focusing initially on the highly stable (over the lake) months of April to June.[13] In looking at the stable season data, we noted that the Chicago Crib site was slightly windier than Buoy 45007 for NE winds in this season (see Figs. 12 & 14, pp. 20 & 22 above). This is not surprising due to the longer over-lake fetch for Chicago Crib than Buoy 45007 for such winds. The Chicago Crib Site was slightly less windy overall in this season. The chosen Mid-Lake Plateau Site should also be somewhat less windy than Buoy 45007 in this season, but not quite to the extent of the Chicago Crib Site due to the greater distance offshore (roughly 22 miles versus 3 miles). Accordingly, we assumed that the Mid-Lake Plateau 24-meter mean wind speed would be halfway between the Buoy 45007 and Chicago Crib averages at that height (actually 23 m for Chicago Crib) in April through June.

In the more neutral stability months over the lake, March and July-August, the Chicago Crib and Buoy 45007 had approximately equal 24-meter wind speeds in July, but the buoy was windier at 24 meters at both the end of the unstable season (March) and the beginning of the unstable season (August). Thus, we used the Buoy 45007 wind speed for July and used the average of the buoy and Chicago Crib for March and August.

In general, in the months with relatively cold air flowing over a warmer lake surface, September through February, the Chicago Crib and other stations exhibit a tendency for mean 5-meter wind speed to increase from west to east across the lake. Being less far out into the lake, the Chicago Crib is not as windy at 5 meters in the navigation season portion of this period as Buoy 45007. We know also from the winter season increases in

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[13] A complication in this endeavor was the absence of direct shear data measurement data. It was necessary to assume shear exponents to compare wind speeds measured at different heights. In doing this, SSE assumed that shear exponents were lower at Chicago Crib in the stable months than at Buoy 45007 because the seasonal lake inversion probably builds up gradually offshore approaching the deeper central part of the lake. It is not as fully developed on the average at the Chicago Crib. Similar considerations apply to the shear at the lakeshore sites.

wind speed at the Muskegon near-shore station that the pattern continues through the winter (see Fig. 6, p. 14 above)..

Since the Mid-lake Plateau Site is neither as far offshore as Buoy 45007 nor as close to shore as the Chicago Crib, it should experience an intermediate wind regime in the unstable season, with the scaling factor basically related to its comparative distance from the western shore of the lake. Buoy 45007 is 40 miles out, the Chicago Crib is 3 miles out, the part of the Mid-Lake Plateau of interest here is 22 miles out. Accordingly, we have increased the Chicago Crib wind resource by 51% of the difference between the Buoy 45007 mean (or estimated mean) and the Chicago Crib mean for these months.

In addition to experiencing somewhat different, lower, wind speeds than the Buoy 45007 Site, the Mid-lake Plateau Site would also experience somewhat different shear exponents. In general, we would expect this site to have slightly lower shear exponents in April to June than Buoy 45007, similar shear in March and July-August, and slightly lower shear exponents in the unstable months of September to January. Necessarily, these incorporate the best judgment of the estimator. We just do not have measurements of variation of shear over the lake surface. The lower exponents in unstable conditions would be related to significantly lower mean wave heights due to lesser over-lake wind fetch and greater frequency of ice-damped wave conditions to the west as compared to the Buoy 45007 Site.

We present our predictions as to monthly mean wind speed at 5, 24 and 80 meters and shear exponents for the Mid-Lake Plateau Site in Table 12 below.

The highlight of Table 12 is our prediction that the mean annual 80-meter wind speed at the selected Mid-Lake Plateau Site closest to (ENE of) Milwaukee is a rather energetic 9.08 m/s (20.3 mph). This is higher than any potential inland site in Wisconsin at 100 meters and higher than the hub-height mean wind speed of any developed site in Minnesota or Iowa.

Table 12: Estimated Mid-lake Plateau Site Shear and Mean Wind Speeds
(wind speeds in m/s)

	Mid-lake	Plateau	Site	
Period	Shear	WS5	WS24	WS80
Jan	0.11	7.17	8.52	9.73
Feb	0.13	7.05	8.65	10.12
Mar	0.15	6.27	7.93	9.5
Apr	0.19	5.89	7.94	9.98
May	0.23	5.16	7.4	9.76
Jun	0.23	4.02	5.77	7.61
Jul	0.16	4.42	5.68	6.89
Aug	0.15	4.96	6.27	7.51
Sep	0.13	5.95	7.3	8.54
Oct	0.11	6.85	8.14	9.29
Nov	0.11	7.28	8.65	9.87
Dec	0.11	7.59	9.02	10.3
Wgtd Mean	0.146	6.05	7.6	9.08

G. Taking a Hard Look at Chicago Crib Wind Data

The reality is that no one has spent the money to do long-term wind measurements at potential offshore wind development sites in Wisconsin to date, so we have to look at NOAA buoy, C-MAN and GLERL data from neighboring states to gain a better understanding of the S.E. Wisconsin offshore wind resource. The available data most representative of a shallow-water offshore site comes from the Chicago Crib Site (see Figure 2, p. 8 above). Three miles east of the lakefront, this site is at about the same offshore distance that we might consider for some shallow-water offshore wind development in S.E. Wisconsin (especially off S. Milwaukee County and Racine and Kenosha Counties). No other measured site in Lake Michigan comes close.

