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LONG-RANGE FORECASTING OF MAXIMUM ICE EXTENT ON THE GREAT LAKES

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LONG-RANGE FORECASTING OF MAXIMUM ICE EXTENT ON THE GREAT LAKES

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A technique, based on prewinter thawing and wintertime freezing degree-days, has been developed for making long-range forecasts of the percent maximum ice extent on the Great Lakes. The number of thawing degree-days is known by early winter, but the crux of the technique is to predict the number of freezing degree-days that will accumulate by March 3, the average date of maximum ice extent on the Lakes during the last 13 winters. This was accomplished by using an average March 3 accumulated freezing degree-day value from both the large and small ice extent winters between 1962-63 and 1968-69, which alternate in a quasi-biennial cycle. The equations and freezing degree-day prediction method were then used to hindcast maximum ice extent on the Lakes during the winters 1969-70 to 1974-75. The results indicated that the regression equation forecasting technique was more accurate than climatology forecasts on Lakes Superior, Michigan, and Huron. On Lake Ontario, it was found that climatology forecasts were equally accurate, and on Lake Erie, the small interannual variation in maximum ice extent made climatology forecasting the best technique. The effect on the technique of the apparent climatic warming during the most recent winters is also discussed. Another technique, which simply applied the average percent maximum ice extent during the alternating relatively cold and relatively warm winters, was also better than climatology, but was not as accurate or versatile as the regression equation method.

1. INTRODUCTION

The winter of 1974-75 marked the first time a fleet of ships was able to operate on the Great Lakes despite the ice cover. That event was facilitated by mild weather and an unusually small ice extent on those portions of Lakes Superior, Huron, and Michigan traversed by ships. Long-range forecasts of ice extent on the Great Lakes would be of considerable value in determining whether or not shipping operations could continue throughout upcoming winters. The purpose of this report is to present a technique for predicting by early December wintertime maximum ice extent on the Lakes, based on a quasi-biennial variation found in both maximum ice extent and average winter air temperatures at meteorological stations around the Lakes. Thirteen years of ice-cover and air temperature data collected around the Lakes were used to develop first a climatology of maximum ice extent and then the forecasting technique.

Richards (1964) developed a series of multiple regression equations for Georgian Bay and Lakes Superior, Huron, Erie, and Ontario showing the relationship between ice extent and air temperature at representative stations near each lake. His equations applied to ice extent throughout the winter, but not necessarily to the seasonal maximum. These equations have the general form

$$Y = b_0 + b_1X_1 + b_2X_2,$$

where Y = percentage ice cover

X_1 = the accumulated freezing degree-days (FDD's) during the winter

X_2 = the prewinter maximum thawing degree-days (TDD's) accumulated from April 1 or May 1.

Accumulated FDD's are an indicator of the severity of a winter up to a given point in time and TDD's give an indication of the antecedent heating available for storage in a lake (Richards, 1964). The number of FDD's for a given day is determined by subtracting the mean daily air temperature in degrees Fahrenheit from 32°F. If the resultant value is negative, then TDD's have accumulated. Under operating conditions, X_2 can be determined by late November or early December, since TDD's seldom accumulate in the winter after that time. The key to the success of the long-range maximum ice extent forecasting technique (for Y) presented here lies in the advance determination of the value of X_1. The remainder of this report will discuss the Great Lakes maximum ice extent climatology and the solution to predicting X_1.

2. MAXIMUM ICE EXTENT CLIMATOLOGY

Table 1 shows the areal percentage maximum ice extent determined for each lake for the winters from 1962-63 to 1974-75, based on data collected by Wilshaw and Rondy (1965), Rondy (1966, 1967, 1968, 1969, 1971, and 1972), and Assel [1972a, 1972b, 1974a, 1974b, and 1975 (personal communication)]. Since Lake Superior has the greatest variation in maximum ice extent (standard deviation = 24 percent ice extent), it was used to develop the basis for the forecasting technique. Forecast equations for Lake Erie were not developed since it has a small variation in maximum ice extent (standard deviation = 6 percent ice extent). A climatological forecast of 92 percent maximum ice extent is sufficiently accurate for most winters.

