NOAA Technical Memorandum NWS TDL-63

AUTOMATED GREAT LAKES

WAVE FORECASTS

Techniques Development Laboratory
Silver Spring, Md.
February 1977

noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / National Weather Service

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(Continued on inside back cover)

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AUTOMATED GREAT LAKES WAVE FORECASTS

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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
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CONTENTS

AUTOMATED GREAT LAKES WAVE FORECASTS

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ABSTRACT. The Techniques Development Laboratory of the National Weather Service began making automated wave forecasts for the Great Lakes in January 1975. These forecasts are based on specialized wind forecasts and the wave forecast method of Bretschneider.

Possible fetch lengths are measured at 15° intervals and are adjusted for fetch width. Duration time is determined by examining the forecast wind directions for a 45° change. Forecasts of wave height are made twice daily and extend to 36 hr at 12-hr intervals. These forecasts are transmitted by teletypewriter and are used operationally by Weather Service Forecast Offices in the Great Lakes area.

INTRODUCTION

Weather service for the Great Lakes was one of the original functions of the United States Meteorological Service. Whitnah (1961), in his book on the history of the United States Weather Bureau, reviews the formation of the Great Lakes service. The Army's Signal Service in 1870 was assigned the responsibility of issuing weather warnings under the direction of Colonel A. J. Myer. On Nov. 8, 1870, Colonel Myer requested Professor I. A. Lapham to assume responsibility for the Great Lakes area. He issued the first storm warning the same day with the warning of high winds at Chicago and Milwaukee; barometer falling and thermometer rising at Chicago, Detroit, Toledo, Cleveland, Buffalo, and Rochester; and high winds probable along the lakes. This forecast was made by considering weather conditions at 20 stations which reported by telegraph.

Shipping activities, from the time they were started in 1815, have been plagued by the destructive action of severe storms and waves. Figure 1 shows the William Truesdale experiencing 25-foot waves on Lake Erie in November 1928. In terms of the number of lives lost and the number of ships that sank, the storm of Nov. 9, 1913 was the worst to occur. Ten ships were sunk and 20 others were driven ashore with a loss of 235 lives. Winds were measured at 65 mi/hr with gusts to over 70. Waves were estimated at 35 ft, following each other in rapid succession.

The most recent sinking of a large ship on the Great Lakes was that of the Edmond Fitzgerald (fig. 2) on Nov. 10, 1975 during a severe storm. The 729-ft

Fitzgerald was carrying 26,216 tons of taconite ore pellets and sank in eastern Lake Superior, northwest of Whitefish Point. Winds in the area were from WNW at 50-60 kt with gusts reported to 75 kt. Significant wave height was about 16 ft (reported by some to be 20-25 ft).

AVAILABLE WIND FORECASTS

Automated wind forecasts for the Great Lakes were implemented by the Techniques Development Laboratory (TDL) in December 1969. These were for Lake Erie and Lake Ontario and were based on 1000-mb geostrophic wind and sea-level pressure forecasts from the Subsynoptic Advection Model for eight cities near the two lakes (Barrientos 1971). Later, an objective method for forecasting winds over Lakes Huron, Michigan, and Superior was developed. This method was based on meteorological forecasts of the Primitive Equation and Trajectory models. The present automated Great Lakes forecast method is based on the Model Output Statistics (MOS) technique (Feit and Barrientos 1974). The predictors of the wind are various forecast elements computed by the National Meteorological Center's Primitive Equation (PE) model. Separate sets of forecast equations were developed for the summer and winter equations.

Wind forecasts are available twice daily to 36 hr in advance at 6-hr intervals for the 12 areas of the Great Lakes, as shown in figure 3. These wind forecasts are the basis of the forecasting of waves on the Great Lakes by TDL.

WAVE FORECAST PROCEDURE

The wave forecasts at specific points within any lake section are based on the wind forecasts for that section of the lake. Wave height and period calculations are based upon the method of Bretschneider (1970, 1973). The usual application of the method requires the subjective estimation of such variables as fetch length and wind duration time. Many alterations to the standard method were made so that it could be completely automated.