The Chicago Crib measurements to date are highly encouraging. The 2001-2003 average at 23 meters (75') above lake level was 7.17 m/s (16.0 mph).

Three features of the Chicago Crib location differ from potential S.E. Wisconsin near-shore sites: (1) proximity to the very large city and the extremely tall buildings of Chicago; (2) proximity to the south end of the lake; and (3) relatively low latitude. All of these features could tend to modestly reduce mean wind speed as compared to a favorably-situated Wisconsin near-shore site.

Looking at the effect of proximity to Chicago, it is subtle at best. We cannot quantify an effect.

S.E. Wisconsin lacks buildings of the enormity and number of the Chicago skyscrapers, but it does have significant lakeshore bluffs rising up to 150 feet from the lake surface, especially in parts of Milwaukee and Ozaukee Counties. These would also have some effect on the wind resource for near-shore sites. This can be seen from the Milwaukee Harbor Entrance winter wind rose (Fig. 9, p. 17 above), which suggests that a lakeshore bluff less than .5 mile to the NW is delivering about a 1 m/s wind speed reduction for wind directions from 310 to 350 degrees at that 11-meter measurement site. Effects would, of course, be less at 80 meters three miles or more offshore, but they might be comparable to the subtle building effects at the Chicago Crib, depending on the height and extent of nearby lakeshore bluff.

The position of the Chicago Crib relatively close to the south end of the lake and the southeast orientation of the nearby shoreline limits the over-lake fetch of winds reaching the site from due south. This can be seen from comparing south winds during the navigation season at Buoy 45007 with those at the Chicago Crib. At the buoy, well exposed from all directions in mid lake, south winds have above-average mean wind speeds (Fig. 14, p. 22 above), while at the crib they have below-average wind speeds for the season (Fig. 12, p. 20 above). By contrast, at the only Wisconsin measurement site with a good south exposure, Sheboygan, the wind roses for both periods show above-average south winds (Figs. 3-4, pp. 11-12 above). Situated near a prominent point tending to focus south winds, Sheboygan is undoubtedly above average in this respect, but the Chicago Crib Site is below average in its south exposure. Many Wisconsin shallow-water offshore sites would have better south exposure.

As to latitude, there may be some modest mean wind speed advantage to higher latitude, especially in summer.

Also difficult to quantify but worthy of brief mention is that a general north-to-south cool lake current along the S.E. Wisconsin Shore may contribute to stronger spring-summer winds in the shallows near the Wisconsin Lakeshore.

The upshot is that while Chicago Crib is by far the best available comparison site for a shallow-water wind project in S.E. Wisconsin we have to date, it is not necessarily quite as windy as such a Wisconsin offshore site at a comparable offshore distance.

H. Potential Near-shore Sites and Wind Resource

Each of the S.E. Wisconsin lakeshore counties has potential near-shore sites. In looking for such potential sites, SSE focused on areas with a depth of less than 30 meters. 30 meters is not likely to be a depth limit in the long run, but 30-35 meters is about as deep as currently planned projects appear likely to go in Europe in the next few years. Over ten years ago, the initial European offshore projects went into very shallow water, typically only 3-5 meters. Technology is rapidly advancing in the direction of developing deeper water sites.

As the offshore wind industry develops, people will likely use different technologies for relatively shallow-water (e.g., less than 30-meter), moderate depth (e.g., less than 100-meter), and very deep water sites (e.g., bottom-anchored floating foundations). However, shallow-water sites are still likely to be developed for some time after deeper-water technologies become available. The close in, shallow, sites will likely retain a development cost advantage and may be pursued more aggressively as the general level of public comfort with the appearance of large offshore turbines increases.

In S.E. Wisconsin, the biggest potential shallow-water sites are off of S.E. Milwaukee and Northern Racine Counties, with areas of depth of 30 meters or less extending up to eight miles offshore (ironically, one of the best vantage points of this largest area is from the Oak Creek (coal) Power Plant or the Bender Park Bluff just north of the plant). A somewhat narrower area of shallows extends south from there, reaching out three to five miles, through Racine and Kenosha Counties all the way to the Illinois State Line.

