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Conditional Probability of December and January Ice Cover at Selected Great Lakes Shore Sites

Raymond A. Assel
NOAA, Great Lakes Environmental Research Laboratory, Ann Arbor, MI 48105

Great Lakes Environmental Research Laboratory
Ann Arbor, Michigan

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Raymond A. Assel

INTRODUCTION

The National Weather Service (NWS) in Cleveland, Ohio requested improved information on ice cover for use in making outlooks of early winter ice cover at eight locations in the shore region of the Great Lakes (Fig. 1) (personal communication, Will Kubina). Bilello (1964) developed an empirical water temperature decline model to simulate the date of initial ice formation on bays and harbors. Greene (1983) applied the Billelo model to several sites along the St. Marys River. Assel and Norton (unpublished) applied the model to several additional Great Lakes shore sites, modified it for operational use, and provided it to the NWS in the mid-to-late 1980s. In this paper, empirical freezing degree-day (FDD) conditional probability and linear regression models of spatial average ice cover are described and discussed. These models are applied to the eight sites of interest to the NWS to estimate early winter (December and January) spatial average ice cover.

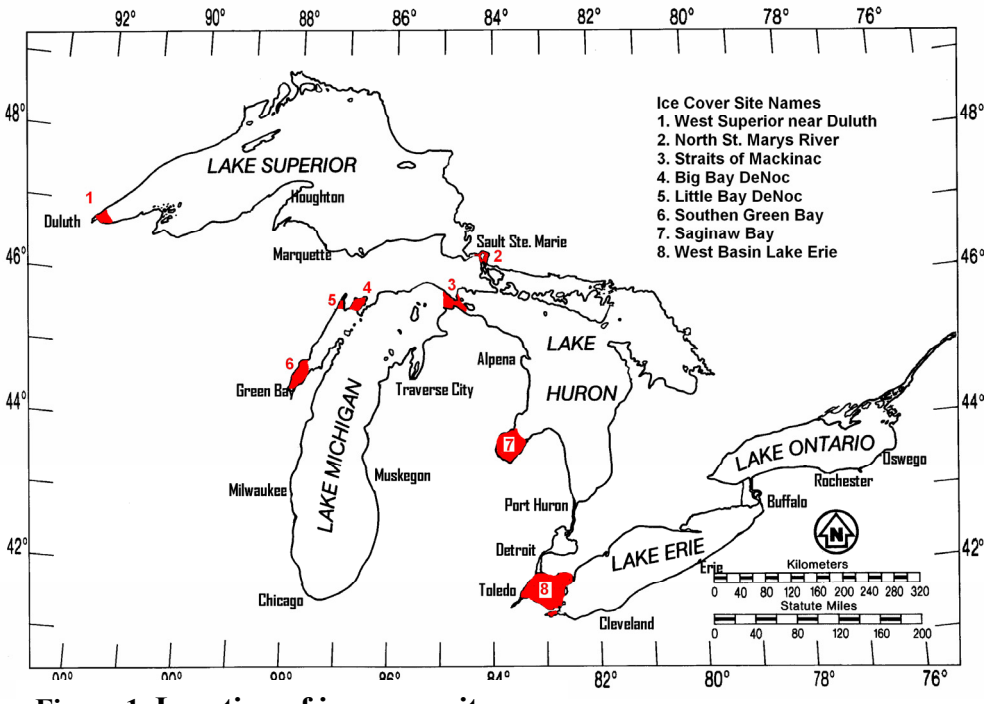

Figure 1. Location of ice cover sites.

METHODS

Accumulated freezing degree-days were related to spatial average ice cover. The FDDs were calculated at stations that the NWS currently maintains for operational applications each winter. FDDs are calculated as the difference between the mean daily air temperature and the freezing point of fresh water. Positive (negative) FDDs accumulate for a given day when the mean daily air temperature is below (above) 32^0F. The daily FDD values are summed to keep a cumulative value through each day from October 1 to May 31. If the cumulative value becomes negative on a given date, a new value is started the next day. FDDs have been found to correlate with spatial average ice cover (Assel 1991).

In this study the spatial averaged ice cover was calculated at the eight sites of interest to the NWS (Table 1). Spatial variations of ice cover on a given date in some of the sites can vary from open water to 100%, because winds can compact the ice cover or move it out of an area. Also some of these areas have sufficient variations in water depths so the shallower areas form ice earlier. For these reasons the spatial average ice cover is most likely to be representative of the entire area of a given site only if it is less than 25% (i.e., the site is mostly open water) or it is over 76% (i.e., the site is mostly ice covered). Spatial averaged ice cover was calculated using original ice cover data, which is on a 5 x 5 km grid cell spatial resolution, and was obtained from digitized ice chart observations given in Assel (2003) over 30 winters:1973-2002. Accumulations of FDDs at selected stations (Table 1) were calculated from October 1 to the date of the observed ice cover at each site for each of the 30-winter seasons. The FDD stations were chosen based on continuity of data record for the 30-winter period of the study and were also based on a statistical correlation analysis between FDD and ice cover.

These data were partitioned into months for further analysis. The empirical conditional probability of 4 ranges of spatial averaged ice cover ($\leq$ 25%, 26-50%, 51-75%, and $\geq$ 76%) was calculated for 10 discrete FDD accumulation ranges (< 200, 200-399, 400-599, 600-799, 800-999, 1000-1199, 1200-1399, 1400-1599, 1600-1799, and1800-1999) for the months of December and January for each of the 8 sites.

These data are presented as ranges of FDD and ranges of spatial averaged ice cover. The FDD on a given date in December or January is used to calculate the *conditional probability* (see Chapter 3 of Meyer 1966) of a spatial average ice cover being in one of the four ranges: 0-25%, 26-50%, 51-75%, 76-100% given a range of FDD values, e.g. 200 - 399 FDD. As an example (from Table 2), the total number of observations for December (at Duluth, Minnesota) for FDD between 200 and 399 is 45. Of this number, 0 occurred for ice cover between 76%-100%, 4 occurred for ice cover between 51%-75%, 9 occurred for ice cover between 26%-50%, and 32 occurred for ice cover between 0%-25%. Therefore the conditional probability of ice cover between 76%-100% for FDD

between 200 and 399 at Duluth in December is 0% [(0/45) x 100), the conditional probability of ice cover between 51%-75% for FDD between 200 and 399 at Duluth in December is 8.9% [(4/45) x 100], the conditional probability of ice cover between 26%-50% for FDD between 200 and 399 at Duluth in December is 20% [(9/45) x 100], and the conditional probability of ice cover between 0%-25% for FDD between 200 and 399 at Duluth in December is 71.1% [(32/45) x 100]. If you add all of the partial conditional probabilities for FDD between 200 and 399 at Duluth for December you get 100% (0% + 8.9% + 20% + 71.1%). In the table 0% conditional probability is replaced by "*" to simplify readability.

Simple linear regression models of FDD vs. ice cover were also developed for each site for December and January. The FDD regression provides an alternative method for estimating spatial average ice cover. Regression equations were calculated using Quattro Pro. Operational application of regression equations are constrained to operate in the range of FDD values for which they will not produce negative ice cover or ice cover greater than 100%. For FDD at the lower limit, the regression output's 0% ice cover and for the upper limit of FDD, the regression output's 100% ice cover. Results are summarized in an Appendix.

Table 1 Ice Sites, FDD Stations, and Site Median Water Depth

Site No.	Name	FDD Station	Depth (m)
1	West Tip of Lake Superior	Duluth, MN	20
2	Northern St. Marys River	Sault Ste. Marie, MI	1
3	Straits of Mackinac	Alpena, MI	13
4	Big Bay De Noc	Green Bay, WI	2
5	Little Bay De Noc	Green Bay, WI	1
6	Southern Green Bay	Green Bay, WI	3
7	Saginaw Bay	Alpena, MI	4
8	West Basin Lake Erie	Toledo, OH	7

RESULTS

The probability of spatial average ice cover falling into one of four ranges (0-25%, 26-50%, 51-75%, 76-100%) conditional on a given FDD range is summarized below for each site for December and January (Table 2 through Table 17). For example, Table 2, for the west tip of Lake Superior, the conditional probability of ice cover in the 0-25% range given FDD accumulations at Duluth, Minnesota in the 0-199 range is 100%. Supplemental information in the table includes the: 1) average of the spatial average ice cover, 2) the average of the FDD, and 3) the number of observations for each spatial ice cover and FDD range. For example in the above case where there was a 100% conditional probability, the ice cover range for the west tip of Lake Superior is 0-25% when the FDD range is 0-199, the average of the spatial average ice cover is 1.2%, the average FDD accumulations is 82.9, and there were 17 observations. This supplemental information is useful for evaluating the degree of confidence one wants to place in the

conditional probability value of ice cover for each table entry. In the above case, one would place a high degree of confidence since the number of observations was relatively large. However, this is not always the case, e.g., in Table 2, the probability of ice cover being between 76% and 100% for FDD between 1000 and 1199 is 71.4%, but this is based on only five observations, so that this conditional probability is tenuous.

Graphs of the spatial average ice cover vs. FDDs for each site for December and January (Figs. 2-17) supplement the data given in Table 2 through Table 17. The graphs also contain a plot (the straight line) of the linear trend in the data. The interval between consecutive axis labels on the graph corresponds to the ice cover and FDD ranges in Table 2 through Table 17. Thus, these graphs provide additional detail about the distribution of the data within each FDD range not given in the Tables. This can be important. For example even though Table 16 indicates that there is a 79% probability that the spatial average ice cover in western Lake Erie will be between 0% and 25% when the FDD at Toledo, Ohio are between 0 and 199, a close look at Figure 16 shows that the probability of 0-25% ice cover between 0 and 100 FDD is much higher than is the probability for 0-25% ice cover between 100 and 199 FDD. These graphs also show where the linear regression model (the straight line) is likely to over-estimate or under-estimate the ice cover.

DISCUSSION

Highlighted entries in Table 2 through Table 17 show where there is a high conditional probability for a given combination of ice cover and FDD ranges. These highlighted entries provide a visual aid for the identification of shifts from a high probability of low spatial average (≤ 25%) to a high probability of high spatial average (≥ 76%) ice cover and for the associated FDD ranges at which they occur. The discussion below briefly describes the highlighted entries for each site and related ancillary information.

Site 1, West Tip of Lake Superior.
This site is exposed to the open expanse of Lake Superior to the east and to a deep near shore trough along the northwest shore. Thus, wind and currents can significantly affect the timing of ice formation and movement independent of air temperature trends as evidenced by the high frequency of ice cover in the 0 - 25% range for FDDs in the 400-599 range (Figs 2-3, Tables 2-3). Assel (1991) found that approximately 1300 FDD were needed for fall cooling of lake waters in the entire west basin of Lake Superior, mean depth 139 m, prior to ice formation in mid-basin areas of that lake.

The probability of low spatial averaged ice cover (0-25%) is high when FDD < 600 occur in both December and January. In December, 67 (17 + 32 + 18) of 97 (17+ 45+ 35) observations were in the 0-25% ice cover range (Table 2), in January, 12 (1+11) of 18 (1+17) were in the 0-25% ice cover range when FDD were < 600 (Table 3). At the other extreme there is a high probability of spatial averaged ice cover ≥ 76% in December for FDD ≥ 1000 and in January for FDD ≥ 800.

Site 2, North St. Marys River.
This site reacts more rapidly to changes in air temperature than site 1 because of its shallower water depth (Table 1). Ice cover is usually ≤ 25% when December FDD is < 200 (Table 4, Fig. 4). Extensive ice cover forms about 46% of the time when FDD are between 200 and 399 (spatial average ice ≥ 76%), but extensive ice cover is more likely to occur when FDD are over 400 (84% of the time). This is also true for January (Table 5, Fig. 5); spatial average ice ≥ 76% occurs about 58% of the time for FDD between 200 and 399, 88% of the time when January FDD are between 400 and 599, and virtually all the time for FDD ≥ 600.

Site 3, Straits of Mackinac.
The Straits of Mackinac area has a median water depth of 13 m. The east-west orientation of the Straits provides a fetch limited environment that is favorable for ice formation. The probability of ice cover ≤ 25% is 96% for FDD < 200 (Fig. 6, Table 6). The average of the spatial average ice cover is 1.8%. This area has a high probability of ice cover ≥ 76% in December when FDD are ≥ 400. The same holds true for January. The probability of ice cover ≤ 25% is 90% for FDD < 200, (Fig. 7, Table 7), and the average of the spatial average ice cover is 5%. At the other extreme, there is a high probability of ice cover ≥ 76% in January when FDD are ≥ 400.

Site 4, Big Bay De Noc.
This is a shallow, protected site (median depth 2 m) at the northern end of Green Bay. There is a 73.8% probability for ice cover ≤ 25% when the FDD accumulation < 200 (Table 8), although there are a few observations with ice cover ≥ 76% for FDD between 100 and 200 (Fig. 8). There is a high probability (79% in December, 71% in January) of extensive ice cover (average of spatial average > 97%) when FDDs ≥ 200 (Table 8, Table 9, Figs. 8-9).

