U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
OCEAN PRODUCTS CENTER
TECHNICAL NOTE

LAKE ERIE WAVE HEIGHT FORECASTS GENERATED BY EMPIRICAL AND DYNAMICAL METHODS - COMPARISON AND VERIFICATION*

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July 1986

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*OPC Contribution No. 2
GLERL Contribution No. 471

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1. INTRODUCTION

Accurate wave forecasts are very important to shippers, coastal industries, commercial fisheries, coastal residents, and recreational boaters and bathers. Lake activities are often interrupted by the destructive action of severe storms and waves. For example, in a storm on November 9, 1913, ten ships were sunk and 20 others were driven ashore with the loss of more than 250 lives. Lakes Huron and Superior were hardest hit. More recently, April 1979, the 315 ft ship LABRADOC, with a crew of 20, foundered on Lake Erie in 20 ft seas and 45 kt winds. Fortunately all hands aboard LABRADOC were rescued by helicopter.

To aid marine forecasters in preparing wave forecasts, automated wave height forecast guidance for the Great Lakes has been generated at the National Weather Service's (NWS) National Meteorological Center since January 1975. These forecasts are made with an empirical wave forcast method developed by NWS's Techniques Development Laboratory (TDL). Wind input to the method is from NWS automated wind forecasts. Recently NOAA's Great Lakes Environmental Research Laboratory (GLERL) and Canada's National Water Research Institute have developed a dynamical wave prediction model for the Great Lakes. This model, which may also be driven with NWS automated wind forecasts, is available to NWS Forecast Offices.

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An opportunity to compare and verify wave height forecasts generated by the two forecast methods presented itself when two sets of Lake Erie wave data were collected in September and October 1981. The first set of measurements is from a NOAA buoy, reporting real-time wave data via satellite, that is moored in the western part of Lake Erie (Fig. 1). The second set consists of nearly continuous measurements of wave height at a GLERL tower located 6 km off the southern shore of the Lake. See Fig. 1.

Before we present the results of our comparison and verification, we will briefly discuss wave generation and automated wind forecasts for the lake. This will be followed by a description of the two wave forecast methods and a comparison and evaluation of 24-h significant wave height (average height of the one-third highest waves of a given wave group) forecasts generated by these methods. The evaluation will include a look at measured data, plots of measured and forecast wave heights, and objective verification statistics. Conclusions and future plans based on this evaluation will also be presented.

2. WAVE GENERATION

Wave height and period are a function of fetch (distance over water that wind has essentially constant direction and speed), wind speed, and duration (length of time the wind has blown over the fetch). Waves are generated not only in the direction of the wind, but at various angles to the wind. The effect of a narrow fetch width, such as found on Lake Erie, is to enhance the contribution of wave growth by wave components from the maximum fetch direction, which may be different from the wind direction (Donelan, 1980).

Shallow water will also affect the height of the individual wave form. At a depth of about one-half the deepwater wave length, waves start to "feel" the bottom, and their height, length, and velocity begin to change. The height of the shoaling wave first decreases slightly and then increases until reaching the breaking point. As waves enter shallow water, they also undergo height changes due to refraction (bending of wave due to bathymetry). Since a typical period for a wave on Lake Erie is 4 s, a wave will begin to interact with the bottom in approximately 40 ft of water. As can been seen in Fig. 1, the NOMAD buoy and GLERL tower are located in less than 60 ft of water. Therefore, the larger waves measured at these locations have certainly been modified by the lake bottom.

3. AUTOMATED WIND FORECASTS

Input to both wave forecast methods are the automated Great Lakes wind forecasts. These forecasts, which have not been adjusted by inflation for either wave forecast method, are based on the Model Output Statistics (MOS) technique (National Weather Service, 1980). The predictors of the wind are various forecast elements computed by NMC's Limited-area Fine Mesh model. Wind forecasts, based on separate equations for summer and winter, are available twice daily to 48 h in advance at 6-h intervals for 12 areas of the Great Lakes. Figure 2 shows the two Lake Erie sectors for which wind forecasts are made. Forecasts are made for the center of each sector.

4. TDL WAVE FORECAST METHOD

The TDL method is based upon the work of Bretschneider (1970 and 1973). This method requires the estimation of such variables as fetch length and wind duration time. The following is a brief description of the method. For a complete write-up see Pore (1977).

A. Forecast Points

The selection of the specific forecast points (Fig. 3) 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 19 points indicated in Fig. 3. Some of these points were chosen to be along the axis of the lakes but most were chosen to be 5 mi from U.S. shore. This distance was used so that the points were not in the shallowest water very close to shore.

B. 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. 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 direction of the wind but at various angles to the wind.

C. Duration Time

In the automated wave forecast method, duration time is determined by checking the wind direction at 6-h 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. With wind directions available at 6, 12, 18, 24, 30, and 36 h before forecast time, the duration is therefore estimated to be 3, 9, 15, 21, 27, or 33 h.

D. Effective Wind Speed

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. For example, duration equal to 15 h is determined by:

$$\mathrm{EWS} = 0.5\ S_0 + 0.25\ S_{-6} + 0.125\ S_{-12} + 0.125_{-18},$$

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 h of the wind before the valid time of the wave forecast. This method was adapted from the TDL Ocean Wave Forecast Program, where it works successfully.

E. 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. An effective fetch is calculated for each of the duration times. The smaller of 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.

F. Forecast Equations

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

$$H = \frac{U^2}{g}\, 0.283 \tanh \left[0.0125 \left(\frac{gF}{U^2}\right)^{0.42}\right]$$

$$T = \frac{2\pi U}{g}\, 1.20 \tanh \left[0.077 \left(\frac{gF}{U^2}\right)^{0.25}\right]$$

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.

5. GLERL WAVE FORECAST METHOD

The GLERL method is based on a method originally proposed by Donelan (1977). It is a parametric type that numerically solves a local momentum balance equation on a numerical grid covering the lake. Schwab et al. (1984) modified the model to conform with the GLERL two-dimensional lake circulation modeling system (Schwab et al., 1981).