N. of Milwaukee Bay, there are narrower shallows with depths of less than 30 meters out to about three miles off Milwaukee, Ozaukee, and Sheboygan Counties. In the northernmost portion of Sheboygan County, the 30-meter contour extends out to about four miles. While the focus of this study is from Sheboygan County south, there is significant shallow and middle-depth potential north of Sheboygan County too.

The S.E. Wisconsin shallow water sites alone have a potential output of thousands of MW (as does the Mid-Lake Plateau).

Within the long stripe of potential shallow-water siting area east of the lakeshore from Whistling Straits in the Town of Mosel south to the state line, the wind resource is likely to vary somewhat due to variations in the distance offshore, the height of lakeshore bluffs nearby, the orientation of the shoreline (bays being less windy and points windier, for example) and other factors. However, generically, the shallows are windy, albeit not as windy as the Mid-Lake Plateau and not as windy at one mile out as at three miles out.

Recognizing that there is a range of potential shallow-water sites with a range of wind resources, we have estimated the wind in this report for a "generic" offshore site not located offshore from either a point or a bay, 2.8 miles out, with a moderate-to-low lakeshore bluff of 60-foot or lower height. For such a site, typical of Southern Racine or Kenosha County, we estimate the mean annual wind resource would be 8.5 m/s (19.0 mph) at 80 meters, the same as the Chicago Crib mean at that level. Table 13 shows estimated shear exponents and monthly wind speed averages at this generic site.

We use slightly lower monthly mean shear estimates for this site than for the Mid-Lake Plateau Site for fall to early winter due to lower wave heights and for the April-to-June stable season due to greater proximity to shore and shallower inversions. We further assume that wind speeds at this typical shallow-water site at 23 meters are the same as at the Chicago Crib, .2 mile further offshore.

Table 13: Estimated Shear and Wind Speeds at Typical Shallow Water Site
(wind speeds in m/s)

	Site 2.8	mi. E of	Shoreline	
Period	Shear	WS5	WS23	WS80
Jan	0.1	6.81	7.93	8.98
Feb	0.12	6.74	8.1	9.41
Mar	0.15	5.95	7.48	9.02
Apr	0.17	6.02	7.8	9.64
May	0.2	5.23	7.1	9.11
Jun	0.2	4.19	5.68	7.29
Jul	0.16	4.46	5.69	6.95
Aug	0.15	4.75	5.97	7.2
Sep	0.12	5.6	6.72	7.8
Oct	0.1	6.4	7.46	8.45
Nov	0.1	6.88	8.02	9.08
Dec	0.1	6.91	8.05	9.12
Wgtd Mean	0.135	5.84	7.16	8.5

Our estimated annual mean wind speed for this site of 8.5 m/s (19.0 mph) at 80 meters is likely to exceed the 100-meter wind speed at any Wisconsin inland site and to be comparable to or higher than that of many developed wind sites in Southwest Minnesota and Northern Iowa.

I. Summary of S.E. Wisconsin Offshore Wind Resources

S.E. Wisconsin has hundreds of square miles of potential shallow-water offshore wind development area within two to eight miles of its Lake Michigan Lakeshore and additional hundreds of square miles of potential moderate-depth wind development area on the Mid-Lake Plateau about 15 to 45 miles east of Milwaukee. These areas have a combined wind potential of more than 10,000 MW.[14] Both areas have energetic

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[14] We have not attempted to precisely estimate the potential in this study. We have developed back-of-the-envelope estimates based on an assumed installed density of 20 MW per square mile for large offshore turbines and estimates of at least 250 square miles potential development area for both shallow and Mid-Lake Plateau Sites.

wind resources, ranging in mean annual wind speed at 80-meter hub height from about 8.5 m/s (19 mph) for shallow-water sites several miles from shore to about 9 m/s (20 mph) or higher for moderate-depth sites more than 15 miles from shore.

II. SSE'S FLYING ANEMOMETER PROVED TO BE A USEFUL WIND SAMPLING TOOL, BUT IT PROVED IMPRACTICAL TO USE IT NEAR THE NOAA SHORELINE STATIONS IN S.E. WISCONSIN.

One of our original goals was to try to use SSE's flying anemometer close enough to one or more of the NOAA shoreline stations in S.E. Wisconsin to sample the wind shear above the station anemometer height. This proved impractical. One of the stations (Sheboygan) was inaccessible on foot. The other two (Milwaukee and Kenosha Harbors) were so accessible to pedestrians and so close to substantial boat traffic that there were safety issues in flying kites near the NOAA anemometers during the height of the summer season. We resolved these issues by doing shoreline flying at safer locations more removed from pedestrian and boat traffic and beachgoers.