Site 5, Little Bay De Noc.
This site is similar to Big Bay De Noc, i.e., a very shallow protected site that responds rapidly to low FDD accumulations. There is a 77.5% probability for ice cover ≤ 25% when FDD is between 0 and 199 (Table 10). However, there is also a 10% chance of ice cover ≥ 76% when FDD are between 100 and 199 (Fig. 10). There is high probability (66.7% in December, 71.7% in January) of extensive ice cover (average of spatial average > 90%) when FDDs ≥ 200 at Green Bay (Table 10, Table 11, Figs. 10-11).

Site 6, Southern Green Bay.
Water depths are similar to the two sites at the north end of Green Bay (sites 4 and 5). Air temperatures are milder. There is a 78.8% probability for ice cover ≤ 25% when FDD at Green Bay, Wisconsin is between 0 and 199 (Table 12) and an almost a 100% chance of ice cover ≤ 25% for FDD ≤ 100 (Fig. 12) . There is a relatively high probability (62.5% in December, 65% in January) of extensive ice cover (average of spatial average > 90%) when FDDs ≥ 200 at Green Bay (Table 12, Table 13, Figs. 12-13). The probability of ice cover ≥ 76% increases to 100% (December) and 98.6% (January) for FDD ≥ 400.

Site 7, Saginaw Bay.
Saginaw Bay has a median depth of 4 m. For December, it can be seen (Fig. 14) that the frequency of ice cover < 25% is large for FDD ≤ 100, and the frequency of ice cover ≥ 76% becomes large when FDD are between 100 and 200. Saginaw Bay has a high probability of ice cover ≥ 76% for FDD ≥ 200 (Table 14). Thus, the transition between lower amounts of ice cover and extensive ice cover occurs between 100 and 200 FDD. The same pattern holds true for January (Table 15, Fig. 15).

Site 8, West Lake Erie.
Western Lake Erie has a median depth of 7 m. In December, there is a high probability of low ice cover, ≤ 25%, when FDD are ≤100 (Fig. 16). (This is consistent with Assel (1991) who found approximately 50 FDD were associated with fall cooling of west basin waters prior to ice formation.) The transition to a probability of higher ice cover, ≥ 76%, occurs for FDDs between 100 and 200. Ice cover ≥ 76% is virtually certain for FDD ≥ 200 (Table 16). There is a greater probability of ice cover ≥ 76% for FDD < 200 in January compared to December and a lower probability of ice cover ≤ 25% (Table 17, Fig. 17). The low ice cover for FDD between approximately 300 and 500 in January (Fig. 17) is due to winters with anomalous declines in ice cover in January (for example: 1974, 1988, 1990, 1999). Of these winters, 1990 is perhaps most notable. In that winter, (Assel and Norton, 1991) an unusually cold December (1989) was followed by a mild January (1990) resulting in a large ice loss in Lake Erie in January, preceded by an anomalous high ice cover in the last half of December. Never the less there is a high probability of high ice cover (≥ 76%) in January for FDD ≥ 200).

CONCLUDING REMARKS

If either regression or conditional probability model is to be used in a forecast mode, the user (NWS) needs air temperature forecasts in order to calculate FDDs. Monthly air temperature forecasts are available from NOAA's Climate Prediction Center's Monthly and Seasonal Forecasts at:
http://www.cpc.ncep.noaa.gov/products/forecasts/month_to_season_outlooks.html .
In any case, the modeled ice cover should be used in conjunction with all other pertinent information (e.g., water temperature anomaly, antecedent ice conditions) that is available at the time the ice cover outlook is being formulated. As the user becomes familiar with these tables, graphs, and regression equations, it is hoped that he / she will gain insight and judgment for the appropriate application and interpretation of these data.

The author wishes to thank Will Kubina at WFO Cleveland for reviewing this report and making comments relative to its application in developing improved operational forecast of early-winter ice cover.

Table 2. Site 1, West Tip of Lake Superior, December FDDs At Duluth MN.

ICE COVER RANGE	FDD RANGE 0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999
Ice Cover Range Probability (%) Contingent on FDD Range										
76 - 100	*	*	20.0	45.7	46.7	71.4	100.0	*	*	*
51 - 75	*	8.9	8.6	20.0	6.7	14.3	*	*	*	*
26 - 50	*	20.0	20.0	8.6	*	14.3	*	*	*	*
0 - 25	100.0	71.1	51.4	25.7	46.7	*	*	*	*	*
Average Ice Cover (%)										
76 - 100	*	*	89.0	88.4	90.1	94.6	100.0	*	*	*
51 - 75	*	56.3	56.0	61.1	58.0	62.0	*	*	*	*
26 - 50	*	36.2	41.4	41.0	*	38.0	*	*	*	*
0 - 25	1.2	8.4	9.2	9.6	10.6	*	*	*	*	*
Average FDD (°F)										
76 - 100	*	*	498.6	691.1	916.7	1083.4	1220.0	*	*	*
51 - 75	*	316.8	571.0	694.0	826.0	1001.0	*	*	*	*
26 - 50	*	314.4	484.1	673.0	*	1021.0	*	*	*	*
0 - 25	82.9	322.3	495.9	723.4	889.7	*	*	*	*	*
Number of Observations										
76 - 100	*	*	7.0	16.0	7.0	5.0	1.0	*	*	*
51 - 75	*	4.0	3.0	7.0	1.0	1.0	*	*	*	*
26 - 50	*	9.0	7.0	3.0	*	1.0	*	*	*	*
0 - 25	17.0	32.0	18.0	9.0	7.0	*	*	*	*	*
Total No.	17.	45.	35.	35.	15.	7.	1.	0.	0.	0.

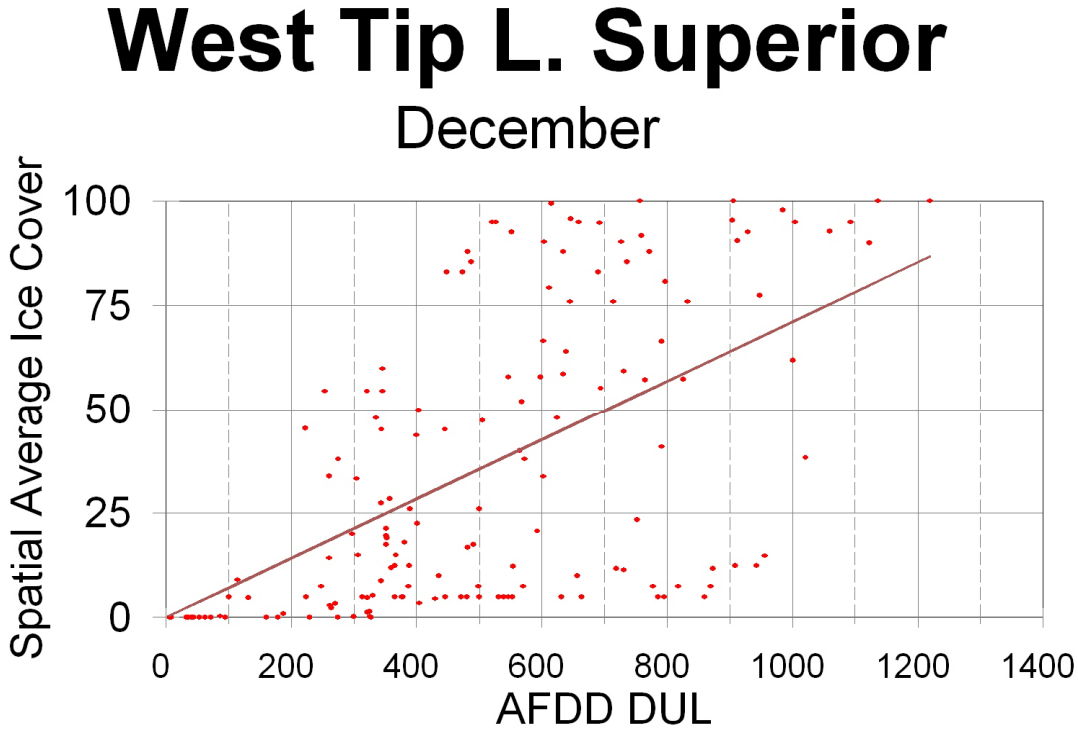

Figure 2. Site 1, West Tip of Lake Superior, December FDDs At Duluth MN.

Table 3. Site 1, West Tip of Lake Superior, January FDDs At Duluth MN.

ICE COVER RANGE	FDD RANGE 0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999
Ice Cover Range Probability (%) Contingent on FDD Range										
76 - 100	*	*	5.9	25.7	61.2	69.7	75.0	74.1	84.6	100.0
51 - 75	*	*	5.9	28.6	20.4	7.6	2.3	18.5	7.7	*
26 - 50	*	*	23.5	20.0	6.1	7.6	13.6	7.4	7.7	*
0 - 25	*	100.0	64.7	25.7	12.2	15.2	9.1	*	*	*
Average Ice Cover (%)										
76 - 100	*	*	98.0	89.0	87.3	94.4	97.6	95.7	99.3	99.6
51 - 75	*	*	64.0	65.1	60.1	67.6	66.0	65.4	55.0	*
26 - 50	*	*	38.8	37.4	35.3	40.6	38.5	41.0	44.0	*
0 - 25	*	8.0	8.2	8.7	9.0	11.4	10.3	*	*	*
Average FDD (°F)										
76 - 100	*	*	424.0	741.1	902.7	1103.4	1303.2	1497.5	1671.8	1887.4
51 - 75	*	*	582.0	720.9	869.5	1128.4	1343.0	1514.8	1779.0	*
26 - 50	*	*	491.3	711.0	937.7	1073.0	1307.0	1458.0	1722.0	*
0 - 25	*	391.0	506.5	669.2	895.0	1083.5	1267.5	*	*	*
Number of Observations										
76 - 100	*	*	1.0	9.0	30.0	46.0	33.0	20.0	11.0	5.0
51 - 75	*	*	1.0	10.0	10.0	5.0	1.0	5.0	1.0	*
26 - 50	*	*	4.0	7.0	3.0	5.0	6.0	2.0	1.0	*
0 - 25	*	1.0	11.0	9.0	6.0	10.0	4.0	*	*	*
Total No.	0.	1.	17.	35.	49.	66.	44.	27.	13.	5.

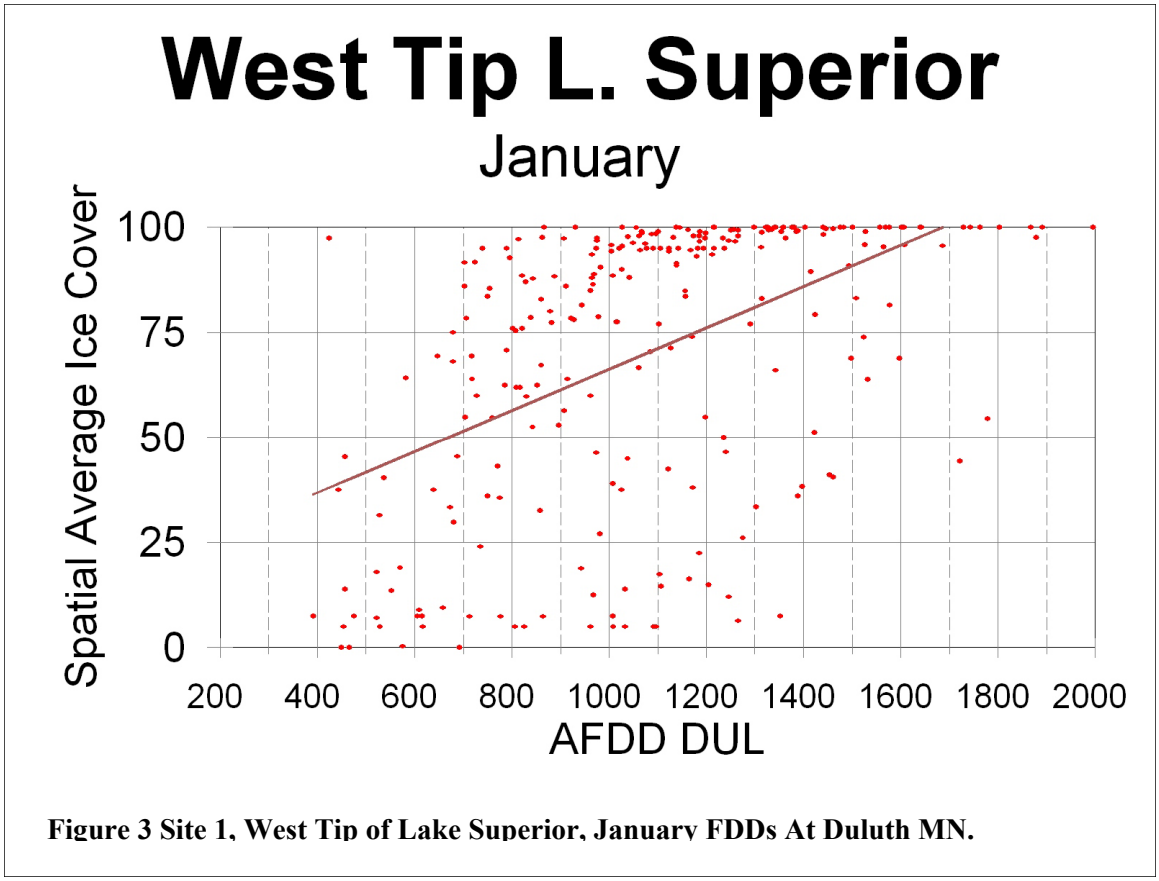

Figure 3 Site 1, West Tip of Lake Superior, January FDDs At Duluth MN.