A. Forecasts Points

The computational grid used by the model is shown in Fig. 4. The Pelee Island in western Lake Erie (the largest one) is treated as a land square in this 10 km grid. This figure shows the relation between the artificial computational grid boundary and the actual shoreline of the lake. The grid size for the interactive version of the model was chosen as an acceptable compromise between the realistic resolution of the shoreline and computational speed. The computational effort involved in the numerical model increases very rapidly with decreasing grid size.

B. Wind Input

The interactive version of the model needs values of wind direction and speed at the chosen interval of 1, 2, 3, 4, 5, or 6 h. If some values are not available, the programs will interpolate between values. Although the model has the capability to incorporate spatially variable wind fields, the interactive version uses a uniform wind over the entire lake. Special versions of the model have been developed to incorporate spatially variable winds.

The program also has the capability to adjust wind measurements for height and stability, but, again, these features are not used in the operational model. It is assumed that the winds are representative overwater winds at 5 m above the water surface under neutral conditions (air temperature equal to water temperature). If the available wind measurements are from a different height above the water, the winds are overland winds, or the overlake air temperature is quite different from the water temperature, the wind speed input to the wave prediction system should be adjusted accordingly.

C. Model Formulation

The basic model equations relate the time rate of change of wave momentum and the divergence of the wave momentum flux to input from the wind:

$$\frac{\partial M_x}{\partial t} + \frac{\partial T_{xx}}{\partial x} + \frac{\partial T_{xy}}{\partial y} = \frac{T_x^w}{\rho_w} \qquad (1)$$

$$\frac{\partial M_y}{\partial t} + \frac{\partial T_{yx}}{\partial x} + \frac{\partial T_{yy}}{\partial y} = \frac{T_y^w}{\rho_w} \qquad (2)$$

The x and y momentum components are:

$$M_x = g \int_0^\infty \int_0^{2\pi} \frac{F(f,\theta)}{C(f)} \cos\theta \, d\theta \, df$$

$$M_y = g \int_0^\infty \int_0^{2\pi} \frac{F(f,\theta)}{C(f)} \sin\theta \, d\theta \, df$$

Here F (f,θ) is the wave energy spectrum as a function of frequency, f, and direction, θ. C(f) is the phase speed and g is the acceleration due to gravity. If we assume that deepwater linear theory applies and that wave energy is distributed about the mean wave direction as cosine squared, Schwab et al. (1984) show that the momentum fluxes can be expressed as:

$$T_{xx} = \left(\frac{\sigma^2}{4} \cos^2\theta_0 + \frac{\sigma^2}{8}\right) g$$

$$T_{xy} = T_{yx} = \left(\frac{\sigma^2}{4} \cos\theta_0 \sin\theta_0\right) g$$

$$T_{yy} = \left(\frac{\sigma^2}{4} \sin^2\theta_0 + \frac{\sigma^2}{8}\right) g$$

where σ^2 is the variance:

$$\sigma^2 = \int_0^\infty E(f)df = \int_0^\infty \int_0^{2\pi} F(f,\theta)\, d\theta\, df$$

and 0_o is the mean wave direction.

These equations also provide relationships between group velocity or peak energy (frequency), variance, and momentum that allow (1) and (2), on the previous page, to be solved for M_x, M_y, and σ once the right-hand side of the equation is specified. In this model the momentum input, the right-hand side of (1) and (2), is given by:

$$\frac{\vec{\tau}^w}{\rho_w} = 0.028 \; D_f \left| \vec{U} - 0.83 \vec{C}_p \right| (\vec{U} - 0.83 \vec{C}_p)$$

where D_f is a form of the drag coefficient defined as:

$$D_f = [0.4 \ln (50/\sigma)]^2$$

Where σ is in meters. The factor 0.028 is the empirical fraction of the stress that is retained by the waves. The important features of the momentum input formula are that the drag coefficient increases for higher waves and that the momentum input depends on the square of the difference between wind speed ($\vec{u}$)and 0.83 times the phase velocity ($\vec{C}_p$).

The main assumption in the present formulation of the model that would be of concern to a forecaster is that the waves are assumed to be governed by linear deep water theory. This means that shoaling, refraction, and breaking are ignored so that even in the grid boxes nearest to shore, the waves are assumed to be unaffected by finite water depth. This limitation may be of some importance in certain parts of Lake Erie. The fossil wave field (swell) is not considered.

6. COMPARISON AND VERIFICATION

For comparison and verification purposes TDL wave forecasts at the forecast points closest to the buoy and tower (points 8, approximately 15 km from the buoy, and 13, about 25 km from the tower respectively, shown in Fig. 3) were used. Referring to the grid for the GLERL method (Fig. 4), forecasts for grid square (10,5) were compared to buoy measurements while forecasts for grid square (28, 9) were compared to tower measurements. Each grid square is about 5 km from the respective measurement platform.

Let's briefly look at the wave data at the buoy and tower. There were a 109 buoy measurements, during the two month period, that could be compared to the 24-h forecasts. The mean measured buoy wave height was 0.84 m. Heights ranged from 0.1 m to 2.2 m. Approximately 95 percent of the measurement were within the 0.1 m to 1.7 m range.

Measurements at the tower were similar, ranging from 0.2 m to 2.4 m with an average value of 0.74 m. However, there were only about half as many measurements at the tower as there were at the buoy.

It is important to keep in mind that forecast winds are used as input for both wave forecast methods. If we assume that all our wave measurements are error free, then the difference between the measured and forecast height is either due to the wind forecast or the wave forecast method. Because we are interested in evaluating the forecast wave height and not the specified (hindcast) height, wind forecasts rather observed winds were used as input to the wave models.