Although the flying anemometer did not provide exactly the information originally intended, it did provide useful information. The lifting kite itself provided one useful tidbit of information. Much of the time, we flew in lake breeze conditions in late July and August, when the lake surface temperature was 70 degrees or higher. Nonetheless, despite the weakening and shortening of the typical duration of the lake breeze associated with the warmer water temperatures of late summer, the lifting kite normally flew at at least 200 feet (most often 100 to 200 feet above the flying anemometer), suggesting that the lake breeze inversion was typically at least that deep even atop the 100-foot lakeshore bluff in Bender Park where we most commonly flew.

The flying anemometer itself provided some sampling information along the shoreline or offshore in several specific areas, which we will now address:

(a) Harrington Beach in Northern Ozaukee County;

(b) Wind Point in Racine County;

(c) Bender Park Bluff in Southern Milwaukee County;

(d) Racine North Pier;

(e) Kenosha Beach;

(f) Veteran's Park on the Milwaukee Lakefront; and

(g) Along an offshore course averaging about 1.2 mile offshore near Racine.

A. Harrington Beach

We flew near a point on the beach at Harrington Beach State Park (43◦ 30' N, see Fig. 2, p. 8 above) in fresh N-NE winds on August 16, 2003, registering a flying anemometer mean wind speed of 7.5 m/s (16.7 mph) at a mean height of 27 meters (89') from 2-6:50 p.m. During the 2-7 p.m. period that day, the NOAA SGNW3 anemometer at Sheboygan Harbor at about 19 meters above lake level averaged 5.64 m/s (12.6 mph). Buoy 45007 to the SE over mid lake experienced cold frontal passage after SGNW3 that day and averaged a wind speed of only 4.53 m/s (10.1 mph) from 2 to 7 p.m. from almost due N in mildly unstable conditions. To the S at Milwaukee Harbor at 11 meters (36'), the mean wind speed from the NNE averaged 4.88 m/s (10.9 mph) from 2 to 7 p.m..

Assuming that the water temperature slightly exceeded the air temperature as it did at Buoy 45007 that afternoon, the shear of the air mass approaching the point at Harrington Beach from the N-NNE that afternoon should have been modest, .15 or lower. Such a shear at Buoy 45007 that afternoon would have resulted in a mean at 27 meters of about 5.8 m/s (13.0 mph) at that location. A similar calculation for SGNW3 using a .15 shear would have resulted in a mean at 27 meters of about 5.95 m/s (13.3 mph) there. A similar calculation for Milwaukee Harbor would have resulted in a mean at 27 meters of about 5.58 m/s (12.5 mph). However, the point at Harrington Beach was significantly windier than all of these calculated values for the 27-meter wind speed at nearby stations.

Possibly, the .15 shear value is too low, but even a .25 shear normally associated with very stable, lighter wind, conditions would not have fully explained the wind speed at Harrington Beach that afternoon.

The wind speed we measured at the point at Harrington Beach was probably locally accelerated by the interaction of the favorable N-NNE wind direction, perhaps augmented by a lake breeze component less established at Sheboygan, and the shape of the local shoreline on the afternoon of August 16

The flying anemometer also might have, but failed to, detect a tendency toward local acceleration at another point in S.E. Wisconsin.

B. Wind Point

We flew successfully at Wind Point on July 25 and at Racine Shoop Park Pier just to the south on August 18, 2003 (see Fig. 2, p. 8). We also attempted to fly unsuccessfully at Wind Point on two other days, but were thwarted by excessive winds on one occasion and threatening thunderstorms on another. On every occasion visited, Wind Point appeared to be windier than other nearby locations. We would have flown there much more frequently if safety issues had not arisen over flying in proximity to tourists common at Wind Point in summer or with respect to keeping the kites away from private property, out of nearby trees, which were abundant at the point, or keeping them from being affected by the turbulence generated by large trees, also abundant nearby. These issues sharply limited the safe wind directions for flying at the point to S and SSW, and because of the accelerated wind at the point, S-SSW winds were frequently too strong for our kites to safely fly there for those directions. This was frustrating, because Wind Point is the most prominent point on Lake Michigan in S.E. Wisconsin. It would have been interesting to evaluate more quantitatively just how aptly it is named (although qualitatively the name seems highly *apropos*).