Table 4. Site 2, North St. Marys River, December FDDs at Sault Ste. Marie, MI.

ICE COVER RANGE	FDD RANGE 0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999
Ice Cover Range Probability (%) Contingent on FDD Range										
76 - 100	4.1	46.0	84.2	100.0	100.0	*	*	*	*	*
51 - 75	4.1	26.0	10.5	*	*	*	*	*	*	*
26 - 50	8.2	4.0	5.3	*	*	*	*	*	*	*
0 - 25	83.6	24.0	*	*	*	*	*	*	*	*
Average Ice Cover (%)										
76 - 100	86.7	91.7	94.6	96.1	97.5	*	*	*	*	*
51 - 75	63.0	65.2	60.0	*	*	*	*	*	*	*
26 - 50	34.3	40.0	45.0	*	*	*	*	*	*	*
0 - 25	1.6	5.7	*	*	*	*	*	*	*	*
Average FDD (°F)										
76 - 100	151.3	299.2	494.7	658.6	857.0	*	*	*	*	*
51 - 75	103.0	291.6	437.5	*	*	*	*	*	*	*
26 - 50	83.5	302.0	414.0	*	*	*	*	*	*	*
0 - 25	94.7	248.3	*	*	*	*	*	*	*	*
Number of Observations										
76 - 100	3.0	23.0	16.0	9.0	4.0	*	*	*	*	*
51 - 75	3.0	13.0	2.0	*	*	*	*	*	*	*
26 - 50	6.0	2.0	1.0	*	*	*	*	*	*	*
0 - 25	61.0	12.0	*	*	*	*	*	*	*	*
Total No.	73.	50.	19.	9.	4.	0.	0.	0.	0.	0.

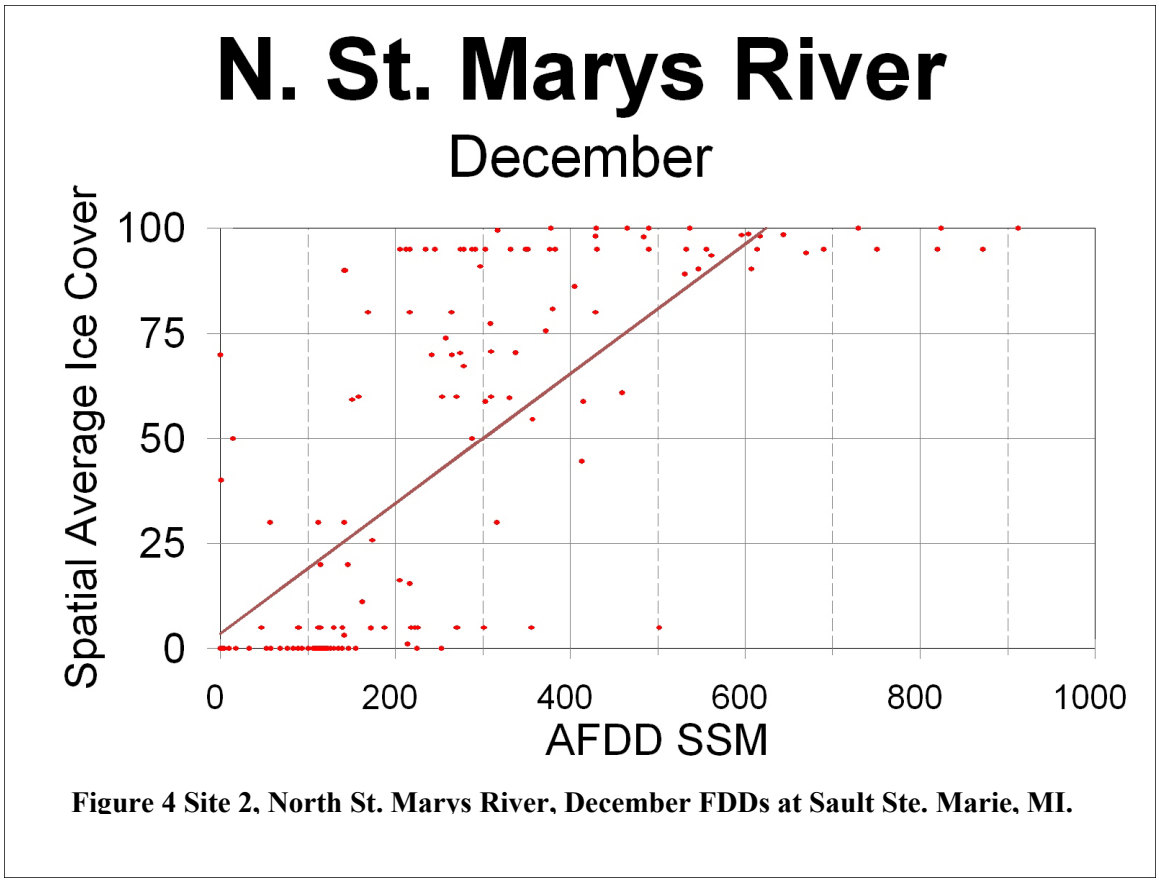

Figure 4 Site 2, North St. Marys River, December FDDs at Sault Ste. Marie, MI.

Table 5. Site 2, North St. Marys River, January FDDs at Sault Ste. Marie, MI.

ICE COVER RANGE	FDD RANGE 0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999
Ice Cover Range Probability (%) Contingent on FDD Range										
76 - 100	40.0	58.3	88.5	98.6	100.0	100.0	100.0	100.0	*	*
51 - 75	20.0	14.6	9.6	1.4	*	*	*	*	*	*
26 - 50	*	12.5	*	*	*	*	*	*	*	*
0 - 25	40.0	14.6	1.9	*	*	*	*	*	*	*
Average Ice Cover (%)										
76 - 100	87.5	91.8	95.9	97.7	98.8	100.0	100.0	100.0	*	*
51 - 75	70.0	64.0	70.0	73.0	*	*	*	*	*	*
26 - 50	*	41.7	*	*	*	*	*	*	*	*
0 - 25	2.5	7.7	5.0	*	*	*	*	*	*	*
Average FDD (°F)										
76 - 100	173.0	338.4	505.6	699.3	896.0	1091.5	1295.2	1511.0	*	*
51 - 75	141.0	337.9	446.4	685.0	*	*	*	*	*	*
26 - 50	*	324.8	*	*	*	*	*	*	*	*
0 - 25	159.0	300.6	439.0	*	*	*	*	*	*	*
Number of Observations										
76 - 100	2.0	28.0	46.0	72.0	35.0	30.0	13.0	1.0	*	*
51 - 75	1.0	7.0	5.0	1.0	*	*	*	*	*	*
26 - 50	*	6.0	*	*	*	*	*	*	*	*
0 - 25	2.0	7.0	1.0	*	*	*	*	*	*	*
Total No.	5.	48.	52.	73.	35.	30.	13.	1.	0.	0.

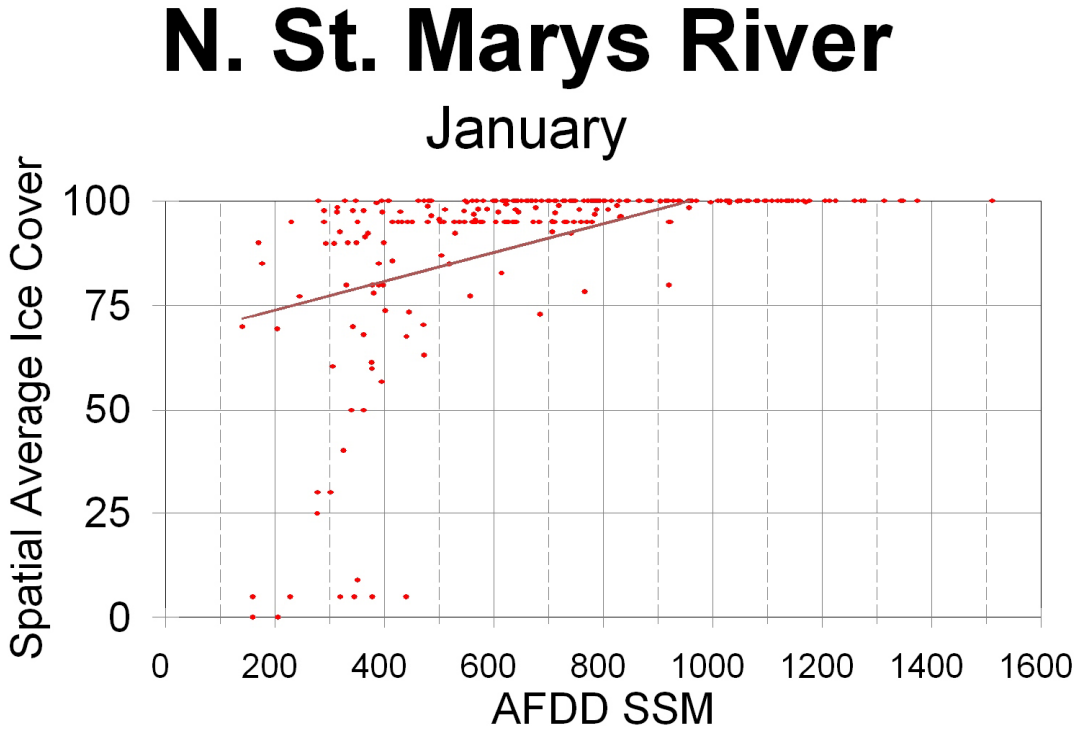

Figure 5 Site 2, North St. Marys River, January FDDs at Sault Ste. Marie, MI.

Table 6. Site 3, Straits of Mackinac, December FDDs at Alpena, MI.

ICE COVER RANGE	FDD RANGE 0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999
Ice Cover Range Probability (%) Contingent on FDD Range										
76 - 100	*	6.7	80.0	100.0	*	*	*	*	*	*
51 - 75	1.8	10.0	20.0	*	*	*	*	*	*	*
26 - 50	1.8	30.0	*	*	*	*	*	*	*	*
0 - 25	96.4	53.3	*	*	*	*	*	*	*	*
Average Ice Cover (%)										
76 - 100	*	85.0	84.8	96.4	*	*	*	*	*	*
51 - 75	55.5	58.7	67.5	*	*	*	*	*	*	*
26 - 50	41.5	39.7	*	*	*	*	*	*	*	*
0 - 25	1.8	6.1	*	*	*	*	*	*	*	*
Average FDD (°F)										
76 - 100	*	357.0	455.0	659.6	*	*	*	*	*	*
51 - 75	187.5	338.7	493.0	*	*	*	*	*	*	*
26 - 50	169.0	293.1	*	*	*	*	*	*	*	*
0 - 25	71.8	256.5	*	*	*	*	*	*	*	*
Number of Observations										
76 - 100	*	2.0	8.0	5.0	*	*	*	*	*	*
51 - 75	2.0	3.0	2.0	*	*	*	*	*	*	*
26 - 50	2.0	9.0	*	*	*	*	*	*	*	*
0 - 25	106.0	16.0	*	*	*	*	*	*	*	*
Total No.	110.	30.	10.	5.	0.	0.	0.	0.	0.	0.

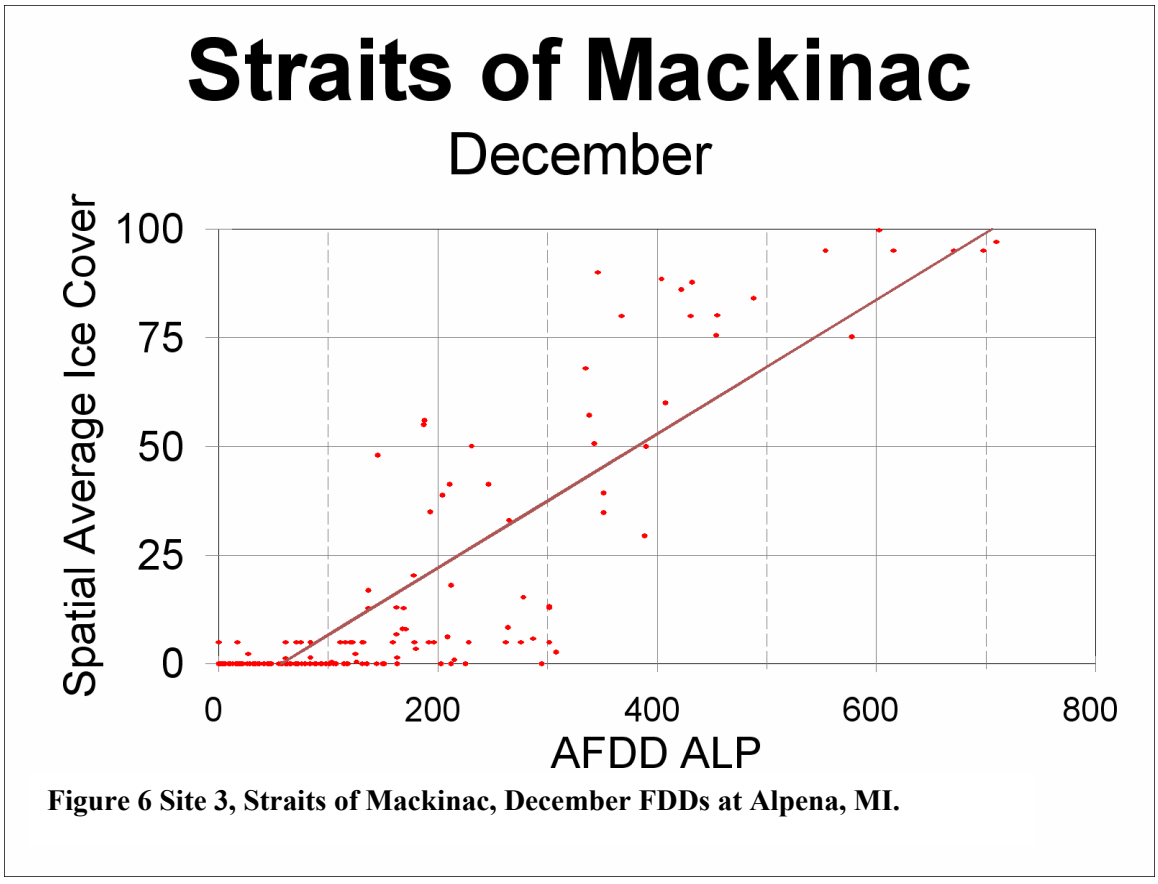

Figure 6 Site 3, Straits of Mackinac, December FDDs at Alpena, MI.