Before we present wave verification statistics it may be helpful to look at plots of the measured and 24-h wave height forecast at the buoy and tower. Fig. 5a shows plots of the buoy measurements and the 24-h GLERL significant wave height forecasts. The corresponding TDL 24-h forecasts are shown in Fig. 5b. TDL forecast are only made to the nearest foot. GLERL forecasts are plotted to the nearest 0.1 m.

The location of each pair of heights is designated by the letter "A". If two pairs of height have the same values, their location is denoted with a "B", three pairs "C", and so on. A line of "perfect fit" is indicated in each figure. For both sets of forecasts there is scatter about the line of "perfect fit". The GLERL method tends to underforecast wave height at the buoy (more plots above than below the line of "perfect fit"). However, the TDL method overforecasts the wave height at the buoy.

The extreme wave measurement 2.2 m is forecast reasonablely well by both methods. The GLERL method underforecasts this height by 0.2 m while the TDL method overforecasts by 0.2 m.

Plots of measurements and forecasts for the southern portion of the Lake (the tower) are shown in Figs. 6a and 6b. Like the plots for the buoy, there is scatter about the line of "perfect fit". However, the scatter is not as great as at the buoy. Keep in mind that there are only half as many measurements at the tower as there are at the buoy. The TDL method tends to over forecast. The GLERL method greatly overforecasts one of the larger wave heights.

For a more objective verification we have computed a number of verification statistics. Correlation coefficients, mean algebraic errors, root-meansquare errors (RMSE), weighted RMSE, and threat scores have been computed for forecasts generated by both methods.

The weighted RMSE (WRMSE), a new verification score introduced by Richardson and Gilman (1983), is calculated in the same manner as the RMSE when the measured significant wave height is 1 m or less. For heights greater than 1 m, the error (observed minus forecast) is weighted by multiplying the error by the measured wave height. The mathematical expression for WRMSE is:

$$\sum_{i=1}^{n} \left(\frac{[(O_i - F_i) W_i]^2}{n} \right)^{1/2} ,$$

where:

n = number of observations,
O_i = i-th measured wave height,
F_i = i-th forecast wave height, and
W_i = i-th weight without units, where
$W_i = 1$ if $|O_i| \leq 1$, or $W_i = O_i$ if $|O_i| > 1$.

This statistic gives a heavier weight to an error that occurs when the measured height is greater than 1 m. Errors associated with high wave heights are more critical and are therefore given more weight.

The threat score $\left[\frac{\#\text{ hits}}{\#\text{ forecasts} + \#\text{ measured} - \#\text{ hits}}\right]$ is the relative frequency of correctly forecasting the event when the event was a threat. Threatening situations are those in which a wave height of 1.5 m occurred or was forecast to occur. A perfect threat score is 1.

Scores in the upper part of Table 1 are based on all buoy data. The scores shown in the lower part of the table were computed from peak (measured wave height equaled or exceeded 1 m) data, which was approximately 37 percent of the total data.

For all data (109 sets) the correlation coefficient, and threat score associated with both methods are approximately the same. The RMSE, weighted RMSE, and mean algebraic error associated with the TDL method are a little lower (better) than the corresponding scores associated with the GLERL method. These same comments also hold for the peak data, shown in the lower part of the table. Note that the threat score associated with the TDL forecasts is a little better (nearer to 1) than the corresponding GLERL score.

Verification scores (Table 2) associated with tower data, in the Southern portion of the Lake, look a little different. The correlation coefficient associated with both methods are much larger for forecasts at the buoy. Keep in mind that correlation coefficients associated with the tower are based on only 68 sets of data. The weighted RMSE associated with the TDL method is lower (better) that the weighted RMSE associated with the GLERL method. However, the mean absolute error favors the GLERL method.

For peak data at the tower (lower part of Table 2) all verification scores except the mean algebraic error point to the TDL method as the better method. Also, the threat score associated with the TDL method is about 30 percent higher (0.67 compared to 0.50) than the corresponding GLERL score. Peak data account for only about 20 percent of the tower data.

7. HIGH WAVE EVENT

The highest wave event, which occurred during the two months of collected data, was associated with a low pressure system on October 18, 1981. This system moved from central Canada to the Great Lakes area. At 0700 A.M. EST October 18 the low was centered over Saulte Ste. Marie with a central pressure of 980 mbs. See Fig. 7. During the 18th Lake Erie was under the influence of southwesterly winds. Winds along the shores of the western and central portion of the Lake averaged 20 kts. Winds at Buffalo averaged about 25 kts with gust to 45 kts.

The measured significant wave height and the 24-h forecasts generated by the GLERL and TDL methods for the buoy and tower locations are plotted in the upper and lower part respectively of Fig. 8. Both forecasts are in reasonable agreement with the measured heights. However, both methods overforecast the maximum wave heights measured at the tower. Maximum wave height of 2.2 m and 2.4 m were measured at the buoy and tower respectively.

8. CONCLUSIONS

Verification scores for all data indicate little difference between the accuracy of the two methods. However, verification scores associates the peak data sample show that the TDL method gives the more accurate forecasts. Based on this study and keeping in mind the small sample size, we recommend that the TDL method continue to be used as the forecast guidance for Lake Erie.

We also recommend that the two methods be verified and compared on a larger sample of data such as used by Kieltyka (1985). This sample of data consisted of measured data at two buoys in the western end of the Lake for the period July through November 1983. In this study wave forecasts generated by the TDL method were compared and verified with data measured at the two buoys. Kieltyka concluded that overforecasts are largely due to the wind forecasts. Wind forecasts are based on 20-m level winds, while the TDL wave method is designed for winds at the 10 m level. With regard to winds, the TDL method has a built in wind smoothing operator in that winds are weighted and averaged. It might be interesting to weight and average the winds used in the GLERL method.

Forecasts appear to be better for the southern portion (tower) than they are for the western end (buoy) of the Lake. This could be attributed to smaller sample of data at the tower and the lack of complications due to the small islands located to the northwest of the buoy.