Forecast Points

The selection of specific forecast points was necessary so that fetch lengths could be measured and made part of the input data to the forecast program. TDL consultations with the NWS Eastern and Central Regions led to the decision to produce wave forecasts at the 64 points indicated in figures 4 through 8. Some of these were chosen to be along the axes of the lakes but most were chosen to be 5 mi from shore. This distance was used so that the points were not in the shallowest water very close to shore.

Fetch Lengths

Fetch lengths for each of the forecast points were determined for 24 directions at 15° intervals. These were found by direct measurement of fetch lines drawn on maps. An example of this procedure is shown in figure 9 for a point in Lake Erie. Some of the fetch lengths were corrected for fetch width by the method of Saville (1954). This method recognizes that waves are generated not only in the exact direction of the wind but at various angles to the wind. Resulting waves at a point therefore are a result of summing up the wave components from the direction of the wind and from other directions. The effect of a narrow fetch width is to limit the contribution of wave growth by wave components from some directions, different from the wind direction. For the Great Lakes wave forecast method we have used Saville's correction factors for the wind being effective over 90° of a fetch and with the wind effectiveness considered to vary as the cosine of the angle of the wind component. The graph of figure 10 from Saville (1954) shows the fetch effectiveness as a function of the ratio of fetch width to fetch length. These fetch effectiveness factors were applied to the measured fetches of our 64 points in those cases where the ratio of fetch width to length was 1.0 or less. The resulting array of fetch lengths for use in operational wave forecasting consists of 1536 values (64 points by 24 directions).

Duration Time

Duration time, in manual wave forecasting procedures, is generally considered to be the time that the wind has blown from about the same direction over the fetch. Duration can be estimated from examination of successive weather maps for significant direction changes in the fetch area. In the automated wave forecast method, duration time is determined by checking the wind direction at 6-hr intervals before the time of the wave forecast valid time. A search is made for a shift of 45° or more from the wind at forecast valid time in the lake section in which the forecast point is located. With wind directions available at 6, 12, 18, 24, 30, and 36 hr before forecast time, the duration is therefore estimated to be 3, 9, 15, 21, 27, or 33 hr.

Effective Wind Speed

The wind values used for the wave forecasts at each forecast point are those for the lake section in which each point is located. For example, wave forecasts for points 1-4 on Lake Michigan are based on the wind forecasts for the northern Lake Michigan section, points 5-11 are based on the winds of the central Lake Michigan section, and points 12-14 are based on winds for the southern section of the lake. No effort is made to consider wind in adjacent lake sections, even though in some cases a fetch may extend into an adjacent lake section.

The wind speed used is an effective wind speed, which is determined by weighting the winds over the duration time such that the winds closest to forecast time are weighted the heaviest. Each wind value is weighted in such a way that it counts as much in the wave generation process as all the previous winds that occurred in the duration time. This method was adapted from the TDL ocean wave forecast program, where it works successfully. The effective wind speeds for the various duration times are determined by the following equations:

(Duration=3 hr) $EWS = 0.5\ S_o + 0.5\ S_{-6}$

$$(\text{Duration}=9\text{ hr})\quad EWS = 0.5\,S_o + 0.25\,S_{-6} + 0.25\,S_{-12}$$

$$(\text{Duration}=15\text{ hr})\quad EWS = 0.5\,S_o + 0.25\,S_{-6} + 0.125\,S_{-12} + 0.125\,S_{-18}$$

$$(\text{Duration}=21\text{ hr})\quad EWS = 0.5\,S_o + 0.25\,S_{-6} + 0.125\,S_{-12} + 0.0625\,S_{-18} + 0.0625\,S_{-24}$$

$$(\text{Duration}=27\ \&\ 33\text{ hr})\quad EWS = 0.5\,S_o + 0.25\,S_{-6} + 0.125\,S_{-12} + 0.0625\,S_{-18} + 0.03125\,S_{-24} + 0.03125\,S_{-30}$$

where EWS is the effective wind speed over the duration time and S is the wind speed at a particular time. The subscript of the wind speed is the time in hours of the wind before the valid time of the wave forecast. The effective wind speed equation for duration of 27 hr is also used for 33-hr duration. The addition of an additional term for S_{-36} in the 33-hr duration equation would be insignificant.