Table 7. Site 3, Straits of Mackinac, January FDD at Alpena, MI.

ICE COVER RANGE	FDD RANGE 0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999
Ice Cover Range Probability (%) Contingent on FDD Range										
76 - 100	2.4	42.2	93.8	95.2	100.0	100.0	*	*	*	*
51 - 75	2.4	16.9	4.6	4.8	*	*	*	*	*	*
26 - 50	4.9	15.7	1.5	*	*	*	*	*	*	*
0 - 25	90.2	25.3	*	*	*	*	*	*	*	*
Average Ice Cover (%)										
76 - 100	81.0	92.5	93.6	96.7	98.2	100.0	*	*	*	*
51 - 75	65.0	65.6	72.3	63.5	*	*	*	*	*	*
26 - 50	27.5	43.8	40.0	*	*	*	*	*	*	*
0 - 25	5.0	10.6	*	*	*	*	*	*	*	*
Average FDD (°F)										
76 - 100	197.0	330.2	488.9	717.5	860.1	1086.5	*	*	*	*
51 - 75	188.0	300.1	520.0	688.5	*	*	*	*	*	*
26 - 50	150.0	276.9	525.0	*	*	*	*	*	*	*
0 - 25	143.9	254.4	*	*	*	*	*	*	*	*
Number of Observations										
76 - 100	1.0	35.0	61.0	40.0	24.0	2.0	*	*	*	*
51 - 75	1.0	14.0	3.0	2.0	*	*	*	*	*	*
26 - 50	2.0	13.0	1.0	*	*	*	*	*	*	*
0 - 25	37.0	21.0	*	*	*	*	*	*	*	*
Total No.	41.	83.	65.	42.	24.	2.	0.	0.	0.	0.

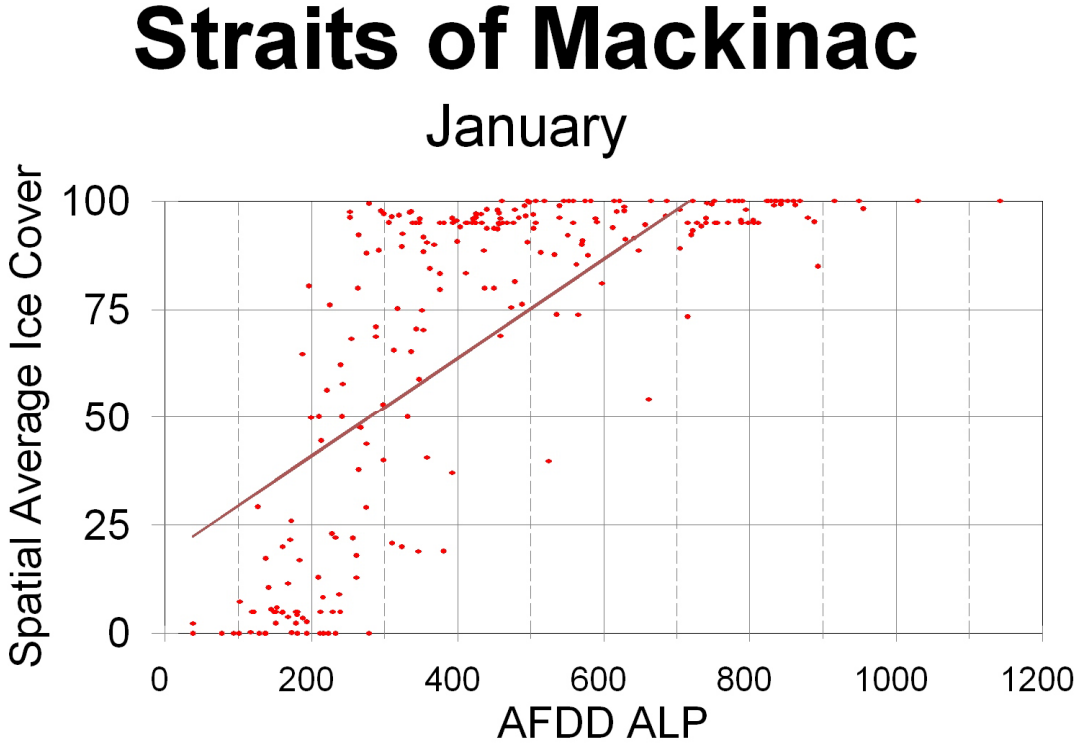

Figure 7 Site 3, Straits of Mackinac, January FDDs at Alpena, MI.

Table 8. Site 4, Big Bay De Noc, December FDDs at Green Bay WI.

ICE COVER RANGE		FDD RANGE 0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999
		Ice Cover Range Probability (%) Contingent on FDD Range									
76 - 100	13.8	79.2	88.2	100.0	100.0	*	*	*	*	*	
51 - 75	6.3	8.3	5.9	*	*	*	*	*	*	*	
26 - 50	6.3	4.2	5.9	*	*	*	*	*	*	*	
0 - 25	73.8	8.3	*	*	*	*	*	*	*	*	
		Average Ice Cover (%)									
76 - 100	88.5	91.6	97.9	97.9	100.0	*	*	*	*	*	
51 - 75	58.2	65.5	60.0	*	*	*	*	*	*	*	
26 - 50	33.8	27.5	40.0	*	*	*	*	*	*	*	
0 - 25	3.7	6.5	*	*	*	*	*	*	*	*	
		Average FDD (°F)									
76 - 100	159.3	293.8	500.7	683.8	873.0	*	*	*	*	*	
51 - 75	127.2	260.5	496.0	*	*	*	*	*	*	*	
26 - 50	145.2	271.5	462.0	*	*	*	*	*	*	*	
0 - 25	72.2	268.5	*	*	*	*	*	*	*	*	
		Number of Observations									
76 - 100	11.0	38.0	15.0	9.0	1.0	*	*	*	*	*	
51 - 75	5.0	4.0	1.0	*	*	*	*	*	*	*	
26 - 50	5.0	2.0	1.0	*	*	*	*	*	*	*	
0 - 25	59.0	4.0	*	*	*	*	*	*	*	*	
Total No.	80.	48.	17.	9.	1.	0.	0.	0.	0.	0.	

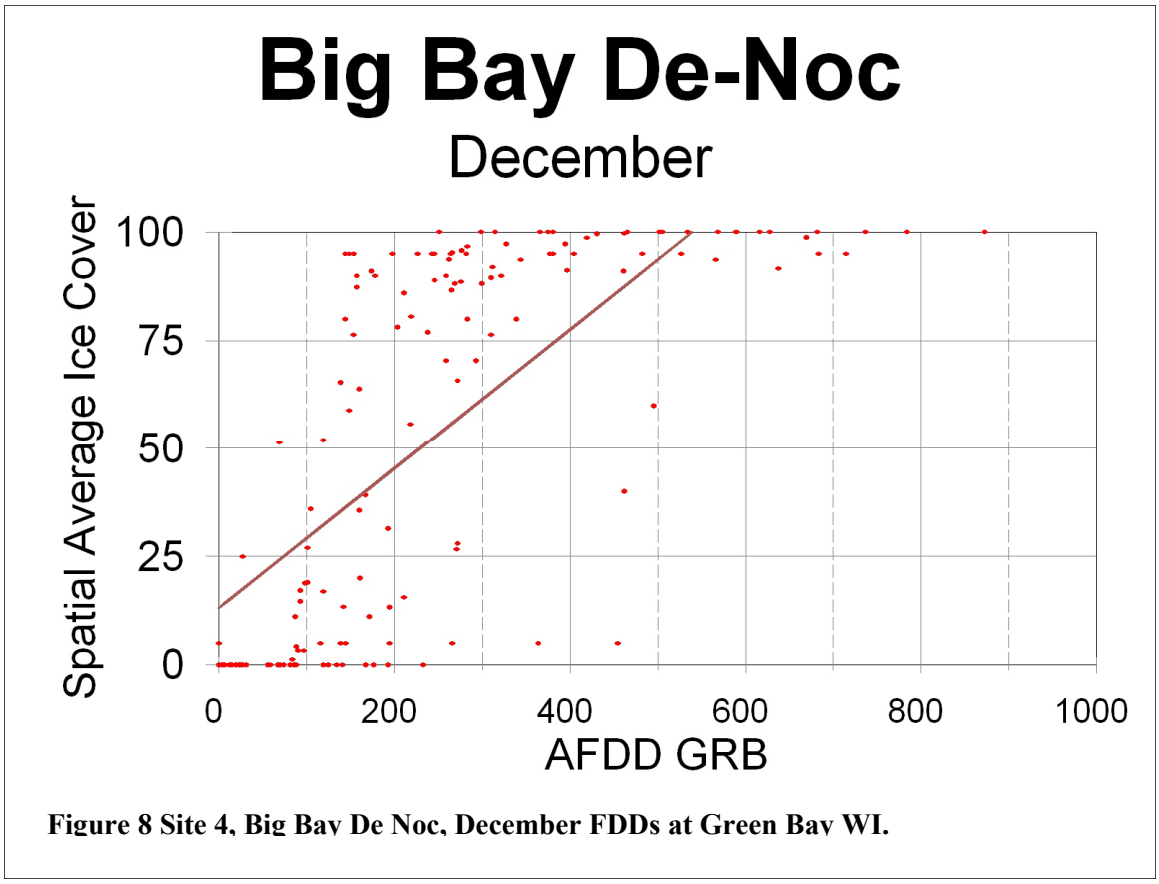

Figure 8 Site 4, Big Bay De Noc, December FDDs at Green Bay WI.

Table 9. Site 4, Big Bay De Noc, January FDDs at Green Bay WI.

ICE COVER RANGE		FDD RANGE 0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999	
					Ice Cover Range Probability (%) Contingent on FDD Range							
76 - 100	33.3	71.7	97.3	100.0	100.0	100.0	100.0	100.0	100.0		*	
51 - 75	22.2	13.3	*	*	*	*	*	*	*		*	
26 - 50	33.3	10.0	2.7	*	*	*	*	*	*		*	
0 - 25	11.1	5.0	*	*	*	*	*	*	*		*	
					Average Ice Cover (%)							
76 - 100	89.3	97.1	98.4	99.6	99.9	100.0	100.0	100.0	100.0		*	
51 - 75	62.0	59.8	*	*	*	*	*	*	*		*	
26 - 50	37.7	36.7	45.0	*	*	*	*	*	*		*	
0 - 25	3.0	9.7	*	*	*	*	*	*	*		*	
					Average FDD (°F)							
76 - 100	182.3	313.9	504.7	706.2	867.3	1075.6	1285.0	1518.0	1642.0		*	
51 - 75	180.0	294.3	*	*	*	*	*	*	*		*	
26 - 50	169.0	318.5	486.5	*	*	*	*	*	*		*	
0 - 25	127.0	288.3	*	*	*	*	*	*	*		*	
					Number of Observations							
76 - 100	3.0	43.0	71.0	50.0	47.0	13.0	3.0	1.0	1.0		*	
51 - 75	2.0	8.0	*	*	*	*	*	*	*		*	
26 - 50	3.0	6.0	2.0	*	*	*	*	*	*		*	
0 - 25	1.0	3.0	*	*	*	*	*	*	*		*	
Total No.	9.	60.	73.	50.	47.	13.	3.	1.	1.		0.	