A final point which should be emphasized is that the TDL method forecasts for discrete points. The GLERL methods allows a forecast at any grid point and therefore gives a better picture of wave conditions on the lake. For this reason marine forecasters should be encouraged to use the interactive wave forecast method (Schwab et el., 1984) developed by GLERL and where possible compare the forecasts from this method to the TDL guidance.

ACKNOWLEDGMENTS

A special thanks to the NOAA Data Buoy Office and GLERL for providing wave data. We are also grateful to Herman Perrotti for providing TDL wave forecasts, Carolyn McCray and Robin Snyder for typing the manuscript, and Patrick McHugh for his careful editing.

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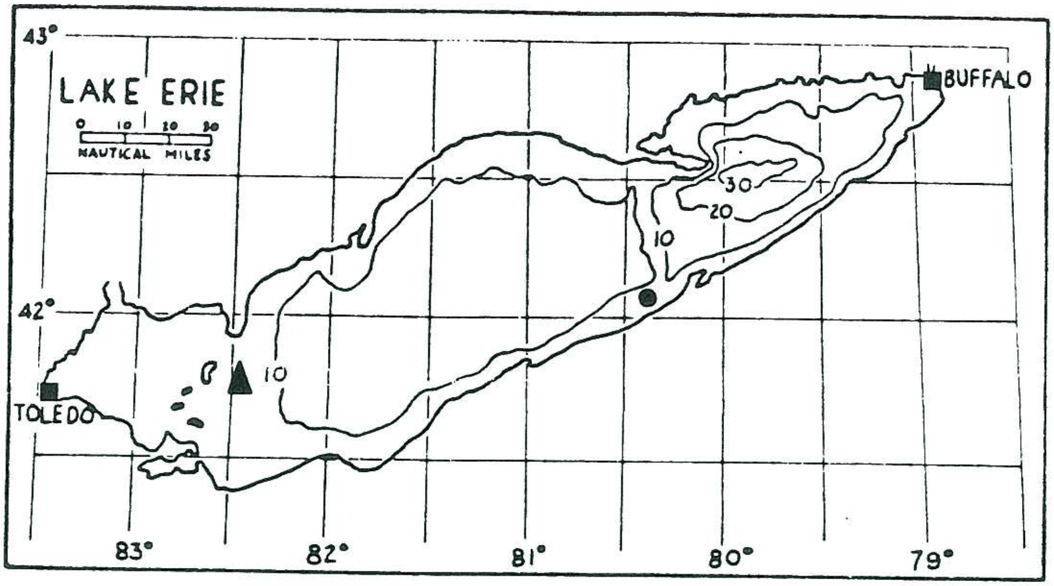

Figure 1. Configuration of Lake Erie and the location of the NOMAD buoy (western end) and the GLERL tower (eastern end). Depth contours are shown at 10-fathom intervals (1 fathom = 6 ft). The location of the buoy and tower are depicted by a filled triangle and circle respectively.

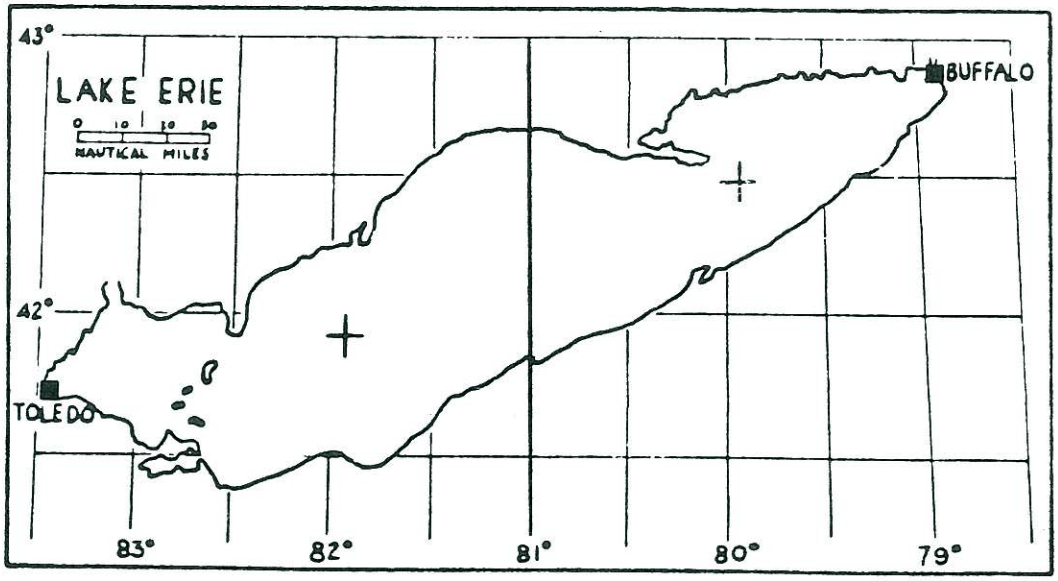

Figure 2. Two locations on Lake Erie for which MOS wind forecasts are made.

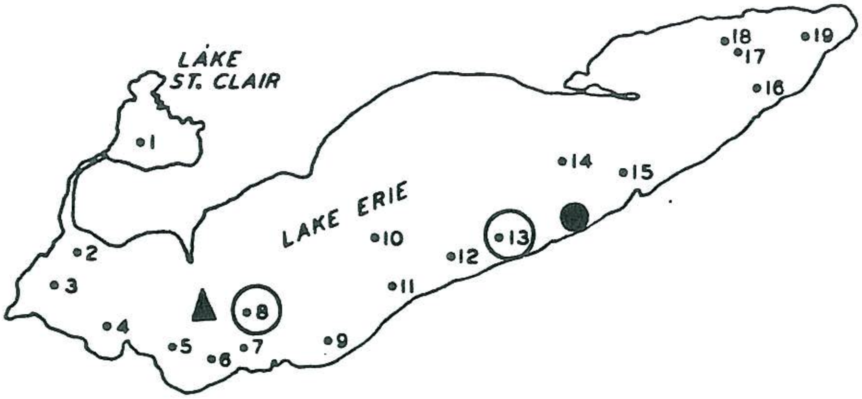

Figure 3. Location of 19 points where significant wave height forecasts are made by the TDL method. Points closest to locations of measured data are circled. A filled triangle and circle indicate the location of the buoy (western portion) and tower (southern position).