For each lake, one National Weather Service station with temperature conditions most highly correlated to maximum ice extent was determined. It was found after a day by day analysis that the best indicator of the percent maximum ice extent was the number of FDD's accumulated by early March. This is because, during the last 13 winters, the average date of maximum ice extent on each lake was found to be March 3 on Lakes Superior, Huron, and Ontario, and March 2 on Lake Michigan. The average date of maximum accumlated FDD's during the winter is not the most highly correlated

Table 1. Percent Maximum Ice Extent on the Great Lakes Since 1962-63

winter	superior	Lake Michigan	Lake Huron	Lake Erie	Late Ontario
1962-63	95	f3	97	98	51
1963-64	31	40	32	91	12
1964-65	90	15	60	NA	10
1965-66	60	46	29	NA	15
1966-67	88		80	90	12
1967-68	90	30	50	98	10
1968-69	40	15	50	80	10
1969-70	80	30	50	95	17
1970-71	48	27	'5	92	10
1971-72	95	20	70	95	20
1972-73	55	20	60	95	20
1973-74	70		65	95	25
1974-75	30	25	45	80	16
13-year mean	67	30	56	92	18
13-year standard deviation	24	15	19	6	11
1962-63 to 1968-69 mean	71	32	57	91	17

NA = Not Available

value to the percent maximum ice extent because it occurs after several days with TDD's have intervened. On Lake Superior the average date of the first major accumulation of TDD's for several days was March 9. Maximum ice extent thus precedes that date since it has been established that only a few TDD's are needed to decrease the lake ice cover (Richards, 1964). The date of occurrence of maximum ice extent during each winter is given in table 2.

Following are the representative stations for each lake, along with their highest correlation between FDD's and maximum ice extent during the last 13 winters:

Houghton, Michigan (Superior) $r = 0.890$
Escanaba, Michigan (Michigan) $r = 0.868$
Alpena, Michigan (Huron) $r = 0.675$
Rochester, New York (Ontario) $r = 0.446$.

The correlations are statistically significant for Lakes Superior and Michigan, but not for Lakes Huron or Ontario.

Table 2. Approximate Dates of Maximum Ice Extent on the Great Lakes

Winter	Lake Superior	Lake Michigan	Lake Huron	Lake Ontario
1962-63	3/3	3/3	3/3	3/3
1963-64	2/27	2/27	2/27	2/27
1964-65	NA	NA	NA	NA
1965-66	2/28	2/24	2/28	NA
1966-67	3/20	3/19	3/19	3/5
1967-68	2/29	2/27	3/17	3/10
1968-69	3/11	3/16	3/7	3/10
1969-70	3/17	3/10	3/11	3/15
1970-71	3/2	2/25	3/2	3/1
1971-72	2/27	3/2	NA	2/27
1972-73	2/25	2/27	2/27	2/28
1973-74	2/17	2/17	2/17	2/15
1974-75	3/6	2/18	2/16	3/6
Mean date	3/3	3/2	3/3	3/3
Standard deviation (days)	9	9	9	8

NA = Not Available

By use of the area1 percentage maximum ice extent (Y) given in table 1, as well as the accumulated FDD's to March 3 (X_1) and tine maximum prewinter TDD's for each lake (given in table 3) for the seasons 1962-63 through 1968-69, multiple regression equations for maximum ice extent were developed. By use of these equations, Y will be predicted for the 1969-70 through 1974-75 winters after the technique for forecasting X_1 is discussed below. The accuracy of the predictions was then computed. These equations are as follows for each lake/station:

Lake Superior/Houghton $Y = 58.5294 + 0.0821X_1 - 0.0263X_2$

Lake Michigan/Escanaba $Y = -63.2764 + 0.0532X_1 + 0.0060X_2$

Lake Huron/Alpena $Y = -45.9019 + 0.0837X_1 + 0.006X_2$

Lake Ontario/Rochester $Y = -58.4906 + 0.0570x_1 + 0.0062X_2$.

The significance of the X_2 term is negligible for Lakes Michigan, Huron, and Ontario as indicated by their positive values and the fact that the ratio of b_1 to b_2 ranges from about 10 to over 100. Nonetheless an F-test of these equations revealed that they were significant at the S-percent level for ail but Lake Ontario.