The first day of readings at the point did not strongly support the hypothesis that it tends to locally accelerate wind speeds. On July 25, from 10:45 a.m. to 16:40 p.m., the flying anemometer reported a mean wind speed of 8.85 m/s (19.8 mph) at a mean height of 30 meters (99') at the point in SSW winds. During the same period, Kenosha Harbor reported a mean of 7.7 m/s (17.2 mph) at 19 m (63') and Milwaukee Harbor reported a mean of 8.7 m/s (19.4 mph) at 11 meters. Under moderately stable conditions suggesting a shear exponent of about .20 in mid lake,[15] Buoy 45007 reported a 5-meter wind speed average of 6.9 m/s (15.4 mph). Using .20 shear at both Buoy 45007 and Milwaukee and adjusting to a 30-meter height, the 30-meter means at these sites would have been 9.9 m/s (22.1 mph) at Buoy 45007 and 10.6 m/s (23.7 mph) at Milwaukee Harbor, somewhat higher than the value reported at Wind Point. Kenosha would likely also have experienced shear in the vicinity of .2 in wind flowing off of a nearby park area to the SSW, suggesting a 30-meter wind speed there of 8.4 m/s (18.9 mph).

The over-water exposure for SSW winds is better at Milwaukee than Kenosha Harbor, so it is not unusual for Milwaukee to be windier than Kenosha for this direction, but we would expect Wind Point to be windier than Milwaukee Harbor. Two possible explanations for why the flying anemometer did not so indicate on this day are (1)

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[15] Using the formula from footnote 8 above, the Buoy 45007 shear exponent would be .204.

the wind speed at the point may have been negatively affected by a tree or trees to the SSW or (2) the anemometer may have been tilted backwards or sideways sufficiently to under-report the wind speed it encountered or both. The sensor cable did hang up on rocks and weeds in the surf that day, and field notes indicated that the anemometer was sometimes leaning to the right (not quantifying the lean). Probably, the flying anemometer under-reported the actual 30 meter wind speed at the point that day, but a tree or trees upwind to the SSW could also have been a factor..

On August 18, we flew at Shoop Park Pier just S of Wind Point from 3:20 to 7:25 p.m. in light SE winds (a problematic direction for the point itself), reporting a mean wind speed of 4.7 m/s (10.5 mph) at 17 meters (57'). This afternoon, Kenosha reported a 19-meter mean of 5.7 m/s (12.8 mph) and Milwaukee Harbor reported an 11-meter mean of 7.0 m/s (15.7 mph) for the same period. Buoy 45007 reported a mean of only 2.1 m/s (4.7 mph) in slightly unstable conditions. This particular day featured a lake breeze in the afternoon, apparently weaker at our location in Shoop Park than at either Kenosha or Milwaukee Harbor. Because we were measuring N of the pier and only a few hundred feet SE of a lakeshore bluff which could have negatively influenced the actual wind speed in front of it as the wind tried to flow around rather than over the bluff at this location, this location probably was less windy for the prevailing wind direction that afternoon than either harbor location. However, the possibility of anemometer lean negatively influencing the reported wind speed cannot be excluded either. As the wind shifted to a more southerly direction on this occasion, the sensor cable, supported on floats in the water, caused the anemometer to lean to the right at times.

Unfortunately, the measurements at Wind Point ultimately proved more helpful in illustrating the need for a mechanism to correct flying anemometer side lean (added in 2004) than in shedding light on the enhancement of winds by the point.

C. Bender Park Bluff

We used the flying anemometer most frequently in a field atop the approximately 100' high lakeshore bluff in Bender Park in S.E. Milwaukee County (see Fig. 2, p. 8). Bender Park is NW of Wind Point about seven miles, situated on a portion of NNW-SSE oriented shoreline topped by a fairly high coastal bluff. In Bender Park itself, the bluff has been smoothed and terraced. It is in grass and low bushes with no significant trees. Immediately to the west of it is a large open field. There are large trees a few hundred yards to the west and moderate-sized trees are closer along the S edge of the property. In our experience flying at Bender Park in 2003, trees tended to come into play for S-SW winds primarily. The site commanded an excellent view out over Lake Michigan to the N-NE-E-SE, and the wind exposure was excellent for these onshore directions. The Oak Creek Power Plant was visible to the SSE about 1.3 mile. Wind flow tended to be much more turbulent and wind exposure notably worse for winds reaching the field from other directions.

A major advantage of the Bender Park field was that it was well off the road and not frequented by pedestrians. It was a safe place to fly.

Another advantage of this site is that it is very close to and overlooks a potential large offshore shallow-water wind farm site. Water of less than 30 meter depth extends out approximately eight miles to the east of the shoreline in Bender Park.

Bender Park is on a bay N of Wind Point. Winds in this area are not necessarily well characterized by the GLERL anemometers at Milwaukee and Kenosha Harbors.

Table 14 below compares the simultaneous flying anemometer averages at Bender Park with Buoy 45007 and Kenosha and Milwaukee Harbors. While well exposed to winds off of the lake and relatively high, our Bender Park measurement location averaged (varying a little from one day to the next) about 700' west of the shoreline.