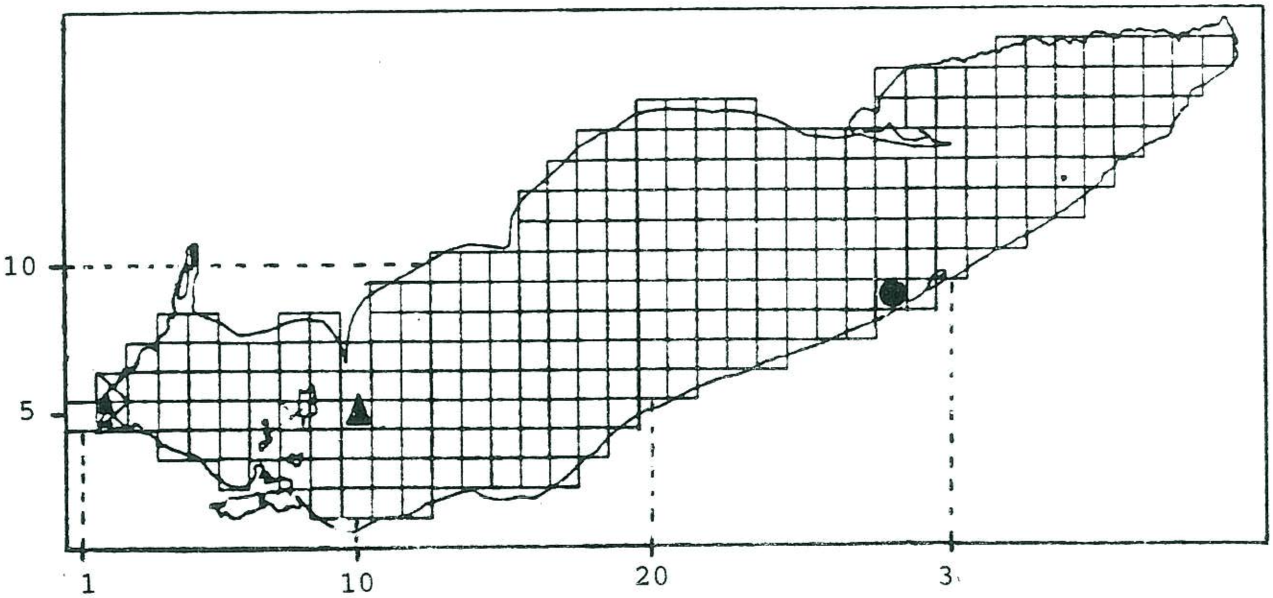

Figure 4. Computational grid used by the GLERL method. Forecasts are made at the center of each grid square. The location of the buoy and tower are depicted by a filled triangle and circle respectively.

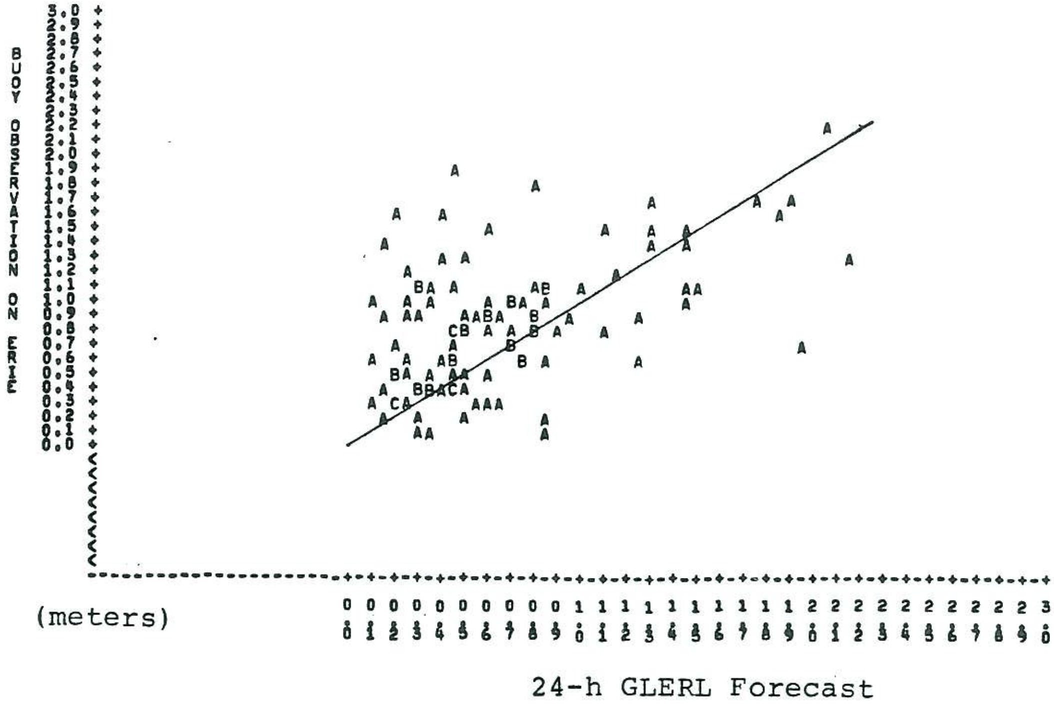

Figure 5a. Plots of buoy measurements and the 24-h GLERL significant wave height forecasts. The location of each pair of heights is designated by the letter "A". If two pairs of heights have the same values, their location is denoted with a "B", three pairs "C", and so on. A line of "perfect fit" is also shown.