Effective Fetch

The wave height for a particular wind speed can be limited by either the fetch length or duration time unless both of these are great enough for fully developed wave conditions to exist. In manual wave forecasting procedures, it is common to enter a wave forecast graph with the wind speed, duration time, and fetch length and to use for the forecast the lowest height indicated by either the duration time or fetch length. In the automation of the method, we do not have access to the wave forecast graph directly. Since we are limiting the calculation to a small number of duration times (3, 9, 15, 21, 27, and 33 hr) and since duration curves are straight lines when plotted on logarithmic graphs of wind speed against fetch, we have determined an equation for an effective fetch for each of the duration times. They are:

$$(\text{Duration}=3\text{ hr})\quad \log(EF) = 0.195 + 0.719\log(EWS)$$

$$(\text{Duration}=9\text{ hr})\quad \log(EF) = 0.794 + 0.725\log(EWS)$$

$$(\text{Duration}=15\text{ hr})\quad \log(EF) = 0.985 + 0.800\log(EWS)$$

$$(\text{Duration}=21\text{ hr})\quad \log(EF) = 1.196 + 0.758\log(EWS)$$

$$(\text{Duration}=27\text{ hr})\quad \log(EF) = 1.317 + 0.769\log(EWS)$$

$$(\text{Duration}=33\text{ hr})\quad \log(EF) = 1.432 + 0.758\log(EWS)$$

where EF is effective fetch in nautical miles and EWS is effective wind speed in knots.

The smaller of the two fetches, the actual fetch or the effective fetch, is used in the wave forecast equation for the calculation of wave height and period. In this manner, wave generation is being limited either by fetch length or duration time.

Forecast Equations

The wave forecast equations programmed for the automated Great Lakes forecasts are those as revised by Bretschneider (1970, 1973). They are:

$$H = \frac{U^2}{g} \; 0.283 \tanh \left[0.0125 \left(\frac{gF}{U^2} \right)^{.42} \right]$$

$$T = \frac{2\pi U}{g} \; 1.20 \tanh \left[0.077 \left(\frac{gF}{U^2} \right)^{.25} \right]$$

where H is significant wave height in feet,
T is significant wave period in seconds,
g is acceleration of gravity (32.2 ft/s^2),
U is wind speed in ft/s, and
F is fetch length in ft.

In the automated application of the method to the Great Lakes, the effective wind speed is used for U and the smaller of the real fetch or the effective fetch is used for F.

The depths of water at the forecast points were of some concern because of the limited wave height that can exist in shallow water. Consideration of the depths at the forecast points and the appropriate fetch lengths indicated that the depth factor would be important at one point, point 2 in western Lake Erie. There, considering the depth to be about 10 ft and using the relationship of breaking wave height to breaking depth, $H_b = 0.78\ d_b$, the wave height is limited to about 8 ft (U.S. Army Coastal Engineering Research Center 1973).

THE FORECAST MESSAGE

The Great Lakes wave forecast program is run twice daily after the 0000 GMT and 1200 GMT PE model runs and the subsequent Great Lakes wind forecast runs. The wave forecasts are available in the Request/Reply System as part of the bulletin with the heading FZUS4 KWBC. A sample bulletin is shown in figure 11. Here the upper portion of the bulletin is the wind forecast message and the lower portion consists of the wave forecasts.

The program computes significant wave height, period, and direction to 36 hr in advance at 6-hr intervals. For operational use, the wave heights at 12-hr intervals are desirable. Therefore, the wave heights are printed to the nearest foot for the 64 forecast points for each of four forecast projections, +00 hr, +12 hr, +24 hr, and +36 hr. In the sample message (fig. 11), the forecasts were made following the 0000 GMT PE run on the 10th of the month. This is indicated by the group 100000 of the heading line. The point numbers are identified in figures 4 through 8. Occasionally there will not be sufficient historical wind data to make all of the wave forecasts, because of missing PE model runs, missing Great Lakes wind forecast runs, or computer problems. When this happens, missing values of wave height forecasts are indicated by the value 99.

FUTURE WORK

Future development work to improve the Great Lakes wave forecasts consists of two types--improvements of the wind forecast method and tuning of the wave forecast model.

The present wind forecast method consists of a separate set of forecast equations for summer (April through September) and for winter (October through March). Monthly stability factors are presently being introduced into the wind forecast model and these are being tested. Hopefully, wind forecasts which consider more detail of the atmospheric stability will have increased accuracy and consequently will lead to improved wave forecasts.