Table 3. Accumulated March 3 Freezing Degree-Days and Maximum Prewinter Thawing Degree-Days by Station and Season

	HOUGHTON		ESCANABA		ALPENA		ROCHESTER	
Winter	FDD's	TDD's	FDD's	TDD's	FDD's	TDD's	FDD's	TDD's
1962-63	2009	4451	1756	5074	1706	5040	1087	6178
1963-64	1319	5081	949	5395	1025	5352	636	6301
1964-65	1837	4764	1484	5057	1226	5344	573	6424
1965-66	1453		939	4488	886	4755	482	6085
1966-67	1689	4477	1201	5084	1200	4971	440	6227
1967-68	1647	4242	1358	4675	1236	4765	787	5984
1968-69	1282	4638	902	5123	1047	5354	542	6441
1969-70	1742	4555	1391	5094	1379	5023	899	6401
1970-71	1658	4778	1311	5391	1252	5459	785	6744
1971-72	1807	4746	1486	5163	1127	5278	499	6388
1972-73	1441	4347	1137	4664	1000	4685	359	6226
1973-74	1530	4955	940	5293	1140	5297	481	6829
1974-75				4767*	789	4945	257	6186
Mean	1584	4601	1215	5021	1155	5098	602	6340
Standard Deviation	242	259	274	287	230	265	231	241
Mean 1972-73 to 1974-75	1384	4616	1007	4908	976	4976	366	6414

* Some monthly values estimated from data from nearby meteorological stations.

The values of X_2 needed for these equations to predict the 1969-70 to 1974-75 ice extents can be found in table 3. Operationally they would have been obtained by early December before each winter. A method for predicting the March 3 value of X_1 will now be discussed.

3. APPLICATION OF THE QUASI-BIENNIAL CYCLE TO MAXIMUM ICE EXTENT FORECASTING

Voeikov (1891) was the first to note a 2-year cycle in ice conditions on European lakes. This phenomenon is largely due to the quasi-biennial oscillation noted in many meteorological parameters (Angel1 and Korshover, 1968; Landsberg, 1962). Using Lake Superior as an example, because of its large interannual variation in percentage maximum ice extent, one may detect the 2-year cycle in that data (table 1) and in FDD's (table 3). In terms of relative area1 extent of percent maximum ice cover around the 13-year mean (67 percent) where "L" equals large and "S" equals small ice extent, the pattern or cycle since 1962-63 has been:

L-S-L-S-L-L-S-L-S-L-S-L-S.

'The alternating year pattern was only broken when two consecutive winters of large ice extent occurred in 1966-67 (88-percent cover) and 1967-68 (90-percent cover).

Figure 1 shows the relationship between the percent maximum ice extent values and 12-month running mean temperatures at Houghton, Michigan. These running mean temperatures are the best method for graphical representation of the quasi-biennial cycle in air temperatures. Figure 1 shows that the "L" ice-cover seasons are associated with a downward movement of the running mean temperatures, indicating that the actual monthly temperatures during those seasons were lower than those of the same months of the previous year. The "S" ice-cover seasons are associated with an upward trend of the running means, indicating higher temperatures than occurred the previous year in those months. Plotting 12-month running mean temperatures enables one to better determine the type of winter to expect. One problem with using the running mean temperatures is that the direction of the trend (upward, downward) usually reverses in early winter.

