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NOAA Technical Memorandum NWS TDL-69

COMPARISON AND VERIFICATION OF DYNAMICAL AND STATISTICAL LAKE ERIE STORM SURGE FORECASTS

Techniques Development Laboratory
Silver Spring, Md.
November 1979

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COMPARISON AND VERIFICATION OF DYNAMICAL AND STATISTICAL LAKE ERIE STORM SURGE FORECASTS

William S. Richardson
Techniques Development Laboratory
Systems Development Office
and
David J. Schwab
Great Lakes Environmental Research Laboratory
Ann Arbor, Mich.

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Richard A. Frank, Administrator
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Richard E. Hallgren, Director

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William S. Richardson
Techniques Development Laboratory
National Weather Service, NOAA
Silver Spring, Md. 20910

and

David J. Schwab
Great Lakes Environmental Research Laboratory, NOAA
Ann Arbor, Mich. 48104

ABSTRACT. The Great Lakes Environmental Research Laboratory and the Techniques Development Laboratory have compared Lake Erie storm surge forecasts produced by a dynamical and a statistical method for several months in 1977 and 1978. The dynamical method yields much better forecasts at Buffalo and slightly better forecasts at Toledo.

1. INTRODUCTION

Storm-generated lake level fluctuations (storm surges) can cause serious problems on Lake Erie. Flooding and shoreline erosion occur when positive surges are superimposed on high lake levels. During times of low lake levels, negative surges can be hazardous to navigation and disturb hydroelectric power generation. The National Weather Service (NWS) is responsible for preparing and issuing storm surge forecasts for the lake. Since 1969 NWS has used a statistically derived storm surge forecast technique, developed by Richardson and Pore (1969) at the Techniques Development Laboratory (TDL), to generate automated storm surge forecast guidance for Buffalo, N.Y. and Toledo, Ohio. The automated storm surge forecast guidance has proved to be a useful forecast tool.

The development of an automated objective method to forecast winds over the Great Lakes by Feit and Barrientos (1974) prompted an investigation by the Great Lakes Environmental Research Laboratory (GLERL) to determine whether a dynamical storm surge model developed by Schwab (1978) could take advantage of these computer generated winds to improve the storm surge forecasts for Lake Erie. The dynamical forecast model is a two-dimensional refinement of one that was proposed by Platzman (1967) but not implemented operationally. Preliminary tests with this linear-finite difference model were so encouraging that GLERL and TDL decided to make objective comparisons between storm surge forecasts made with the GLERL dynamical model and forecasts produced by the TDL statistical method.

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*GLERL Contribution No. 191

The comparison and verification of dynamical and statistical forecasts with measured surge data will be the basis for making a recommendation to NWS as to which method or combination of methods should be used to produce Lake Erie storm surge forecast guidance. Before we present this comparison and verification, the causes of Lake Erie storm surges and two methods used to forecast these surges will be discussed briefly.

2. CAUSES OF STORM SURGES

Lake Erie storm surges are generally associated with the passage of extratropical storms through the Great Lakes area. Winter storms that approach the Great Lakes from the central part of the country can cause strong winds over Lake Erie. When these strong winds blow along the main axis of the lake, storm surges are generated. Strong southwest winds blowing over the lake cause a tilted lake surface--the water level is elevated in the eastern portion of the lake (Buffalo end) and lowered at the western end (Toledo). Storm surge heights and surface winds associated with an extreme example of this situation are shown in figure 1. Occasionally a storm will pass south of Lake Erie causing northeast winds over the lake. When this happens, the slope of the water surface is reversed with elevated water levels at the Toledo end of the lake. An extreme event of this type is shown in figure 2.

Storm surges on Lake Erie are caused primarily by wind stress on the lake surface. The effect of atmospheric pressure, which causes higher water levels in areas of low pressure, is less important. Storm surges are especially pronounced on Lake Erie because of its shallow depth and geographic orientation.

3. FORECAST METHODS

3.1 Dynamical

The dynamical method uses impulse response functions to calculate the storm surge height. The surge at a given time is calculated as the weighted sum of forcing terms during some period before the specified time, i.e.

$$h_k = \sum_{i=1}^{m} \sum_{j=1}^{n} \vec{g}_{ij} \cdot \vec{\tau}_{ik-j} \ . \qquad (1)$$

Here the surge at time k is h_k, $\vec{g}_{ij}$ is the water level response at time j due to an impulse from forcing station i, $\vec{\tau}_{ik-j}$ is the forcing function at station i and time k-j, m is the number of forcing stations, and n is the length of the response function. The forcing function is calculated as

$$\vec{\tau}_{ij} = c|\vec{V}_{ij}|\vec{V}_{ij}, \qquad (2)$$

where $\vec{V}_{ij}$ is the wind vector at station i and time j, and c is a dimensionless constant, 4×10^{-6}.