The Coastal Engineering Research Center (CERC) of the Corps of Engineers has several recording wave systems in operation. The locations of these are at points near Preseque Isle and Cleveland in Lake Erie, and near Michigan City in Lake Michigan. Additional gages are being planned by CERC and the Great Lakes Environmental Research Laboratory of NOAA. From records of the wave spectra, values of the significant wave height and period are determined. The forecasts of significant wave height and period are then compared to the observations of significant height and period. Only a small amount of these data have been compared so far. However, it is evident that the wave forecasts are generally a little too high. This is expected as the Bretschneider wave height forecast equation was developed on wind speeds at the 10-m level and the wind forecasts being used are for a somewhat higher level and therefore have greater speeds. The plan is to statistically determine correction factors for the forecast wave heights, based on comparison of the wave forecasts with the wave observations.

Another area of future improvement may be the use of more realistic values of fetch lengths during the winter months when ice is a limiting factor. The present model ignores the ice problem.

SUMMARY

The automated Great Lakes wave forecast system of the Techniques Development Laboratory was implemented for operational use in January 1975. The forecast method is based on the Bretschneider forecast system and TDL forecasts of wind over the Great Lakes. The wave forecasts are transmitted by teletypewriter and are used as guidance forecasts at Weather Service Forecast Offices. Future work on the wave forecast method includes determination of correction factors for the wave forecast values. These will be statistically derived with use of wave observations recorded by the Army's Coastal Engineering Research Center and NOAA's Great Lakes Environmental Research Laboratory.

ACKNOWLEDGMENTS

Appreciation is expressed to Mr. Herman Perrotti of TDL's Marine Techniques Branch for the operational implementation and maintenance of the computer program. Appreciation is also expressed to Mary B. Battle for typing the manuscript.

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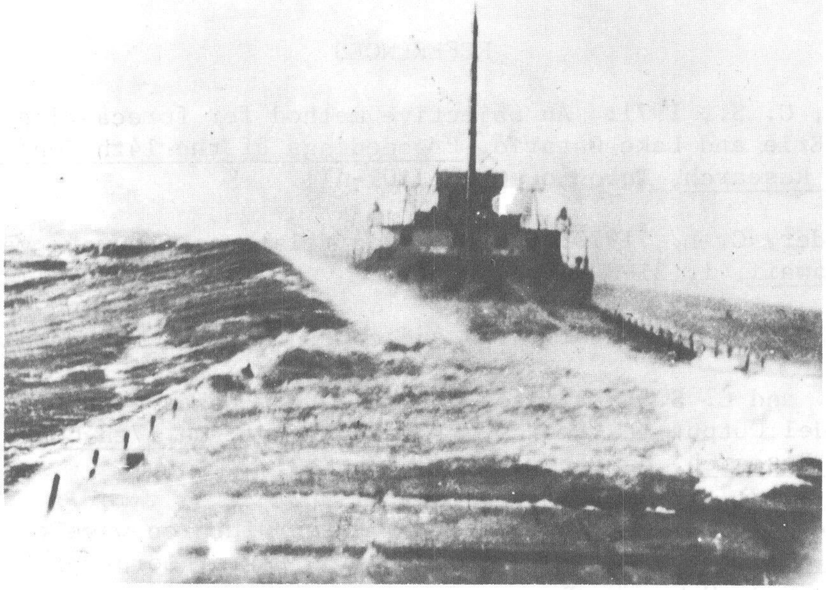

Figure 1.--The William H. Truesdale in a severe storm on Lake Erie in November 1928. Waves were 25 ft high.