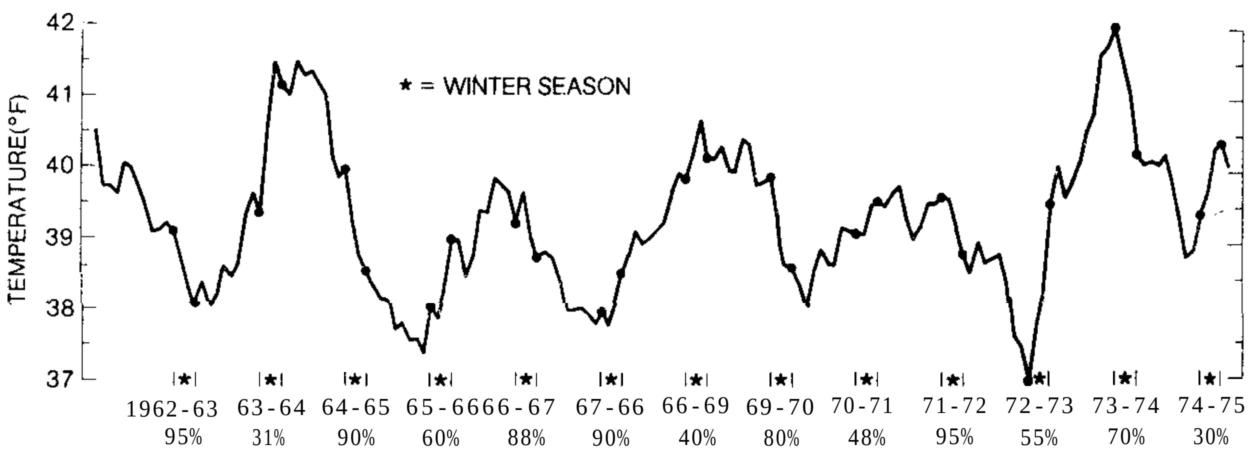

Figure 1. Relationship between the percent maximum ice extent values on Lake Superior and the 12-month running mean air temperatures at Houghton, Michigan. The filled circles indicate the temperatures at the beginning and end of each winter.

The numerical values of the 12-month running mean temperatures are also important. For example, the "S" winters of 1965-66 and 1972-73 had somewhat high ice extents (60 percent and 55 percent, respectively) while the 1963-64 winter had a very low ice extent (31 percent) because the running mean temperatures during 1965-66 and 1972-73 were under 39°F, but during 1963-64 they were over 40°F. Similarly, during the winter of 1973-74, a comparatively small ice extent occurred (70 percent) compared to the other "L" winters because the running mean temperature was over 40°F in 1973-74 and under 40°F during the other "L" winters. Running mean temperature variations around 40°F can markedly alter the percent maximum ice extent on Lake Superior. A 2°F anomaly for the entire winter on either side of 40°F becomes a difference of 200 FDD's (assuming 100 days per winter) and according to the Lake Superior/Houghton equation a variation of 15 to 20 percent areal maximum ice extent around the mean may occur (X_2 is constant).

The application of the 2-year cycle to maximum ice extent forecasting on the Great Lakes begins with two assumptions:

1) The expected relative maximum ice extent ("L" or "S") will be opposite that of the previous winter. This would have resulted in a major prediction error only during the 1967-68 winter when "S" conditions would have been forecast. As was discussed above, running mean temperatures are the best way to determine which type of winter will occur; however, during 1967-68 that technique would have proved futile also (see fig. 1), since an upward swing in the graph occurred. Because of that, simply expecting an opposite winter from that which existed the winter before is the best approach until it can be determined in future winters that using the 12-month running mean temperature graph will not repeatedly result in making the same error.

2) The relative ("L" or "S") ice extent predicted for the other Great Lakes will follow the pattern of Lake Superior. The best method of determining the relative ice extents on the other lakes is to follow their running mean temperature graphs (Appendix A), but, for the sake of simplicity in testing the technique by the use of 1969-70 through 1974-75 forecasts, it was assumed that their "L-S" pattern would follow that of Lake Superior. By checking the values in table 1 or by comparing figure 1 with those in Appendix A, one notes that Lake Ontario does not clearly follow the Lake Superior pattern, nor did Lake Huron between 1967-68 and 1969-70.

The next step in the procedure is to assign numerical values to X_1 for both the "L" and "S" seasons for each lake and then substitute them into the regression equations during the appropriate winter. Based on the FDD data in table 3, average "L" and "S" values were determined by using the 1962-63 through 1968-69 winters, and those values in turn were used in the regression equations to compute Y during 1969-70 to 1974-75 after it was predetermined which type of winter would occur. These X_1 values for each lake are shown in table 4. Another method for obtaining a maximum ice extent forecast would be to simply predict an average value of the actual ice extents during the "L" and "S" winters of 1962-63 through 1968-69 and use it to make the test predictions between 1969-70 and

1974-75. The accuracy of this average ice extent methodology was also determined and compared to the accuracy of the regression equations. The average maximum ice extent values are also shown in table 4. The differences in both FDD's and average ice extents between "L" and "S" winters were found to be statistically significant at the lo-percent level on all lakes, except Lake Ontario, when using a 2-tailed t-test. This further shows the significant difference between alternate winters over the Great Lakes.