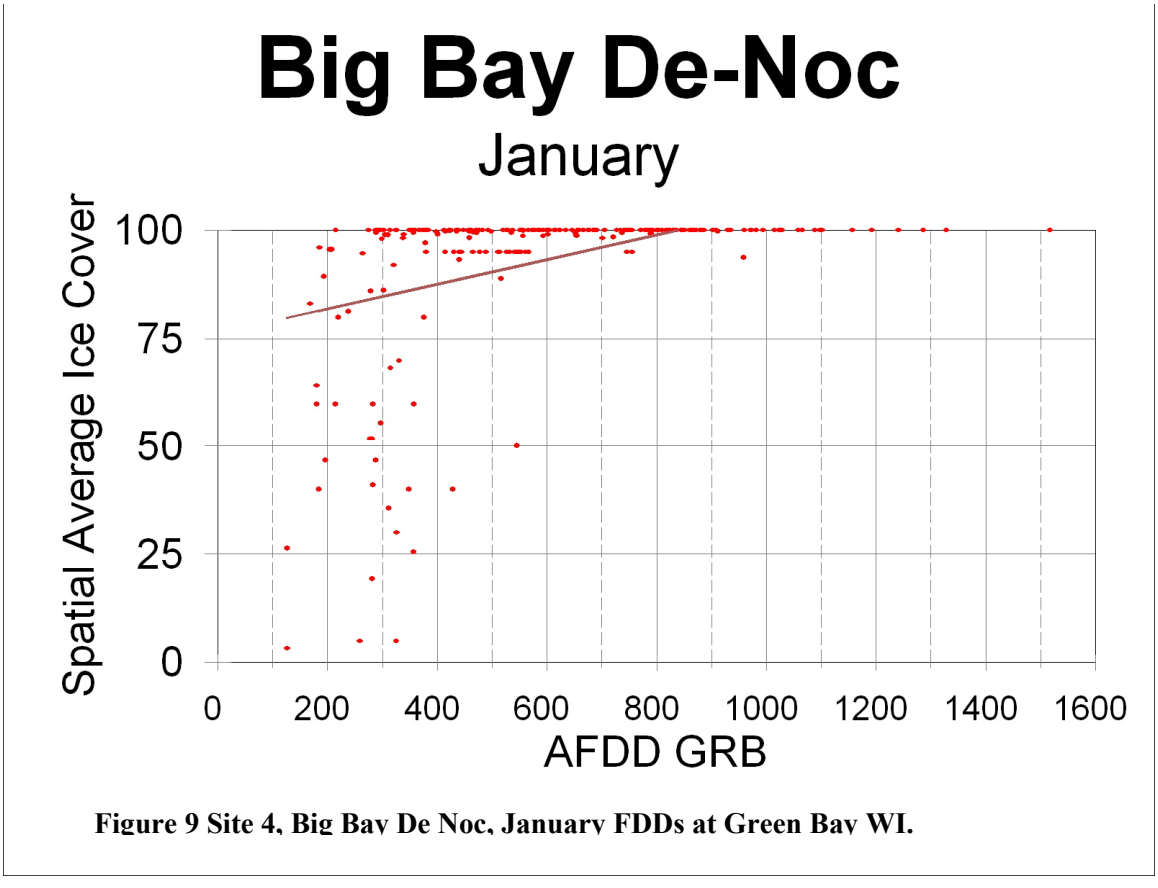

Figure 9 Site 4, Big Bay De Noc, January FDDs at Green Bay WI.

Table 10. Site 5, Little Bay De Noc, December FDDs at Green Bay WI.

ICE COVER RANGE		FDD RANGE 0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999
		Ice Cover Range Probability (%) Contingent on FDD Range									
76 - 100	11.3	66.7	88.2	100.0	100.0	*	*	*	*	*	
51 - 75	5.0	8.3	5.9	*	*	*	*	*	*	*	
26 - 50	6.3	12.5	5.9	*	*	*	*	*	*	*	
0 - 25	77.5	12.5	*	*	*	*	*	*	*	*	
		Average Ice Cover (%)									
76 - 100	88.1	91.9	96.3	97.6	100.0	*	*	*	*	*	
51 - 75	59.0	64.8	60.0	*	*	*	*	*	*	*	
26 - 50	33.6	34.5	40.0	*	*	*	*	*	*	*	
0 - 25	4.7	11.5	*	*	*	*	*	*	*	*	
		Average FDD (°F)									
76 - 100	153.7	293.1	500.7	683.8	873.0	*	*	*	*	*	
51 - 75	158.3	271.8	496.0	*	*	*	*	*	*	*	
26 - 50	91.6	276.0	462.0	*	*	*	*	*	*	*	
0 - 25	79.0	283.5	*	*	*	*	*	*	*	*	
		Number of Observations									
76 - 100	9.0	32.0	15.0	9.0	1.0	*	*	*	*	*	
51 - 75	4.0	4.0	1.0	*	*	*	*	*	*	*	
26 - 50	5.0	6.0	1.0	*	*	*	*	*	*	*	
0 - 25	62.0	6.0	*	*	*	*	*	*	*	*	
Total No.	80.	48.	17.	9.	1.	0.	0.	0.	0.	0.	

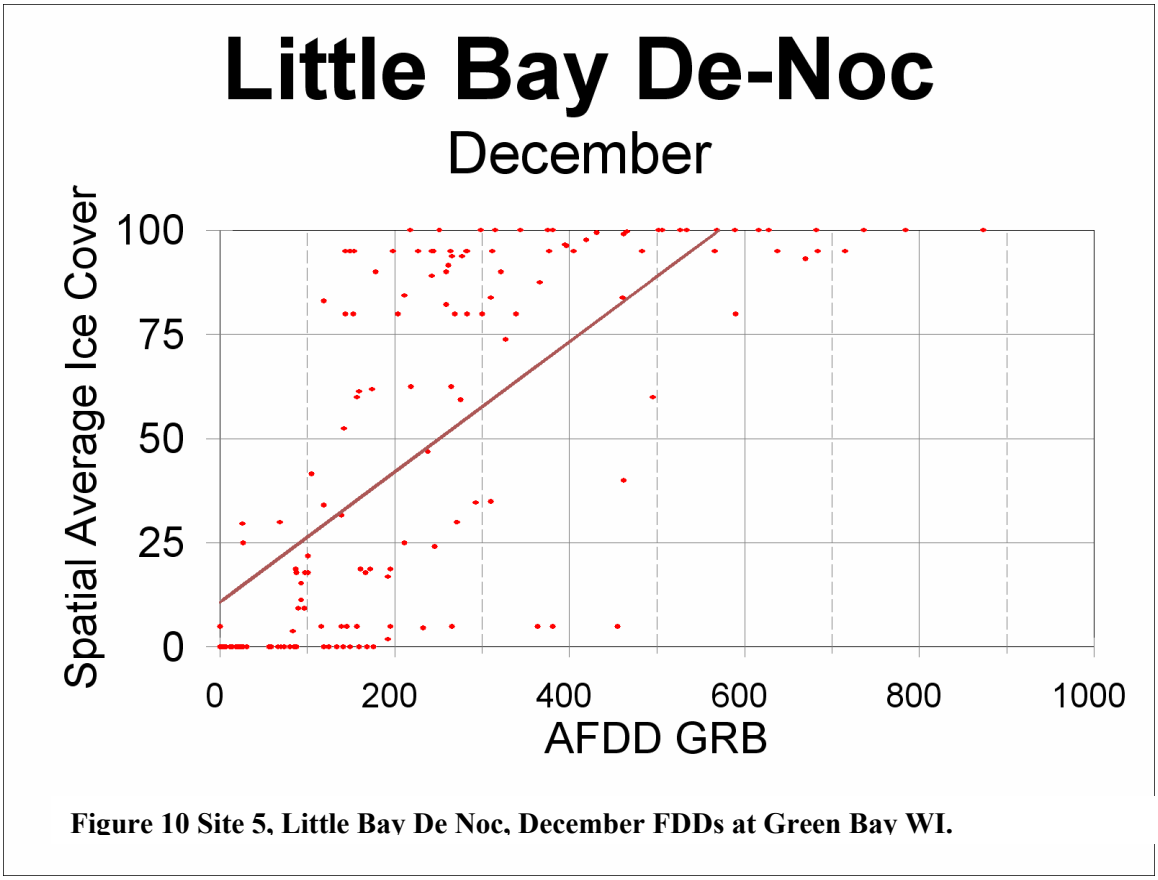

Figure 10 Site 5, Little Bay De Noc, December FDDs at Green Bay WI.

Table 11. Site 5, Little Bay De Noc, January FDDs at Green Bay WI.

ICE COVER RANGE		FDD RANGE 0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999	
		Ice Cover Range Probability (%) Contingent on FDD Range										
76 - 100	11.1	71.7	98.6	100.0	100.0	100.0	100.0	100.0	100.0		*	
51 - 75	33.3	11.7	1.4	*	*	*	*	*	*		*	
26 - 50	22.2	11.7	*	*	*	*	*	*	*		*	
0 - 25	33.3	5.0	*	*	*	*	*	*	*		*	
		Average Ice Cover (%)										
76 - 100	100.0	94.3	97.8	99.3	99.7	100.0	100.0	100.0	100.0		*	
51 - 75	62.0	59.1	70.0	*	*	*	*	*	*		*	
26 - 50	38.0	40.4	*	*	*	*	*	*	*		*	
0 - 25	8.7	10.0	*	*	*	*	*	*	*		*	
		Average FDD (°F)										
76 - 100	169.0	321.1	504.0	706.2	867.3	1075.6	1285.0	1518.0	1642.0		*	
51 - 75	187.3	278.4	521.0	*	*	*	*	*	*		*	
26 - 50	153.5	286.3	*	*	*	*	*	*	*		*	
0 - 25	167.7	288.3	*	*	*	*	*	*	*		*	
		Number of Observations										
76 - 100	1.0	43.0	72.0	50.0	47.0	13.0	3.0	1.0	1.0		*	
51 - 75	3.0	7.0	1.0	*	*	*	*	*	*		*	
26 - 50	2.0	7.0	*	*	*	*	*	*	*		*	
0 - 25	3.0	3.0	*	*	*	*	*	*	*		*	
Total No.	9.	60.	73.	50.	47.	13.	3.	1.	1.		0.	

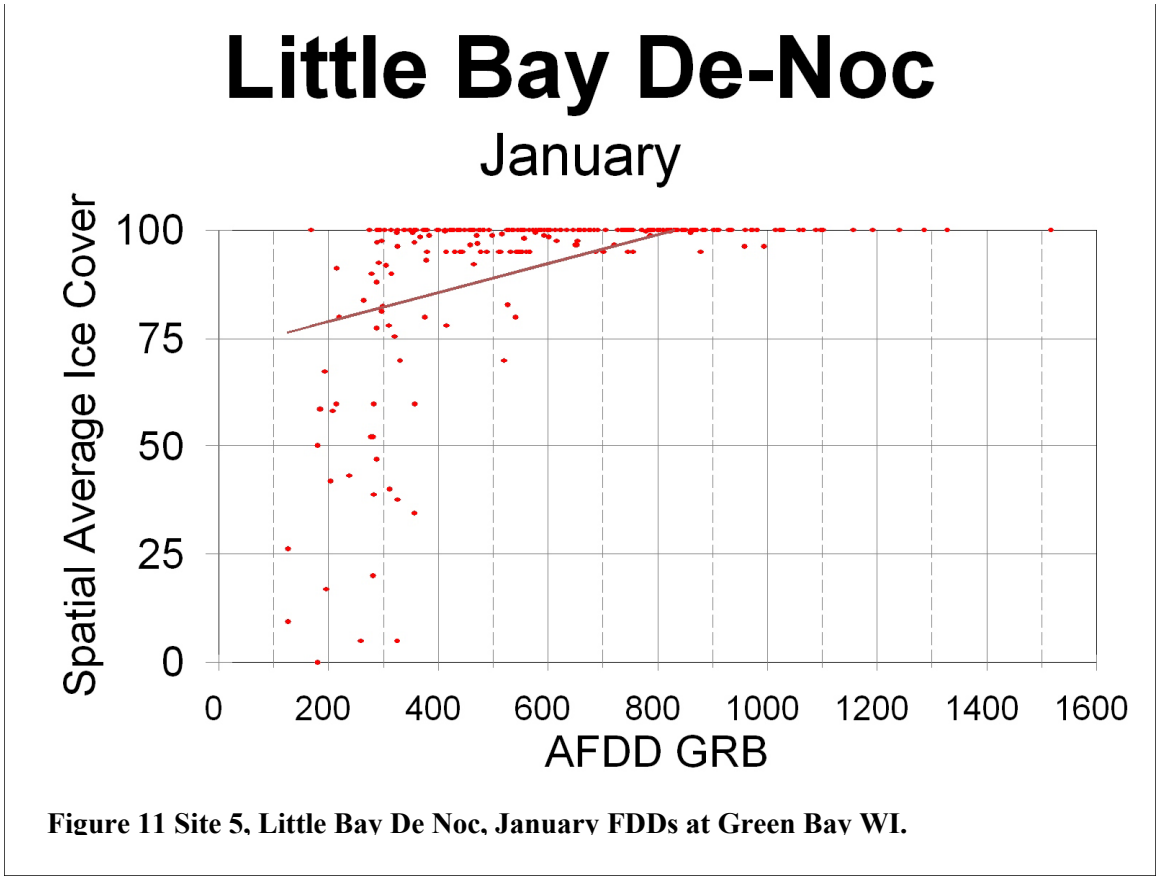

Figure 11 Site 5, Little Bay De Noc, January FDDs at Green Bay WI.

Table 12. Site 6, South Green Bay, December FDDs at Green Bay, WI.