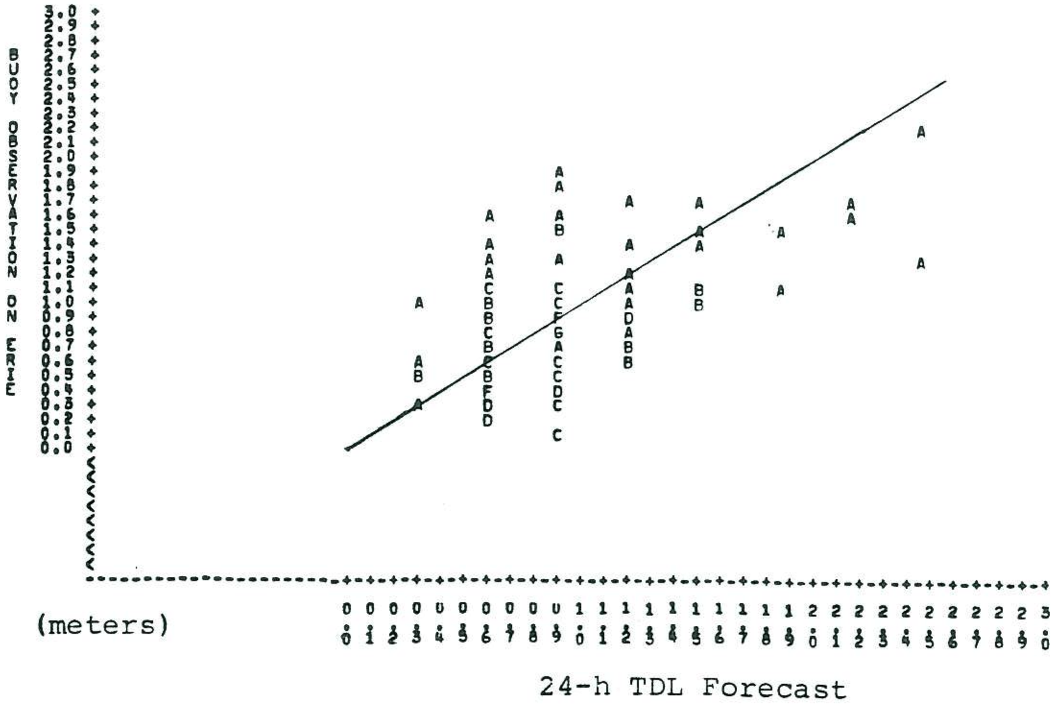

Figure 5b. Same as Figure 5a. except for 24-h TDL significant wave height forecasts.

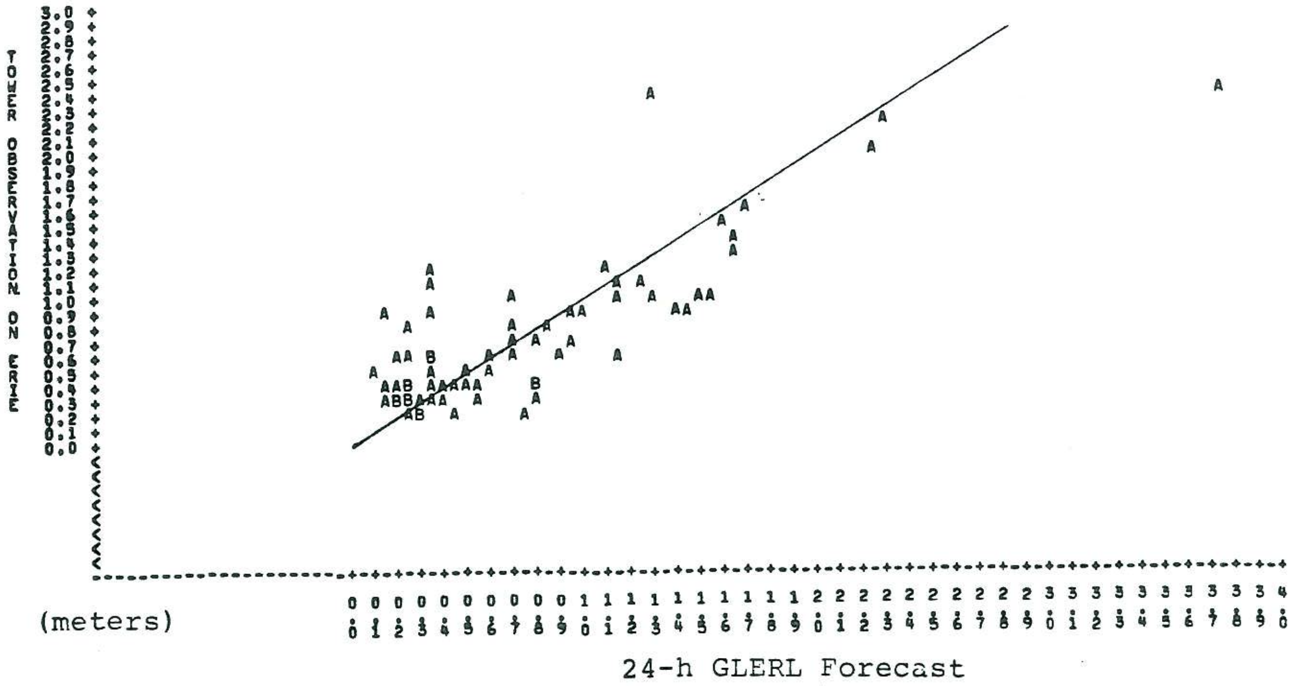

Figure 6a. Plots of tower measurements and the 24-h GLERL significant wave height forecasts. The location of each pair of heights is designated by the letter "A". If two pairs of heights have the same values, their location is denoted with a "B", three pairs "C", and so on. A line of "perfect fit" is also shown.