Table 4. March 3 Average Freezing Degree-day Accumulation and Average Maximum Ice Extent During "L" and "S" Winters 1962-63 to 1968-69

Lake	Average 3/3 FDD's in "L" winters	Average 3/3 FDD's in "S" Winters	Average Ice Extent in "L" Winters in Percent	Average Ice Extent in "S" winters in Percent
Superior	1796	1351	91	44
Michigan	1450	930	45	14
Huron	1342	986	72	37
Ontario	722	553	21	12

The appropriate values of X_1 for each lake from table 4 were substituted into the regression equations to determine if they were accurate predictors of maximum ice extent during the test winters 1969-70 through 1974-75. The standard error of estimate was computed, based on the forecast and actual values of percent maximum ice cover, and then compared to the standard error of estimate for climatology forecasts, i.e., forecasts which simply used the 1962-63 through 1968-69, 7-year average ice extent value (bottom of table 1) to predict the future years and which have a standard error of estimate equal to the standard deviation. In a similar manner, the average ice extent values during 1962-63 through 1968-69 were used to predict the 1969-70 through 1974-75 values, and their standard error of estimate was also computed and compared to climatology forecasts and the regression equation forecasts. The expected relative ice extents for the 1969-70 through 1974-75 winters were L-S-L-S-L-S for each lake.

The results of the predictions, shown in table 5, indicate that both the regression equation and the average ice-extent methodologies considerably improve over climatology predictions, but that the regression equation technique is the more accurate of the two. The regression technique is

Table 5. Comparison of 1969-70 to 1974-75 Forecast Results

Lake	Climatology forecasts SE (in % max. ice extent, A)	% improvement with equations (B)	% improvement with average ice values (C)	Seasons when (B) was more accurate than (C) (6 possible)	Seasons when (B) was more accurate than (A) (6 possible)	Seasons when (C) was more accurate than (A) (6 possible)
superior	26.7	56.2	49.4	4	5	4
Michigan	19.0	23.0	19.3	4	2	2
Huron	24.6	46.3	37.0	6	4	4
Ontario	15.0	64.0	68.0	1	2	2

also more favorable from the standpoint that one may directly apply subjective knowledge of 12-month running mean temperature values as well and that, at least with Lake Superior, the prewinter heating term (X2) is an important factor. The regression equation technique would also improve with advancements in long-range air temperature forecasting techniques. The last three columns in table 5 show that only on Lake Ontario were there consistently poor results in the regression equation technique when compared to other methods. Columns two and three of table 5 show a high improvement (64 percent and 68 percent, respectively) in the Lake Ontario forecasts compared to climatology. This discrepancy between high improvement when using SE values and low forecast accuracy is due to the fact that the climatology SE for that lake was 15 percent, a figure made unusually high by the anomalous ice cover during the 1962-63 winter (51-percent ice extent). With that season eliminated from the original data, the climatological SE becomes only 2 percent through the 1968-69 season, a value which is difficult to improve upon and which suggests that for Lake Ontario, as for Lake Erie, climatology forecasts would be best.

Regression equations were developed for the lakes based on all 13 years of data:

Lake Superior/Houghton $Y = 10.6502 + 0.0881X_1 - 0.0181X_2$

Lake Michigan/Escanaba $Y = -32.6521 + 0.0469X_1 + 0.0011X_2$

Lake Huron/Alpena $Y = 30.4539 + 0.0563X_1 - 0.0077X_2$

Lake Ontario/Rochester $Y = 23.5068 + 0.0215X_1 - 0.0030X_2$

Although it was considered statistically unreliable to hindcast ice extent during the same 13 seasons from which data were collected to develop the regression equations, it was found that the accuracy of the technique was still considerably better than using climatology forecasts everywhere except on Lake Ontario. There it was found that the standard error (SE) of the regression equation technique was equal to that for climatology predictions (when the 1962-63 data is included).

Recent evidence indicates (Dickson et. al., 1975) that northern hemisphere winters have become milder than those of the 1960's. This may be seen at the representative stations around the Great Lakes in table 3. The March 3 FDD accumulation (Xl) during the last three winters (1972-73 through 1974-75) have all been lower than the 13-year average and the average value of Xl for those three winters (bottom of table 3) is about 200 FDD's lower at each station. The lower X_1 3-winter average value is significantly lower than the X_1 value of the first 10 winters at the lo-percent level at Houghton and RocAester and barely misses being significant at Escanaba and Alpena when using a Z-tailed t-test. If the regression equation forecasting technique does not take into account this apparent tendency toward milder winters, the results could be consistent error of up to 20 percent in areal maximum ice extent on Lake Superior and up to 10 percent on Lakes Michigan and Huron. To reflect the physical and changing nature of the climate, it is recommended that operational use of such a technique depend on lower values of X_1 than those given in table 4 or those which might be derived by using all 13 years of data. Values of X2 show little consistent change from lake to lake in the last 3 years.