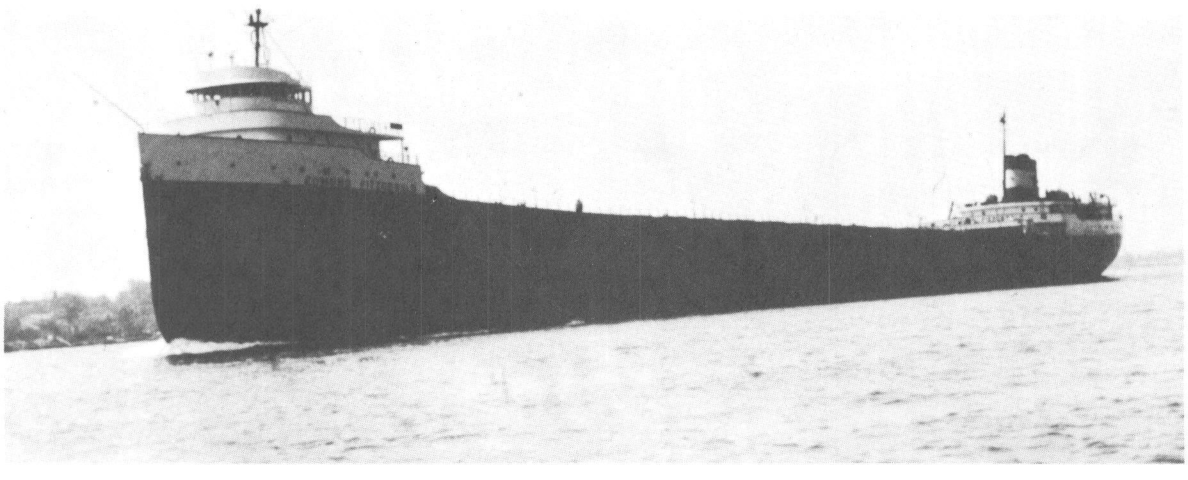

Figure 2.--The Edmond Fitzgerald, which sank in eastern Lake Superior during the intense storm of November 10, 1975.

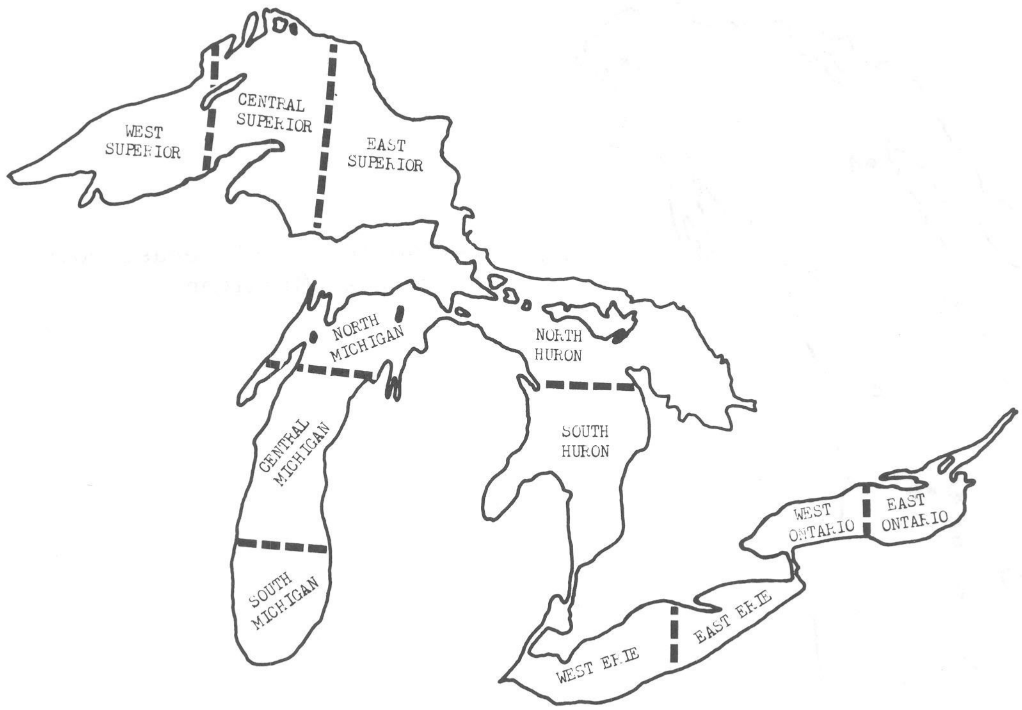

Figure 3.--The 12 areas of the Great Lakes for which automated wind forecasts are made.