Table 14: Comparison of Nearby Wind Speeds with Bender Park Measurements
(wind speeds in m/s)

	Flying	Anem	Mea	sure	ment	Com	pari	Son	2003		Buoy	
		Begin	Hgt	WS		KEN	19	MKE	11	450	07 5	AT-
Day	Elev	End	M	m/s	WD	m/s	WD	m/s	WD	m/s	WD	WT
727	680	1430 1730	22	5.54	45	6.84	80	6.15	32	6.63	327	1.25
808	680	1905 0025	16	9.16	30	10.78	8	8.28	23	9.13	350	-.92
809	680	1620 1930	24	5.63	25	7.74	23	4.57	37	6.3	345	-1
817	670	1600 1900	16	3.89	80	3.78	88	3.35	109	4.2	98	-.57
819	680	1815 2235	27	7.47	150	6.7	144	8.67	144	4.74	184	-.7
820	680	1700 2055	30	7.82	170	6.8	162	9.76	147	6.9	166	.28
822	680	1520 1815	22	4.83	35	6.35	17	4.26	49	6.9	13	-1.2
827	680	1455 2230	25	8.05	35	9.18	22	7.65	38	8.95	8	-1.7
828	680	1425 1840	24	6.97	165	7.12	154	8.05	144	7.18	146	-1.1
829	680	2000 2345	19	5.81	80	4.98	75	5.62	59	5.88	358	-1.6
1019	680	1830 2145	13	5.01	85	3.73	106	2.2	83	1.95	113	-3.0

Table 14 shows that there was a tendency for both NE winds and SE winds measured at Bender Park to be less than those at Kenosha Harbor (for NE winds) or those at Milwaukee Harbor (for SE winds). Both Table 14 and the relevant wind roses (Figs. 8-11, pp. 16-19 above) show that Milwaukee Harbor did better for SE winds while Kenosha Harbor did better for NE winds. In both cases, these shoreline locations had higher averages for winds approaching the shore from nearly a right angle. Table 14 shows that the same was true atop the Bender Park Bluff. The wind there was relatively strong compared to Kenosha and Milwaukee Harbors and Buoy 45007 for wind from an easterly direction, which is close to perpendicular to the local shoreline. For winds more nearly parallel to the shoreline, however, Bender Park was less windy relative to the shoreline and offshore locations. There is nothing particularly surprising about this, since the park is next to a bay, and the measurement sites were somewhat inland and above the height of the lakeshore bluff.[16] Overall, the measurements from directions other than east were consistent with some weakening of the winds due to distance inland and/or location on the edge of a bay.

D. Racine North Pier

On August 23, we flew the flying anemometer from Racine North Pier out over a quiet portion of Racine Harbor. That afternoon, it measured an average of 3.76 m/s at an average height of 9 meters while Kenosha Harbor averaged 4.07 m/s at 19 meters, Milwaukee Harbor averaged 4.23 m/s at 11 meters, and Buoy 45007 averaged 3.7 m/s at 5 meters. These measurements provided no particularly valuable insights.

E. Kenosha Beach

Also not particularly valuable were measurements taken above Kenosha Beach on

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[16] It is important to note that the frequently indicated slightly unstable condition (negative air-water temperature difference at Buoy 45007) during Bender Park measurements generally did not apply <u>at</u> Bender Park during SSE measurements. There, it was generally stable for winds off the lake during July-August.

July 20. Unknown to us, the nearby Kenosha Harbor Station was out of commission that day. We recorded a mean of 6.33 m/s at a height of 17 meters on the beach while Milwaukee Harbor reported 6.71 m/s in west winds and Buoy 45007 reported 5.1 m/s in southwest winds.

F. Milwaukee Veterans Park

On August 24, we flew the flying anemometer from a soccer field about .3 mile west of the N Milwaukee Harbor Entrance in gusty SW winds (see Fig. 2, p. 8). For the winds prevailing that day, the GLERL anemometer had an over-water wind fetch over the Milwaukee Harbor of about one mile, while the flying anemometer had about a .4 mile fetch over athletic fields with a few trees of moderate height after about a .5 mile fetch over the harbor. Thus, this day gave some flavor of how being further offshore or closer to the tip of a point by only a modest amount, less than 100 yards in this case, can make a significant difference.

On this occasion, the flying anemometer reported a mean of 7.76 m/s at 26 meters, while the Milwaukee Harbor Anemometer reported a mean of 7.61 m/s at 11 meters. Buoy 45007 reported an average of 7.87 m/s. The Kenosha Harbor, with only 100 yards over-water fetch for this wind direction, reported a mean of 5.78 m/s. Assuming a shear exponent of .15, the flying anemometer probably would have registered an average at 26 meters at Milwaukee Harbor .3 mile east of about 8.66 m/s. This difference of about .9 m/s can be attributed to sticking out into the water just a little bit further for the wind direction on that occasion.