4. CONCLUSIONS

Two techniques for predicting maximum ice extent on the Great Lakes were developed and compared to each other and to climatology, based on data from 1962-63 to 1974-75. It was found that both techniques could predict maximum ice extent better than climatology on Lakes Superior, Michigan, and Huron. On Lakes Ontario and Erie, climatology is the best technique for predicting maximum ice extent, due to the low interannual variation in ice extent and (on Lake Ontario) to the lack of a clearly defined Z-year cycle in air temperature upon which the forecasting technique depends. The more accurate and useful of the two techniques, involving regression equations, FDD's, and TDD's, would be responsive to improvements in long-range air temperature forecasting techniques and is flexible in that more appropriate values for the FDD term may be inserted in accordance with changing climatic conditions. Although the TDD term is largely insignificant in the Lakes Michigan, Huron, and Ontario equations, it is very important in ice extent forecasts for Lake Superior, where forecasts of its large interannual ice extent variation would be most useful.

Using the regression equation technique, the forecaster determines the number of prewinter TDD's accumulated by early December and at that time must predict the number of FDD's which will accumulate by the upcoming March 3. The success of the technique depends on the ability to predict whether the upcoming winter will be an "L" or an "S" type, which helps determine the FDD value chosen for the regression equations. Average FDD values from previous winters of the same type were used in the equations in this report (table 4), but lower values may be more representative. One may determine the type of winter by either predicting the type opposite that of the previous winter or by using graphs of U-month running mean temperatures to predict the trend of the graph and expected running mean temperatures during the upcoming winter relative to a long-term average temperature.

The techniques described herein are the best now available to predict winter seasonal temperatures around the Great Lakes and their maximum ice-extent. Considering the possibility that winters have temporarily become milder, one may extrapolate forward in time and suggest that it may be possible to continue navigation on the Great Lakes throughout upcoming winters with characteristics resembling those of the 1974-75 winter. The technique described here will help determine which winters those might be.

5. ACKNOWLEDGMENTS

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APPENDIX. TWELVE-MONTH RUNNING MEAN AIR TEMPERATURES

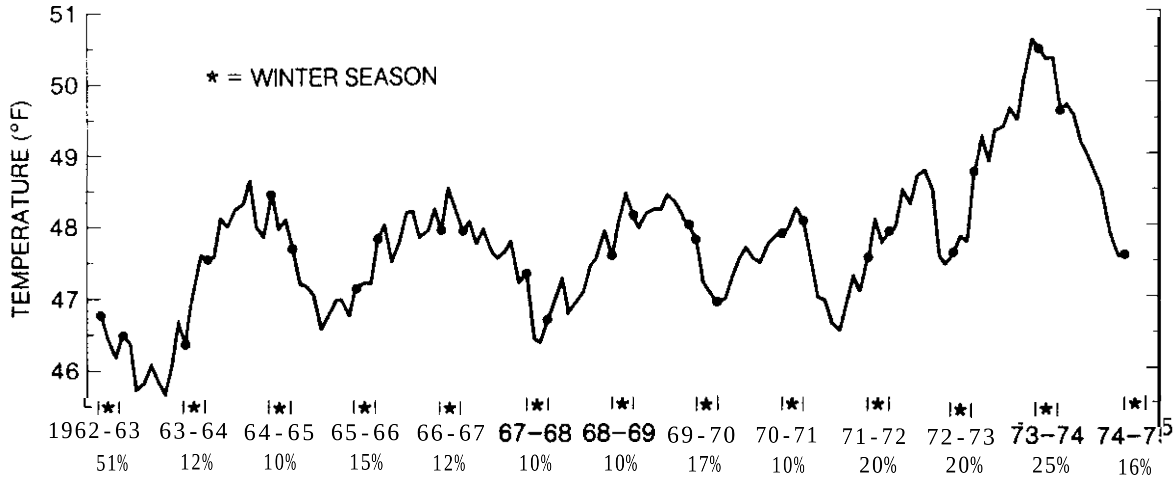

Figure A.1. Relationship between the percent maximum ice extent values on Lake Ontario and the 12-month running mean air temperatures at Rochester, New York. The filled circles indicate the temperatures at the beginning and end of each winter.