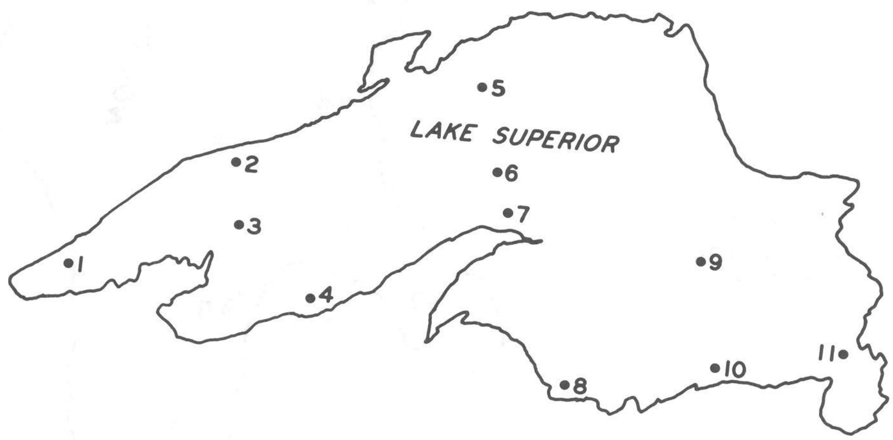

Figure 4.--The 11 wave-forecast points on Lake Superior.

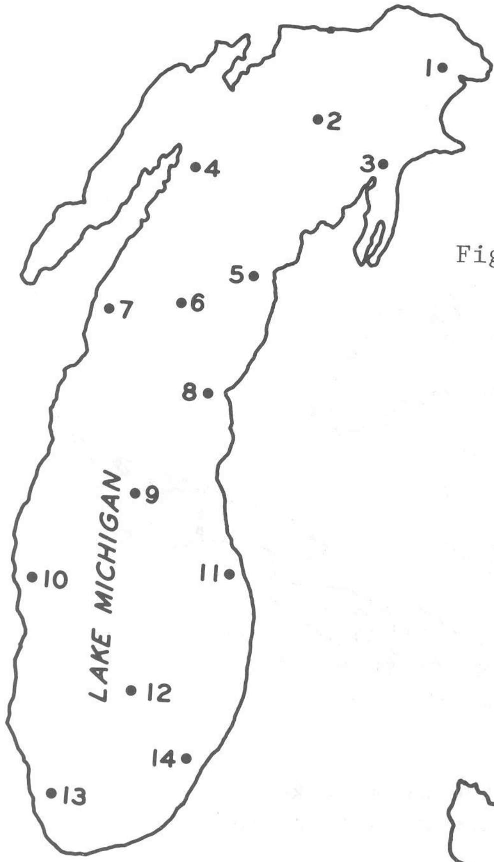

Figure 5.--The 14 wave-forecast points on Lake Michigan.

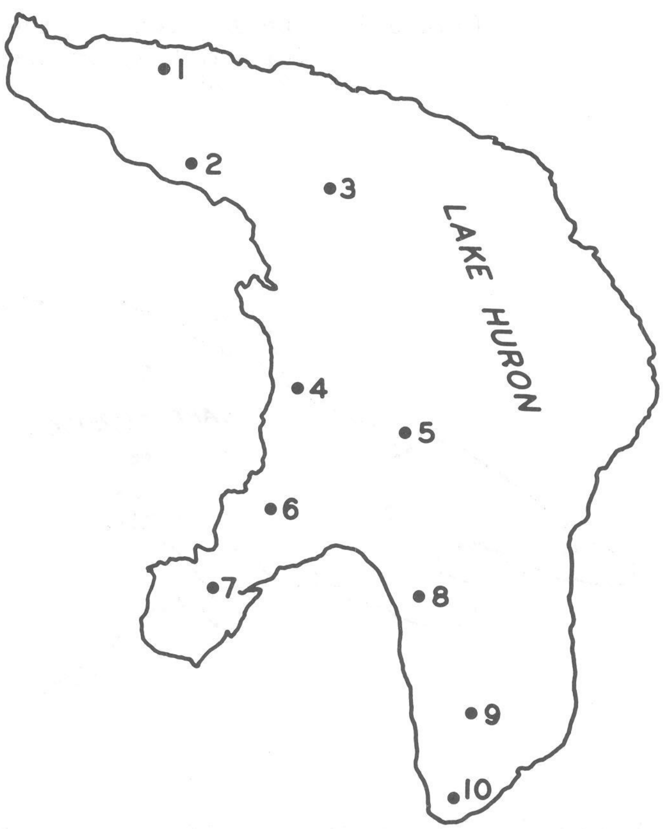

Figure 6.--The 10 wave-forecast points on Lake Huron.