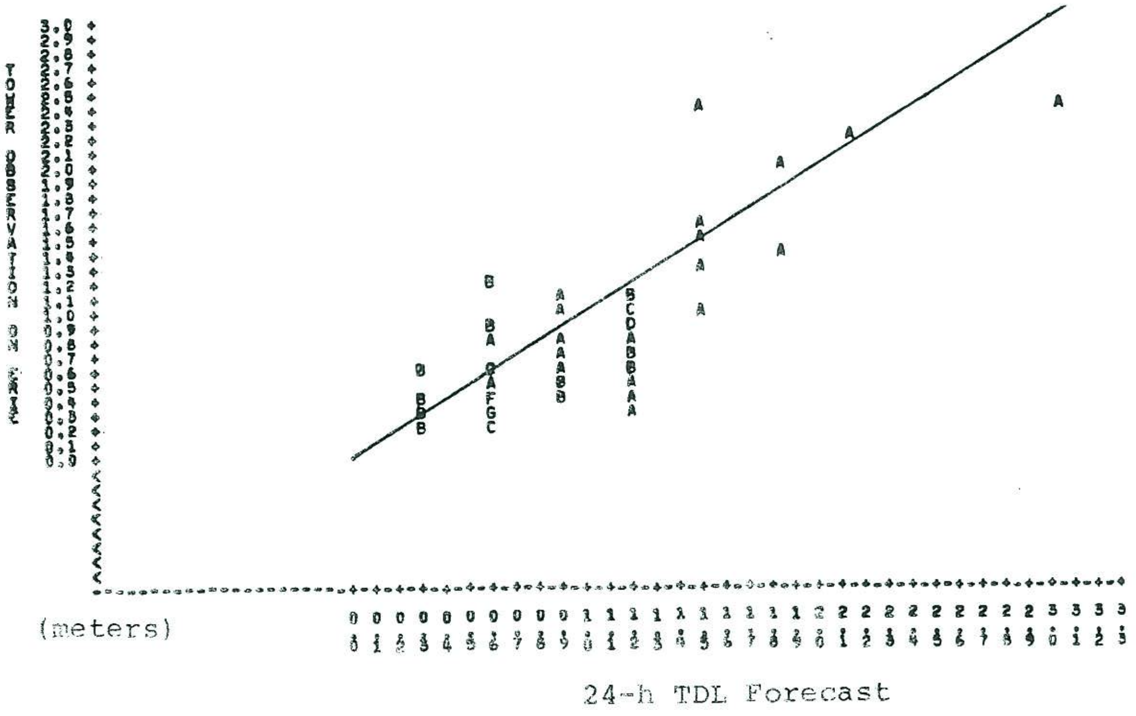

Figure 6b. Same as Figure 6a, except for 24-h TDL significant wave height forecasts.

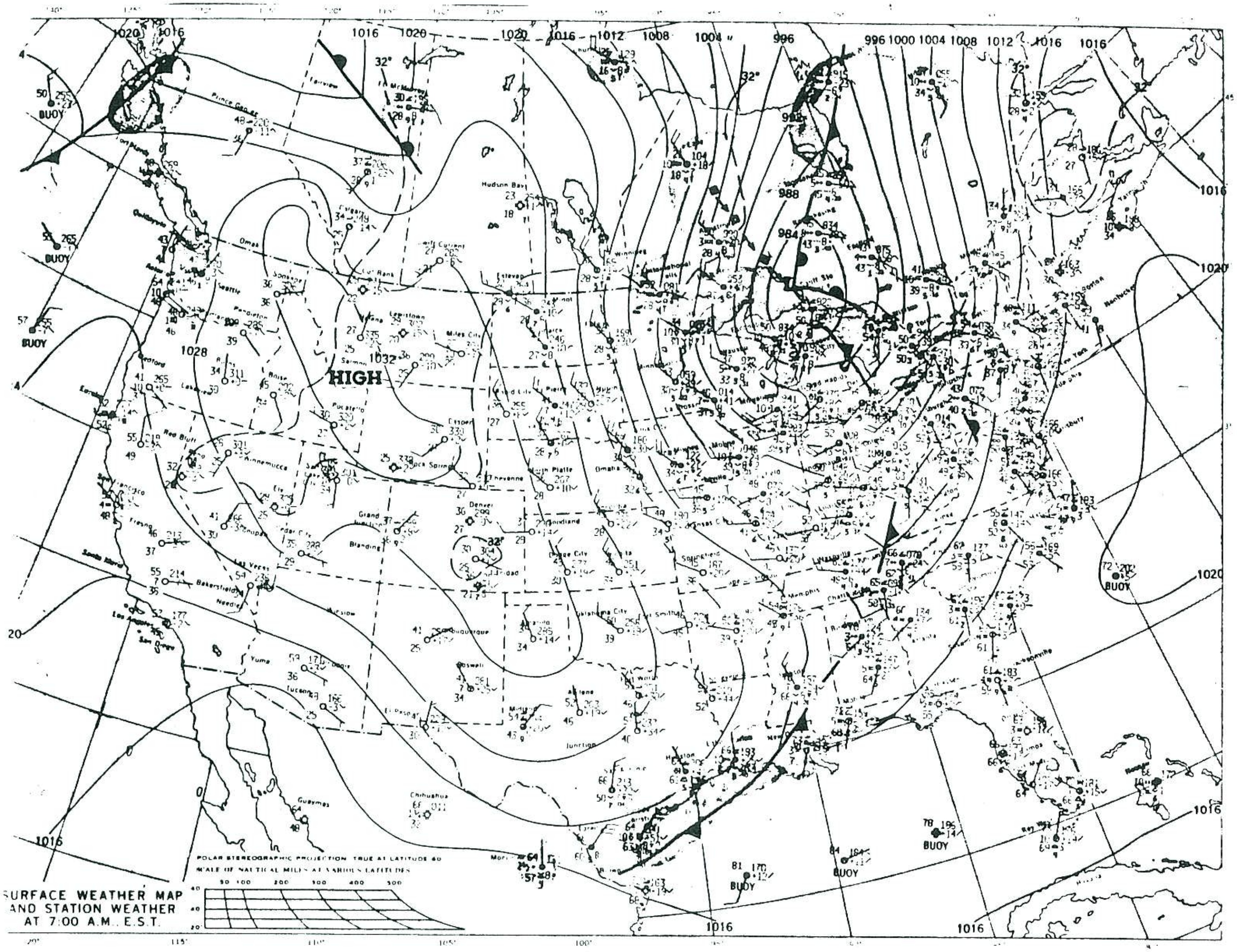

Figure 7. Weather pattern associated with the October 18, 1981 high wave event.