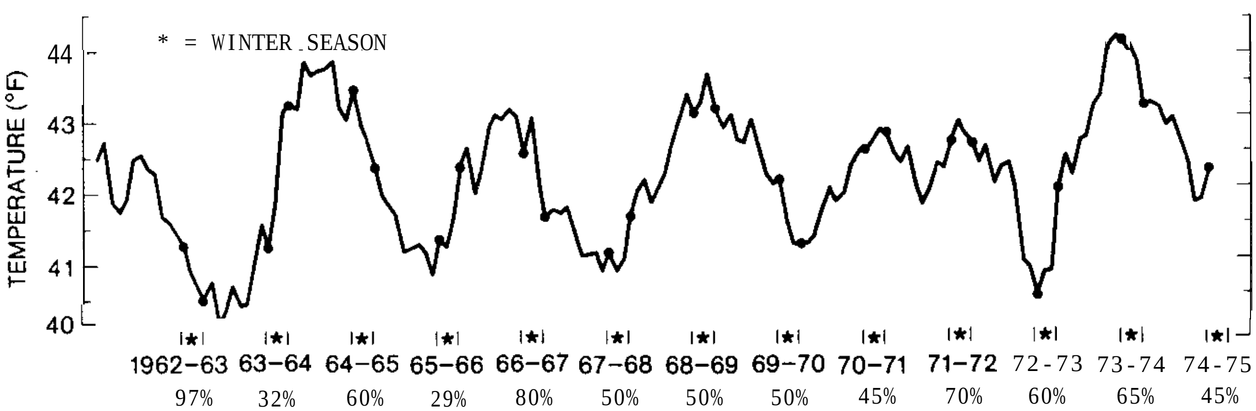

Figure A.2. Relationship between the percent maximum ice extent values on Lake Huron and the 12-month running mean air temperatures at Alpena, Michigan. The filled circles indicate the temperatures at the beginning and end of each winter.

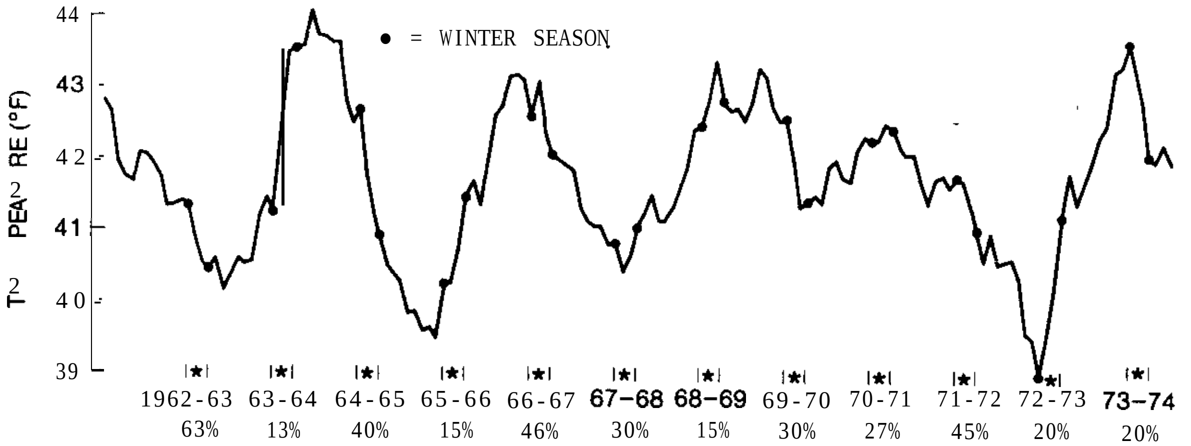

Figure A.3. Relationship between the percent maximum ice extent values on Lake Michigan and the 1%month running **mean** *air temperatures at Escanaba, Michigan. The filled circles indicate the temperatures* at *the beginning* and *end of each winter.*