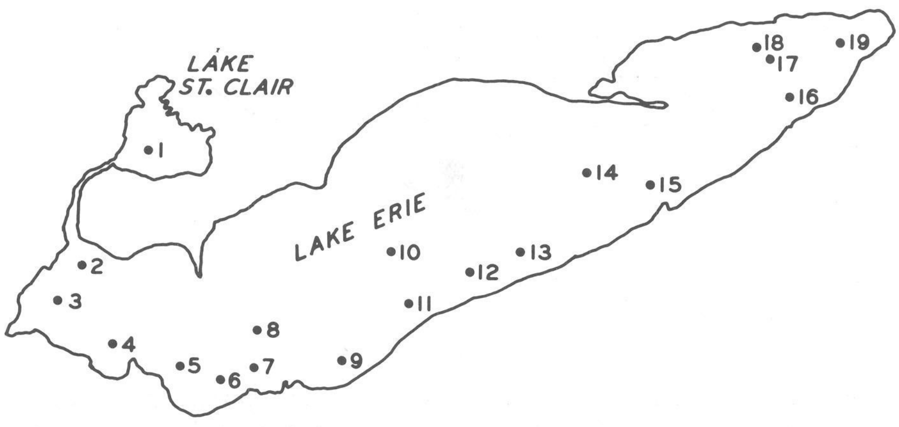

Figure 7.--The 19 wave-forecast points on Lake Erie.

Figure 8.--The 10 wave-forecast points on Lake Ontario.

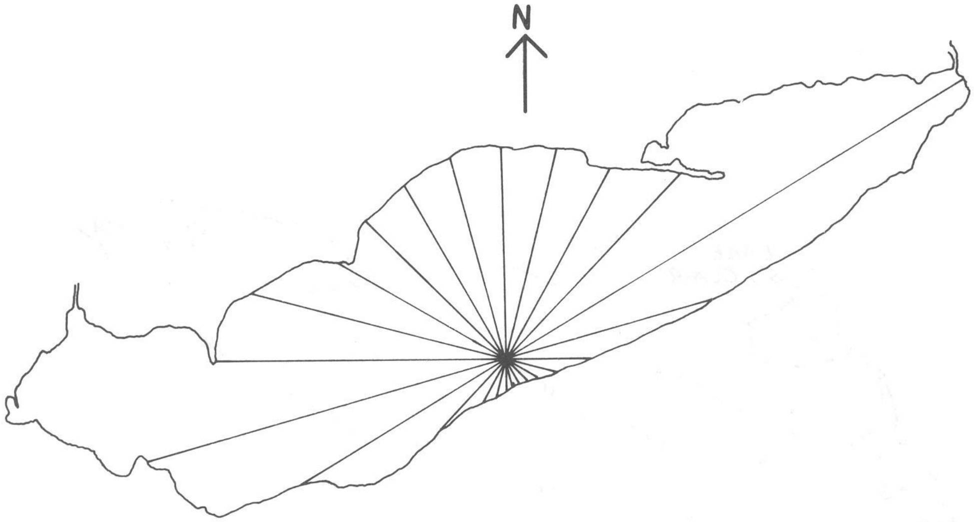

Figure 9.--Fetch lengths for a wave-forecast point in southern Lake Erie. Fetch lengths are measured at 15° intervals for each forecast point.