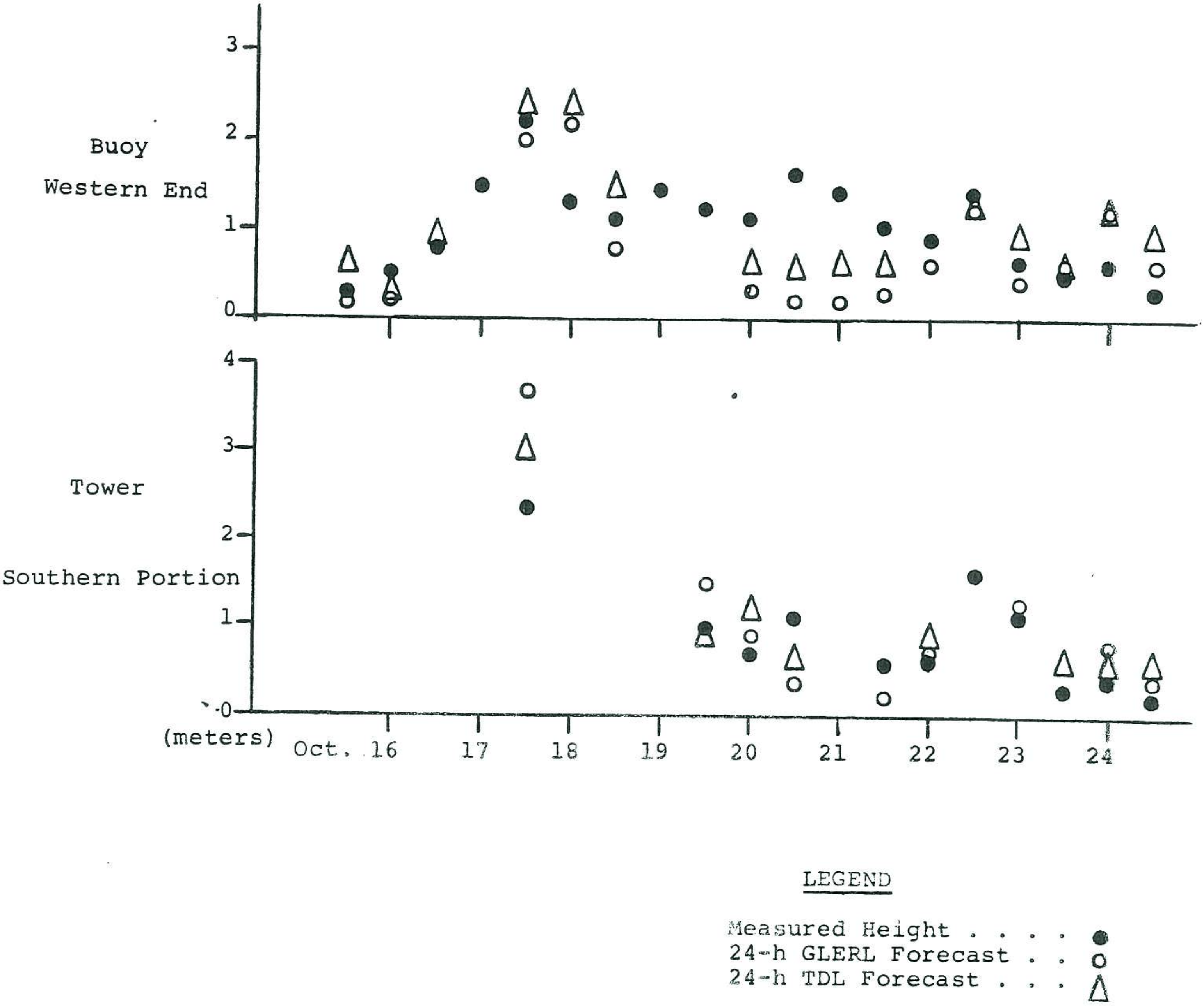

Figure 8. The measured significant wave heights and the 24-h forecasts generated by the GLERL and TDL methods for the buoy and tower locations for October 16 - 24, 1981. Coincident plots of forecasts and measurements are plotted as measurements. The date of each day is placed at 1200 GMT. Buoy measurements and forecasts are plotted in the top part of the figure. Tower measurements and forecasts are shown in the lower part.

Table 1. Verification scores associated with the TDL and GLERL 24-h Lake Erie wave forecasts at the buoy.

All Data	TDL Forecast	GLERL Forecast
Correlation Coefficient	0.53	0.52
Mean Algebraic Error (meters)	-0.09	0.18
RMSE (meters)	0.42	0.48
Weighted RMSE (meters)	0.54	0.63
Peak Data		
Correlation Coefficient	0.38	0.40
Mean Algebraic Error (meters)	0.15	0.40
RMSE (meters)	0.52	0.66
Weighted RMSE (meters)	0.75	0.95
Threat Score	0.30	0.25

Table 2. Same as Table 1 except for the tower at the eastern end of Lake Erie.

All Data	TDL Forecast	GLERL Forecast
Correlation Coefficient	0.79	0.81
Mean Algebraic Error (meters)	-0.19	-0.03
RMSE (meters)	0.37	0.37
Weighted RMSE (meters)	0.47	0.59
Peak Data		
Correlation Coefficient	0.79	0.71
Mean Algebraic Error (meters)	0.06	-0.04
RMSE (meters)	0.38	0.58
Weighted RMSE (meters)	0.74	1.17
Threat Score	0.67	0.50