Kenosha was notably less windy on this occasion. Estimating its 26 meter wind speed using a .15 shear exponent at 6.06 m/s as compared to an estimated 8.66 m/s at 26 meters at Milwaukee Harbor, we conclude that much of this difference may have been due to about a mile longer over-water fetch this particular day.

G. Sailing With Flying Anemometer Off Racine

On October 12, we took flying anemometer measurements from a moving sailboat near Racine while sailing from a point 1.8 miles ESE of Wind Point SSW to a point 1.2 miles NE of where County Line Road extended touches Lake Michigan (see Fig. 2, p. 8). Wind speed on this offshore course averaged about 7.2 m/s (16.1 mph) at 23 meters from 274 degrees.

During the same period, Milwaukee Harbor reported a mean wind speed of 6.4 m/s (14.2 mph) from 279 degrees and Kenosha Harbor reported a mean wind speed of 6.2 m/s (13.9 mph) from 265 degrees. Correcting the Milwaukee and Kenosha Harbor measurements to a height of 23 meters assuming a wind shear exponent of .15 on this stable afternoon produces means of 7.1 and 6.2 m/s, respectively.

Kenosha Harbor was one third the distance of Milwaukee Harbor from the midpoint of the course sailed that day. If we take a weighted average of the two, assigning three times as much weight to the closer Kenosha location, and take this as representative of the wind speed at the Racine Harbor Entrance, that value was 6.425 m/s at 23 meters. The mean on the offshore course was thus 12 percent higher than the estimated harbor entrance value.

This apparent enhancement of the wind resource was produced by only about an average 1.2 mile offshore wind fetch on October 12. In general, it is reasonable to expect that the mean wind speed will increase fairly rapidly with offshore distance in the first few miles east of the lakeshore.[17]

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[17] If we look at the near-shore and shoreline stations in S.E. Wisconsin, we observe that only Sheboygan

III. THE FLYING ANEMOMETER HAS PROMISE AS A FUTURE WIND SAMPLING TOOL, BUT IT DOES REQUIRE FURTHER REFINEMENT.

We are pleased with our progress with the flying anemometer over the last year.

Our work with the flying anemometer over the last year has demonstrated that it can sample winds aloft to about 40 meters height with reasonable accuracy if the anemometer spindle is kept reasonably vertical. The device can operate in a strictly kite-lifted mode in winds of about 3.5-11 m/s (8-25 mph). It comes down in lighter winds, and tends to behave erratically in wind gusts exceeding 13 m/s (30 mph), when a supporting kite may start pulling violently to the side or diving.

We have refined the flying anemometer several times in the last year, including since completing the field work associated with the current grant. The current version of the flying anemometer is lighter, stronger, and better at self leveling than its predecessors. It can operate unattended in conjunction with a yaw-mechanism-and-data-logging assembly we developed early this year. That can log wind speed and direction for a period of hours to a few days without attention—if the wind speed remains conttinuously within the safe operating range.

The flying anemometer can fly safely over an open field or a body of water. The flying anemometer itself is designed to float, and sensor cables can be rigged to float.

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is offshore for all wind directions. It is, unsurprisingly, the windiest of the three, averaging a 2001-2003 19-m mean of 5.97 m/s (13.4 mph). Considering the effect of anemometer height, Milwaukee Harbor is second windiest, with a mean of 5.51 m/s (12.3 mph) adjusted to 19 meters (assuming annual average .17 shear exponent), limited by a lakeshore bluff to the northwest and a point to the north. The Kenosha Harbor Anemometer is virtually on the shoreline, being only a little offshore for NNW winds. It had a three-year 19-m average of 5.48 m/s (12.3 mph). The pattern of the means increasing with greater effective distance from the shoreline is clear among these stations. It is even clearer if we compare the three-year mean of the Chicago Crib Anemometer, 7.17 m/s (16.0 mph) at 23 meters, or about 6.97 m/s (15.6 mph) at 19 meters. The location more than 2.5 miles further offshore than Sheboygan is 1 m/s windier. This is not a coincidence. Mean over-water fetch of the wind rapidly increases with distance offshore in the first few miles east of the lakeshore. Mean wind speed should--and does--also increase in this area.