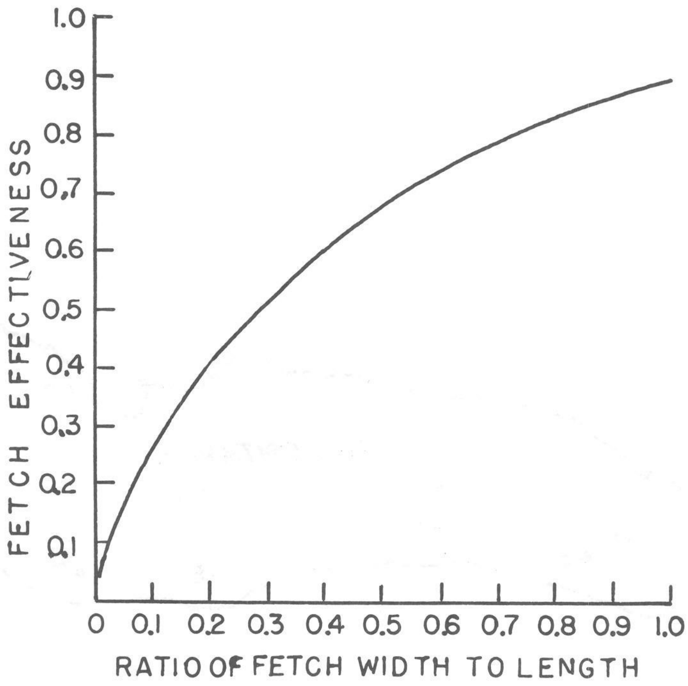

Figure 10.--Relation of effective fetch to width-length ratio for wind effective over 90° of fetch and wind effectiveness considered to vary as the cosine of the angle of wind component. (Saville 1954).

FZUS4 KWBC 100000

WIND FORECASTS FOR THE GREAT LAKES

LOCATION	06Z	12Z	18Z	00Z	06Z	12Z
EAST ONTARIO	1920	1728	2131	2429	2627	2422
WEST ONTARIO	1822	1829	2231	2329	2624	2019
EAST ERIE	1822	2028	2331	2328	2620	1916
WEST ERIE	1926	2132	2331	2527	2720	2615
SOUTH HURON	1825	2136	2435	2531	2725	2318
NORTH HURON	1625	2135	2433	2632	2728	2620
SOUTH MICHIGAN	2135	2437	2630	2929	3022	3118
CENTRAL MICHIGAN	2132	2539	2733	2832	2925	2920
NORTH MICHIGAN	1827	2435	2732	2833	2928	2821
EAST SUPERIOR	1425	2330	2826	2931	2927	3021
CENTRAL SUPERIOR	1323	3024	3023	2928	3022	2918
WEST SUPERIOR	1717	3123	3029	2827	2816	2614

GREAT LAKES WAVE FORECAST HEIGHT IN FEET

00 HR

POINT NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
SUPERIOR	03	06	05	02	05	04	02	02	05	02	04								
MICHIGAN	03	03	04	07	07	07	07	07	07	03	07	06	03	05					
HURON	03	02	04	04	04	03	03	04	03	02									
ERIE	02	03	03	03	03	02	03	03	02	04	03	03	02	03	02	02	03	03	03
ONTARIO	03	02	03	02	03	02	02	03	04	04									

12 HR

POINT NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
SUPERIOR	02	02	03	03	04	04	04	04	05	05	05								
MICHIGAN	06	06	06	05	07	07	04	07	07	04	07	09	04	10					
HURON	06	03	07	05	07	06	05	04	06	03									
ERIE	03	05	04	03	03	04	04	05	03	07	05	04	03	04	03	03	04	05	04
ONTARIO	04	03	04	03	04	02	02	02	04	04									

24 HR

POINT NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
SUPERIOR	03	04	06	08	04	06	08	04	10	10	10								
MICHIGAN	08	09	07	04	09	07	04	09	08	04	11	08	04	09					
HURON	08	04	07	04	08	05	06	04	06	04									
ERIE	03	05	05	03	03	04	06	06	04	08	07	08	05	08	06	06	08	08	07
ONTARIO	05	05	06	04	07	03	04	07	08	08									

36 HR

POINT NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
SUPERIOR	02	03	04	04	03	04	05	03	09	08	09								
MICHIGAN	06	07	05	03	06	05	03	06	05	03	07	06	03	07					
HURON	06	03	05	03	07	05	04	03	04	03									
ERIE	02	03	03	03	02	03	04	04	05	05	05	05	02	03	02	02	03	03	03
ONTARIO	03	03	03	03	06	03	04	06	06	07									

Figure 11.--Sample wind and wave forecast message as transmitted by teletypewriter. The winds are expressed as DDff, where DD is direction in tens of degrees and ff is speed in knots. The wave forecasts are expressed in feet. The wave forecast points are identified in figures 4-8.

(Continued from inside front cover)

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