ICE COVER RANGE		FDD RANGE 0 199	200 399	400 599	600 799	800 999	1000 1199	1200 1399	1400 1599	1600 1799	1800 1999
				Ice Cover Range Probability (%) Contingent on FDD Range							
76 - 100	7.5	62.5	100.0	100.0	100.0	*	*	*	*	*	
51 - 75	6.3	20.8	*	*	*	*	*	*	*	*	
26 - 50	7.5	6.3	*	*	*	*	*	*	*	*	
0 - 25	78.8	10.4	*	*	*	*	*	*	*	*	
				Average Ice Cover (%)							
76 - 100	82.3	90.4	96.5	98.2	100.0	*	*	*	*	*	
51 - 75	63.2	67.2	*	*	*	*	*	*	*	*	
26 - 50	36.0	41.0	*	*	*	*	*	*	*	*	
0 - 25	2.7	2.6	*	*	*	*	*	*	*	*	
				Average FDD (°F)							
76 - 100	158.5	301.0	498.1	683.8	873.0	*	*	*	*	*	
51 - 75	140.0	276.6	*	*	*	*	*	*	*	*	
26 - 50	170.0	257.7	*	*	*	*	*	*	*	*	
0 - 25	74.6	250.6	*	*	*	*	*	*	*	*	
				Number of Observations							
76 - 100	6.0	30.0	17.0	9.0	1.0	*	*	*	*	*	
51 - 75	5.0	10.0	*	*	*	*	*	*	*	*	
26 - 50	6.0	3.0	*	*	*	*	*	*	*	*	
0 - 25	63.0	5.0	*	*	*	*	*	*	*	*	
Total No.	80.	48.	17.	9.	1.	0.	0.	0.	0.	0.	

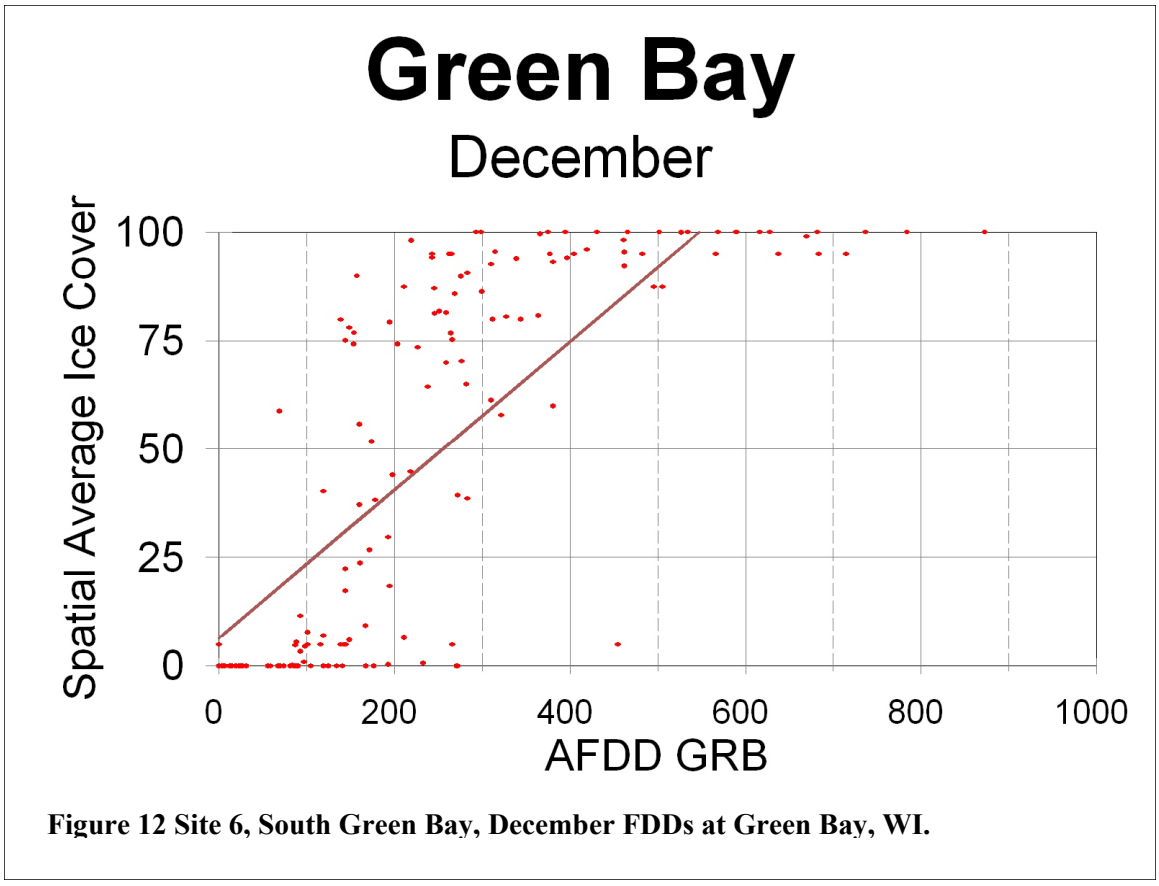

Figure 12 Site 6, South Green Bay, December FDDs at Green Bay, WI.

Table 13. Site 6, South Green Bay, January FDDs at Green Bay, WI.

ICE COVER RANGE	FDD RANGE 0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999	
Ice Cover Range Probability (%) Contingent on FDD Range											
76 - 100	33.3	65.0	98.6	100.0	100.0	100.0	100.0	100.0	100.0		*
51 - 75	22.2	13.3	1.4	*	*	*	*	*	*		*
26 - 50	11.1	6.7	*	*	*	*	*	*	*		*
0 - 25	33.3	15.0	*	*	*	*	*	*	*		*
Average Ice Cover (%)											
76 - 100	90.0	93.2	97.1	99.4	99.0	100.0	100.0	100.0	100.0		*
51 - 75	71.5	63.6	72.0	*	*	*	*	*	*		*
26 - 50	36.0	33.5	*	*	*	*	*	*	*		*
0 - 25	2.3	10.7	*	*	*	*	*	*	*		*
Average FDD (°F)											
76 - 100	186.0	321.3	505.3	706.2	867.3	1075.6	1285.0	1518.0	1642.0		*
51 - 75	176.5	291.8	428.0	*	*	*	*	*	*		*
26 - 50	180.0	277.0	*	*	*	*	*	*	*		*
0 - 25	150.0	294.8	*	*	*	*	*	*	*		*
Number of Observations											
76 - 100	3.0	39.0	72.0	50.0	47.0	13.0	3.0	1.0	1.0		*
51 - 75	2.0	8.0	1.0	*	*	*	*	*	*		*
26 - 50	1.0	4.0	*	*	*	*	*	*	*		*
0 - 25	3.0	9.0	*	*	*	*	*	*	*		*
Total No.	9.	60.	73.	50.	47.	13.	3.	1.	1.		0.

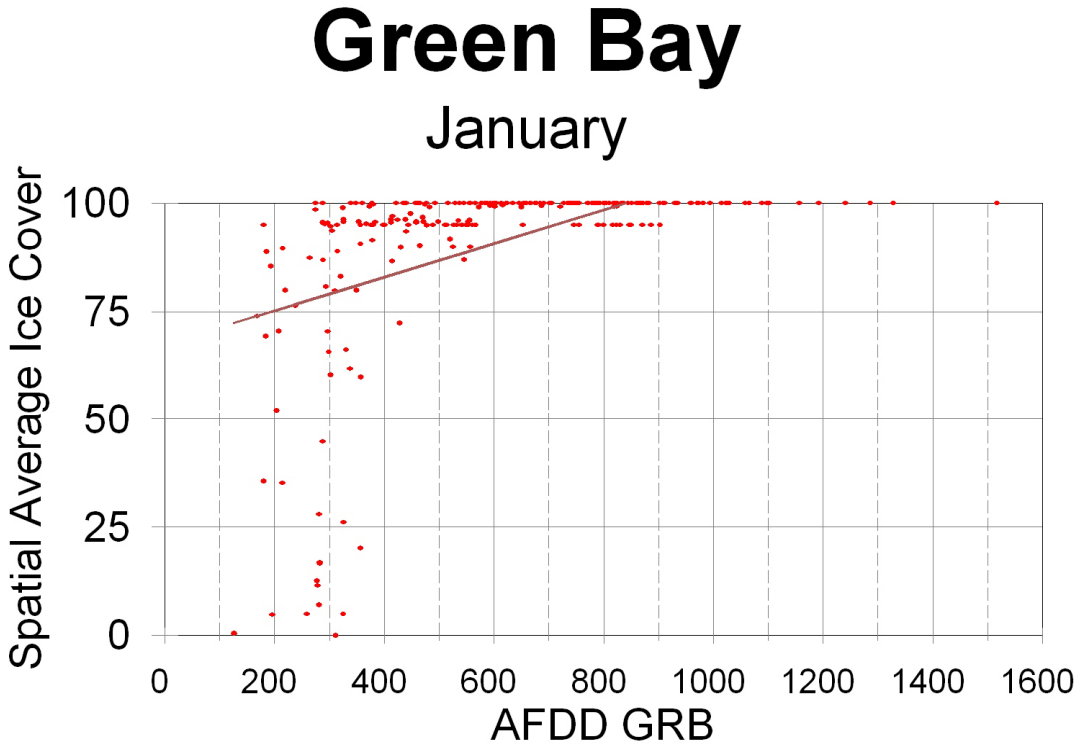

Figure 13 Site 6, South Green Bay, January FDDs at Green Bay, WI.

Table 14. Site 7, Saginaw Bay, December FDDs at Alpena, MI.

ICE COVER RANGE		FDD RANGE 0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999
				Ice Cover Range Probability (%) Contingent on FDD Range							
76 - 100	12.7	83.3	100.0	100.0	*	*	*	*	*	*	
51 - 75	5.5	6.7	*	*	*	*	*	*	*	*	
26 - 50	11.8	*	*	*	*	*	*	*	*	*	
0 - 25	70.0	10.0	*	*	*	*	*	*	*	*	
				Average Ice Cover (%)							
76 - 100	88.6	92.7	97.3	97.0	*	*	*	*	*	*	
51 - 75	59.0	64.0	*	*	*	*	*	*	*	*	
26 - 50	35.8	*	*	*	*	*	*	*	*	*	
0 - 25	1.8	14.3	*	*	*	*	*	*	*	*	
				Average FDD (°F)							
76 - 100	147.6	292.7	462.6	659.6	*	*	*	*	*	*	
51 - 75	129.2	216.0	*	*	*	*	*	*	*	*	
26 - 50	140.2	*	*	*	*	*	*	*	*	*	
0 - 25	47.6	241.0	*	*	*	*	*	*	*	*	
				Number of Observations							
76 - 100	14.0	25.0	10.0	5.0	*	*	*	*	*	*	
51 - 75	6.0	2.0	*	*	*	*	*	*	*	*	
26 - 50	13.0	*	*	*	*	*	*	*	*	*	
0 - 25	77.0	3.0	*	*	*	*	*	*	*	*	
Total No.	110.	30.	10.	5.	0.	0.	0.	0.	0.	0.	

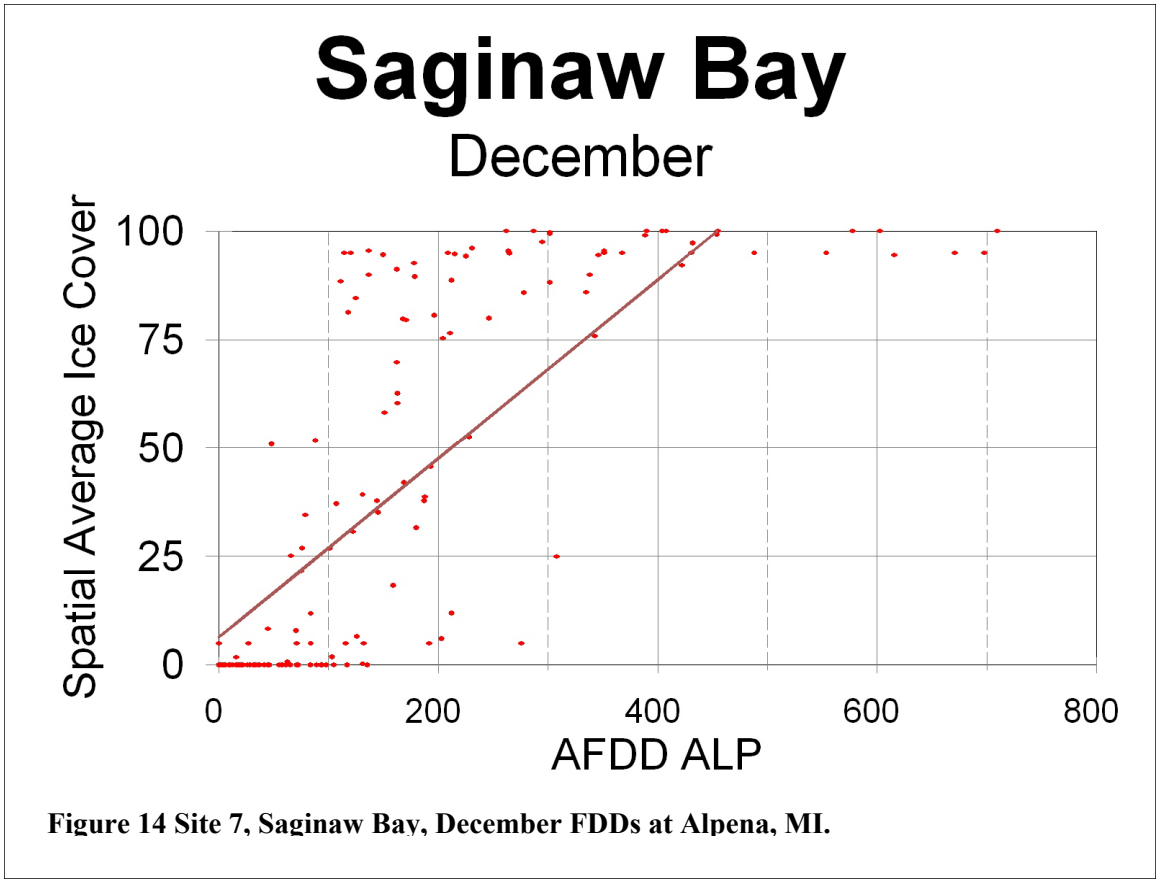

Figure 14 Site 7, Saginaw Bay, December FDDs at Alpena, MI.