We have flown it over water. It has integral floats/shock absorbers and is highly resistant to damage on impact with the ground. When it comes down to the surface in light winds, it settles gently under the kite, with the kite acting as a parachute. In strong winds, when a diving kite may bring it down to the ground more abruptly, it is also generally undamaged in the process. Indeed, it has been known to come down as a kite dives, hit the ground, and then go right back up again as the supporting kite re-launches itself. On one occasion, it did this and resumed spinning (the anemometer somehow unwrapped the string which had wrapped around its cups on impact).

While we normally use one or more kites to lift the flying anemometer, we have also used a combination of several helium balloons and a kite to do so. The flying anemometer can be kept airborne even in calm winds by the use of balloons. We could keep it up for a few days unattended by such means if gusts stayed below 30 mph.

We plan several near-term improvements in SSE's flying anemometer system:

(1) a reduction in the weight of the current string-pulley suspension system;

(2) a lightweight guard to prevent the string from wrapping around the anemometer spindle or cups when the flying anemometer grounds;

(3) additional tweaking of the balance and self-leveling system and the 2004 yaw system to facilitate unattended operation;

(4) development of a system for sensing the kite string elevation angle so that can be automatically logged as the yaw angle already is;

(5) development of an improved configuration of small kites or another lifting system to improve performance in high-wind conditions; and

(6) development of a lightweight flying data logger or data transmission

system incorporating at least a shaded air temperature sensor[18] to avoid the need for the kite to lift sensor cables (as it does now) and extend the measurement height range to about 90 meters.

We also plan to test the improved flying anemometer near the DeForest Wind Monitoring Site or another instrumented anemometer site to verify its accuracy.

In terms of the potential uses of the flying anemometer, we see it primarily as a near-term wind sampling tool, mostly in kite-lifted configurations. At Global Wind Power 2004, several wind-energy meteorologists expressed some interest in the concept as a wind micro-siting tool, but additional successful accuracy testing would be necessary to sell the device even to these individuals. Longer term, the flying anemometer may have broader applications, including perhaps longer-term measurements in high-value applications such as offshore monitoring at locations where a tower would be prohibitively expensive, but this will require further development. At present, neither balloons nor kites provide a completely suitable lifting means for long-term unattended offshore measurements. High-wind performance is the biggest concern in this context. Once a kite ditches in the water, it will likely not rise again of its own accord, and it could create a hazard to navigation.

We see a need for at least another year of development and testing work on the flying anemometer before it would have any significant sales potential as a product.

While continuing to improve and test the flying anemometer, we plan to use it

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[18] A temperature sensor would be useful for inland and offshore wind applications and non-wind applications, including air pollution studies and air toxic emergency response. It would help evaluate atmospheric stability and low-level inversion height. Other sensors might include compass, GPS and/or sensitive pressure (height) sensors, and the logger could accommodate a plug-in sensor for the toxic substance *du jour*.

primarily to provide wind sampling services. Inland wind sampling above fixed anemometer height is one likely application. Another is offshore sampling from a boat as demonstrated October 12, 2003, off Racine, or from an anchored buoy or another offshore location (e.g., Racine Reef Lighthouse 2.05 miles east of the Racine Lakefront). Another possible application is air pollution studies or toxic air contaminant emergency response. SSE's flying anemometer is highly portable and can be set up quickly by experienced personnel, facilitating this last use. In this connection, it might be used to refine the necessary evacuation area for a toxic chemical spill.

Conclusion

There is a very large wind resource above the S.E. Wisconsin waters of Lake Michigan only a few miles east of the lakeshore. From about three miles out and beyond in non-bay areas, the available wind resource at probable hub height for large-scale offshore wind turbines in the shallows reaches or exceeds 8.5 m/s (19 mph). For locations on the Mid-Lake Plateau further offshore in the region east of Milwaukee, the available wind resource is about 9 m/s (20 mph) or higher. Should hub heights above 80 meters be used, wind resources would be even higher.

Wind measurements in shallow-water regions of the lake or on portions of the Mid-Lake Plateau which might be considered for future offshore wind development would be desirable to verify the apparently excellent offshore wind resource.

SSE's flying anemometer proved to be a useful wind sampling tool in the lakeshore area, although pedestrian and boat traffic made it difficult to use it successfully in close proximity to NOAA lakeshore anemometers to gain direct insight into the wind shear above anemometer height. The flying anemometer proved to be a very useful tool for offshore sampling measurements.

SSE's flying anemometer has near-term potential for use in providing wind sampling services on and offshore and for air pollution or air toxic dispersion studies. If further developed and refined and if further testing verifies reasonable accuracy, its potential uses will likely increase. It may ultimately have some potential for sale as a product.

Reference

Liu, P.C., and Schwab, D.J. 1987. *A Comparison of Methods for Estimating u* from Given* u^z *and Air-sea Temperature Differences.* Journal of Geophysical Research. 92 (C6), 6488-6494.