Table 15. Site 7, Saginaw Bay, January FDDs at Alpena, MI.

ICE COVER RANGE	FDD RANGE 0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999
Ice Cover Range Probability (%) Contingent on FDD Range										
76 - 100	61.0	86.7	100.0	100.0	100.0	100.0	*	*	*	*
51 - 75	12.2	8.4	*	*	*	*	*	*	*	*
26 - 50	9.8	1.2	*	*	*	*	*	*	*	*
0 - 25	17.1	3.6	*	*	*	*	*	*	*	*
Average Ice Cover (%)										
76 - 100	90.7	94.5	97.4	98.5	98.5	100.0	*	*	*	*
51 - 75	64.0	62.3	*	*	*	*	*	*	*	*
26 - 50	37.3	29.0	*	*	*	*	*	*	*	*
0 - 25	4.4	4.0	*	*	*	*	*	*	*	*
Average FDD (°F)										
76 - 100	155.4	305.4	490.9	716.1	860.1	1086.5	*	*	*	*
51 - 75	149.6	263.1	*	*	*	*	*	*	*	*
26 - 50	177.8	229.0	*	*	*	*	*	*	*	*
0 - 25	94.9	214.0	*	*	*	*	*	*	*	*
Number of Observations										
76 - 100	25.0	72.0	65.0	42.0	24.0	2.0	*	*	*	*
51 - 75	5.0	7.0	*	*	*	*	*	*	*	*
26 - 50	4.0	1.0	*	*	*	*	*	*	*	*
0 - 25	7.0	3.0	*	*	*	*	*	*	*	*
Total No.	41.	83.	65.	42.	24.	2.	0.	0.	0.	0.

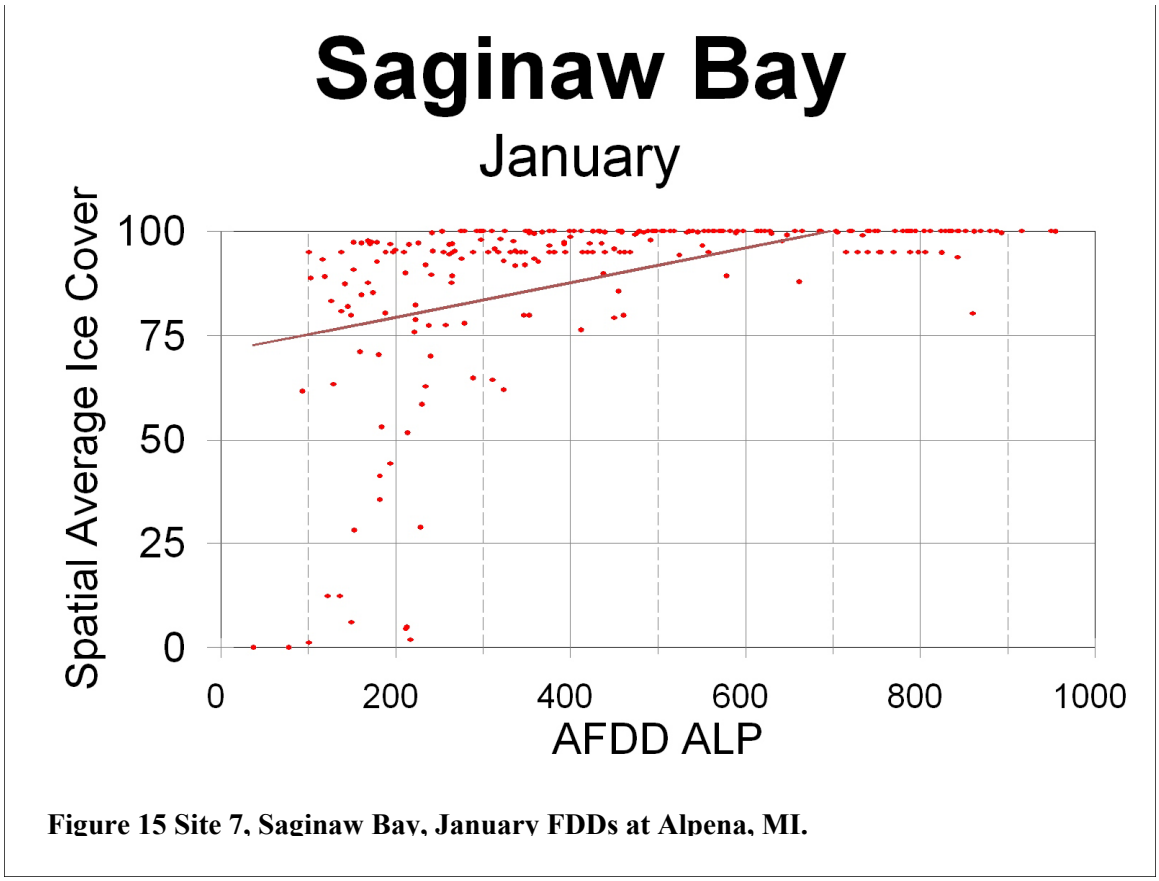

Figure 15 Site 7, Saginaw Bay, January FDDs at Alpena, MI.

Table 16. Site 8, West Lake Erie, December FDDs at Toledo, OH.

ICE COVER RANGE		FDD RANGE 0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999
				Ice Cover Range Probability (%) Contingent on FDD Range							
76 - 100	7.5	93.8	100.0	*	*	*	*	*	*	*	
51 - 75	3.7	*	*	*	*	*	*	*	*	*	
26 - 50	9.7	*	*	*	*	*	*	*	*	*	
0 - 25	79.1	6.3	*	*	*	*	*	*	*	*	
				Average Ice Cover (%)							
76 - 100	88.2	91.8	95.8	*	*	*	*	*	*	*	
51 - 75	60.2	*	*	*	*	*	*	*	*	*	
26 - 50	35.8	*	*	*	*	*	*	*	*	*	
0 - 25	2.9	24.0	*	*	*	*	*	*	*	*	
				Average FDD (°F)							
76 - 100	134.4	278.2	451.6	*	*	*	*	*	*	*	
51 - 75	101.8	*	*	*	*	*	*	*	*	*	
26 - 50	89.6	*	*	*	*	*	*	*	*	*	
0 - 25	24.1	202.0	*	*	*	*	*	*	*	*	
				Number of Observations							
76 - 100	10.0	15.0	5.0	*	*	*	*	*	*	*	
51 - 75	5.0	*	*	*	*	*	*	*	*	*	
26 - 50	13.0	*	*	*	*	*	*	*	*	*	
0 - 25	106.0	1.0	*	*	*	*	*	*	*	*	
Total No.	134.	16.	5.	0.	0.	0.	0.	0.	0.	0.	

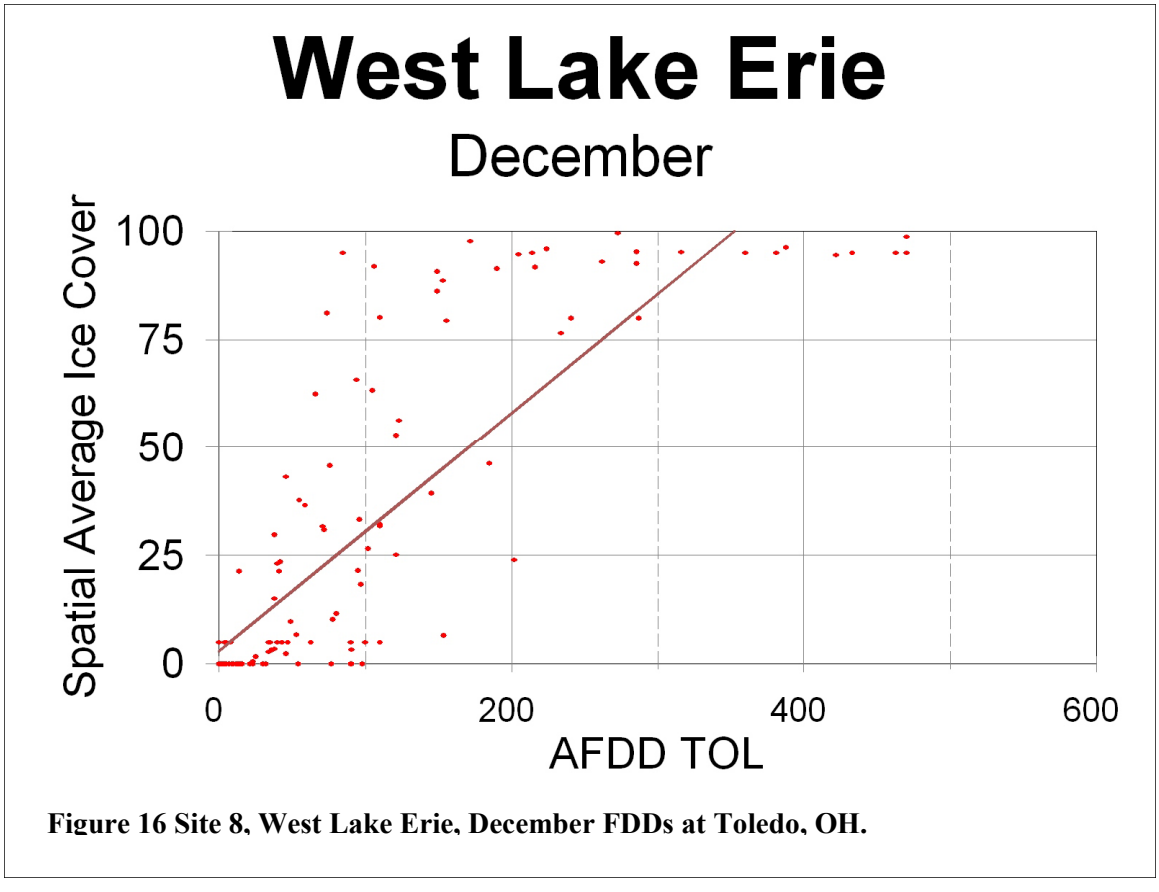

Figure 16 Site 8, West Lake Erie, December FDDs at Toledo, OH.

Table 17. Site 8, West Lake Erie, January FDDS at Toledo, OH.

ICE COVER RANGE		FDD RANGE 0 - 199	200 - 399	400 - 599	600 - 799	800 - 999	1000 - 1199	1200 - 1399	1400 - 1599	1600 - 1799	1800 - 1999
		Ice Cover Range Probability (%) Contingent on FDD Range									
76 - 100	34.8	78.8	94.2	100.0	100.0	*	*	*	*	*	
51 - 75	14.9	11.5	5.8	*	*	*	*	*	*	*	
26 - 50	14.2	3.8	*	*	*	*	*	*	*	*	
0 - 25	36.2	5.8	*	*	*	*	*	*	*	*	
		Average Ice Cover (%)									
76 - 100	89.2	93.6	95.2	98.6	99.7	*	*	*	*	*	
51 - 75	62.4	67.3	63.3	*	*	*	*	*	*	*	
26 - 50	38.7	41.0	*	*	*	*	*	*	*	*	
0 - 25	8.0	19.0	*	*	*	*	*	*	*	*	
		Average FDD (°F)									
76 - 100	120.9	298.0	473.9	632.3	878.7	*	*	*	*	*	
51 - 75	103.0	285.0	438.0	*	*	*	*	*	*	*	
26 - 50	113.7	391.0	*	*	*	*	*	*	*	*	
0 - 25	54.2	384.0	*	*	*	*	*	*	*	*	
		Number of Observations									
76 - 100	49.0	41.0	49.0	9.0	3.0	*	*	*	*	*	
51 - 75	21.0	6.0	3.0	*	*	*	*	*	*	*	
26 - 50	20.0	2.0	*	*	*	*	*	*	*	*	
0 - 25	51.0	3.0	*	*	*	*	*	*	*	*	
Total No.	141.	52.	52.	9.	3.	0.	0.	0.	0.	0.	

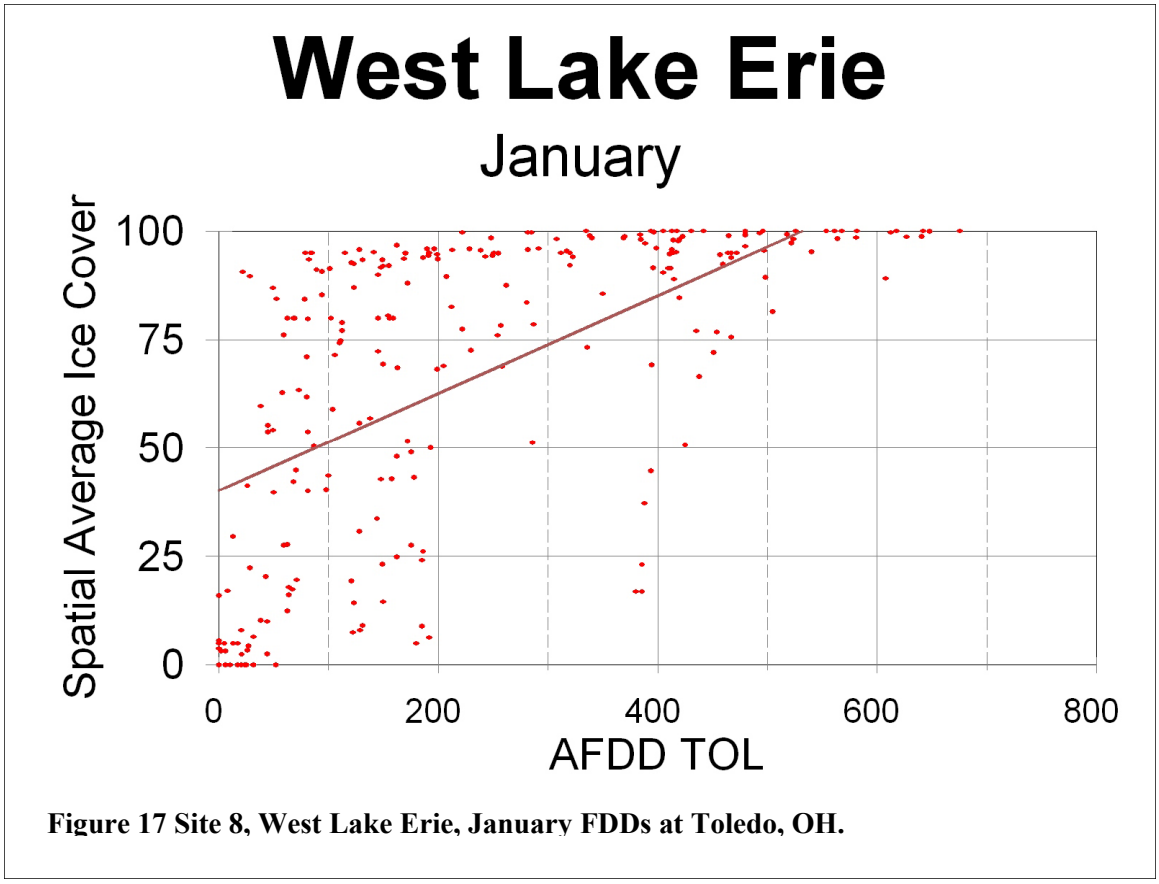

Figure 17 Site 8, West Lake Erie, January FDDs at Toledo, OH.

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APPENDIX SUMMARY OF REGRESSION ANALYSIS.

Following is a tabular summary of a linear regression analysis of spatial average ice cover for each of the eight ice sites and the FDD stations used for the regressions. Note that the regression equations should be used only between the upper and lower bound of the FDD values given for each site. For values above the upper limit, the spatial average ice cover is assumed to be 100%, for values below the lower limit, the ice cover is assumed to be zero in December, and the value it would have had at the lower limit in January.

The regression equation coefficients, B and C in the table below, are artifacts of the combination of meteorological station location relative to the ice site and local ice site conditions (water depth, water motion [currents, springs, and river outlets], shore configuration and topography, and possibly others). The December regression intercept term, B, is zero at five of the eight (Straits of Mackinac, Big Bay De Noc, and Little Bay De Noc being the exceptions). A zero intercept means that when FDDs are zero, the ice cover is also zero. The intercept terms for the January regression equations are not zero because there is extensive ice cover at these eight sites during January most winters. The fact the January intercept term is > 65 at five of the eight sites indicates that these sites usually have an extensive ice cover even in early January for most winters. Exceptions occur for the West Tip of Lake Superior, Straits of Mackinac, and West Lake Erie. These three sites have deeper waters then the other sites and so contain more heat to retard ice formation. The proximity of deeper off-shore waters [and milder air temperatures and the Detroit River in the case of west Lake Erie] are contributing factors for observed lower intercept term. The other regression equation coefficient, C, in the table below, is a measure of the rate of increase in spatial average ice cover relative to the rate of increase in FDDs. In December, it is largest for West Lake Erie and smallest for West Superior (Fig. A-1). In January, it is largest for Saginaw Bay (West Lake Erie a close second) and again smallest for West Lake Superior (Fig. A-2).

Ice Site No. and Name	FDD Station used for Regression Analysis Ice = B + C x FDD	December						January					
		B	C	SE	R^2	FDD Range		B	C	SE	R^2	FDD Range	
						Lower	Upper					Lower	Upper
1. West Superior	Duluth	0	0.0711	28.2	0.34	0	1406	17.1	0.04916	28.9	0.24	391	1686
2. North St. Marys River	Sault Ste Marie	0	0.1655	27.9	0.55	0	604	67.1	0.03438	18.1	0.23	141	957
3. Straits of Mackinac	Alpena	-8.7	0.1549	14.3	0.74	57	701	17.9	0.1144	25.4	0.53	38	716
4. Big Bay De Noc	Green Bay	12.9	0.1640	29.1	0.54	0	530	76.2	0.02839	16.4	0.17	127	838
5. Little Bay De Noc	Green Bay	10.6	0.1592	28.7	0.53	0	561	72.3	0.03338	16.6	0.22	127	829
6. Green Bay	Green Bay	0	0.1898	26.3	0.61	0	526	67.5	0.03866	19.1	0.22	127	840
7. Saginaw Bay	Alpena	0	0.2281	26.4	0.6	0	438	71.1	0.04147	18.7	0.21	38	696
8. West Lake Erie	Toledo	0	0.2881	19.1	0.71	0	347	40.1	0.1125	27.8	0.38	0	476

SE = the standard error of estimate, R^2 is the square of the variance accounted for by the regression equation adjusted for the number of variables in the regression equation. Regression coefficients were significant at the 95% confidence level.

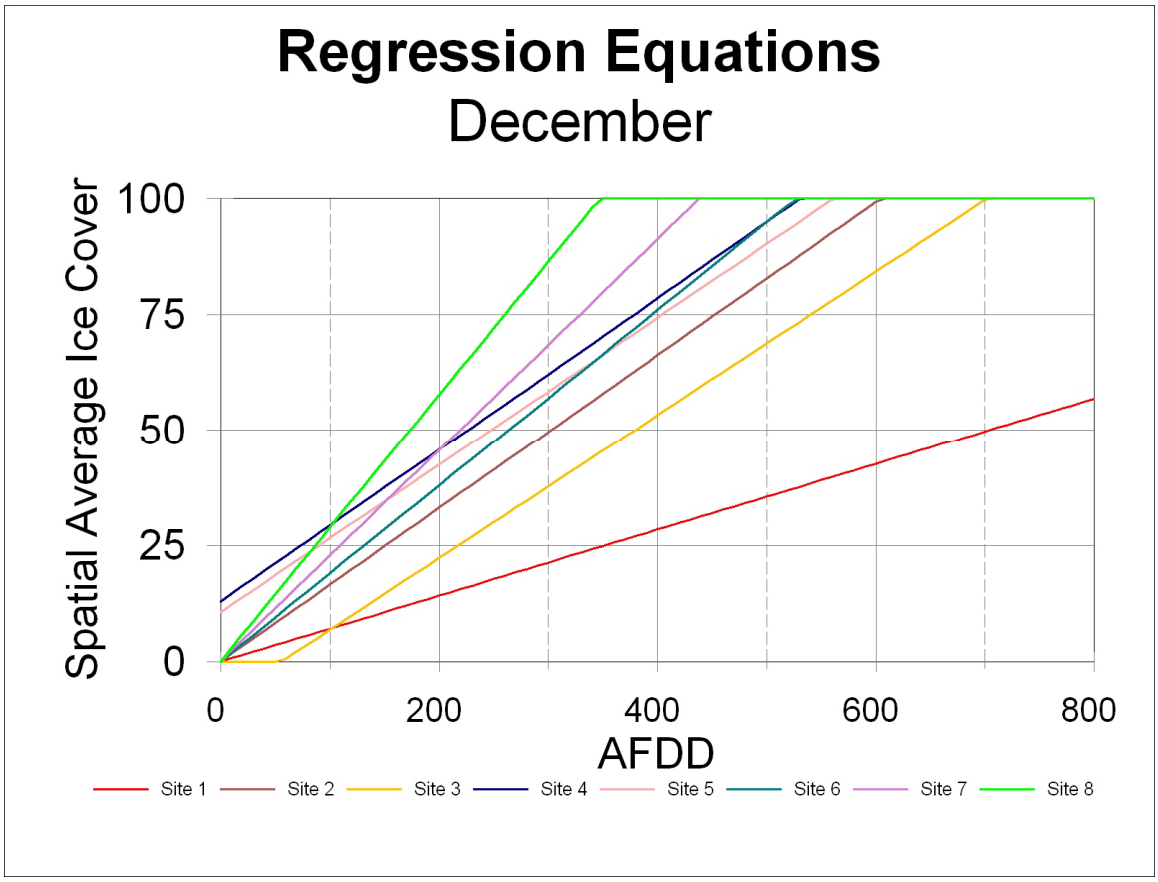

Fig A-1. Note that Site 1 (West Tip of Lake Superior) and Site 8 (West Lake Erie) make the extremes. Western Lake Erie reacts the most rapidly to increasing FDD accumulations and West Tip of Lake Superior reacts the least rapidly to increasing FDD accumulations.

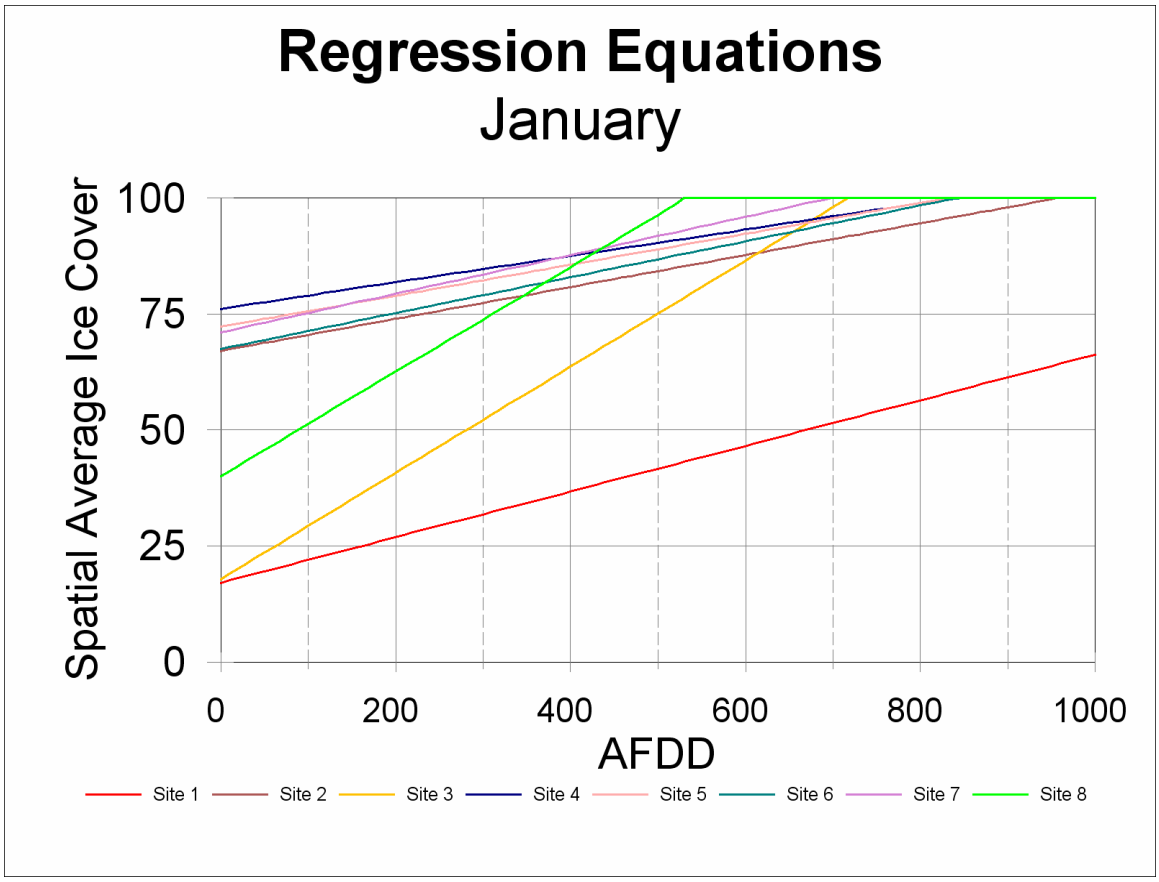

Fig. A-2. There is tight packing of the regression lines for sites 2, 4, 5, and 6. Site 1 still has the slowest change in ice cover relative to increasing FDDs, but Site 7 now has the most rapid reaction to increasing FDDs, with Site 8 virtually the same as Site 7 in rate of increase relative to FDD increase.