The response functions $\vec{g}_{ij}$ were calculated by means of a linear finite difference numerical model of Lake Erie as described by Schwab (1978). To take into account hourly changes in the forcing function, the response functions are recorded as hourly values. We determined that a 36-h response function was sufficient for Lake Erie storm surges. Water level responses at Buffalo and Toledo were computed for forcing at the two Lake Erie wind forecast points shown in figure 3 (numbers 3 and 4) plus Buffalo and Toledo. Forcing functions for storm surge forecasts are calculated according to (2) with hourly winds interpolated from the 6-h automated wind forecasts over Lake Erie (Feit and Barrientos 1974) and the 6-h automated surface wind forecasts at Buffalo and Toledo (Carter 1975). It was also shown by Schwab (1978) that when hourly winds observed at seven airports around the lake were used as forcing functions, the dynamical model produced excellent results (see fig. 4).

3.2 Statistical

The currently operational statistical method was developed by Richardson and Pore (1969). Water level deviations from the monthly mean at Buffalo and Toledo (storm surges) were correlated with analysed 6-h sea level pressure at grid points of the National Meteorological Center's (NMC's) Primitive Equation model (Shuman and Hovermale 1968), shown in figure 3. A screening correlation program (Miller 1958) was used to find the best predictors of storm surges. The regression equations have the form

$$h_k = A_o + \sum_{j=1}^{n} A_j P_j, \qquad (3)$$

where h_k is the storm surge at time k, A_o is a constant, A_j is a regression coefficient, P_j is the sea level pressure at a NMC grid point with lag times of 0, 1, 2, 3, 4, or 5 hours, and n is the number of predictors. In 1973 the regression equations were rederived with sea level pressure and storm surge data from 1940 to 1971. Six equations were derived for Buffalo, one for each hour. Three equations were derived for Toledo because water level data, which were used in the development of the equations, were available for even hours only. Observed pressures at NMC grid points, 2, 3, 7, 8, 12, and 13 in figure 3 were used as predictors with lags of 0, 1, 2, 3, 4, or 5 hours. Operational storm surge forecasts were made with sea level pressure forecasts of the NMC Limited-area Fine Mesh II model (National Weather Service 1977). We found that the use of multiple equations caused spurious oscillations in the statistical storm surge forecasts. We remedied this problem by applying only one equation for each 6-h interval between pressure forecasts. The equation used was the one which predicted the greatest water level fluctuation during the 01- to 48-h forecast period.

4. COMPARISON AND VERIFICATION

The dynamical and statistical methods were compared and verified with measured storm surge data from November and December 1977, and April, November, and December 1978. Storm surge data from these months were chosen because an earlier study (Pore et al. 1975) showed that the most significant surges occurred during these months. Also, there is generally little lake ice to interfere with storm surge generation during November, December, and April.

The comparison and verification consist of analyses of measured and forecast storm surge events and overall statistical measurements for the entire 5-month period. Storm surge events are times when significant storm surges (magnitude of the surge is 3 ft or greater) occurred or were forecast to occur by either method at Buffalo or Toledo[1]. The statistical measurements consist of correlation coefficients and root-mean-square errors (rmse's).

While 0- to 36-h surge forecasts were verified and compared, only the verification and comparisons of the 13- to 24-h forecasts are presented in this paper, as we determined this period to be the most significant for operational forecasts. These midrange forecasts are representative of the total range of forecasts. Observed and forecast storm surge graphs, correlation coefficients, and rmse's are presented first for Buffalo and then for Toledo. The observed and forecast storm surge heights are plotted every hour for Buffalo and every 2 hours for Toledo. Figures containing pairs of surge graphs depict the observed surge and dynamical forecast in the top panel of each pair. The lower panel of the pair shows the observed surge and statistical forecast for the same event. The dynamical method forecasts water level deviations from the average lake level while the statistical method forecasts surges relative to <u>station</u> mean levels. Therefore, observed water level deviations are shown relative to the lakewide mean level for the dynamical method and relative to the station mean for the statistical method. Lake and station means differ by no more than 0.5 ft. No attempt is made to distinguish storm surges from seiches. All departures of the lake level at Buffalo and Toledo from an averaged lake level or a station mean are referred to as storm surges. Time is GMT.

4.1 Buffalo

Figure 5 compares observed peak surges with forecast peak surges for Buffalo. This comparison, which is shown for storm surge events when the magnitude of an observed or forecast peak surge is equal to or greater than 3 ft, reveals the following:

1. The statistical method forecasts large negative surges when none are observed (15 cases) and overforecasts by 4 ft the one observed large negative surge.

2. The statistical method overforecasts minor positive surges by about 2 ft (5 cases).

3. <u>Both</u> methods underforecast large positive surges by 2 to 3 ft (6 cases).

The probable causes for these discrepancies are examined in a later section. Here we will only describe and summarize the results of the comparison and verification.

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[1] Storm surge height is given in feet, the unit used operationally by the National Weather Service.

The observed large negative surge at Buffalo, and three cases for which the statistical method overforecasts minor negative surges, are shown in figure 6. For these four events, the dynamical forecasts are in excellent agreement with measured surges. Minor positive surges (less than 3 ft) are overforecast by the statistical method on November 27, 1977, December 17, 1978, and December 25, 1978 (fig. 7). The dynamical forecasts are again in good agreement with measured surges.

Figure 8 shows examples of peak positive surges which were underforecast. The dynamical method underforecasts the first surge of the "double peak" event (December 2, 1977) by more than 3 ft. The statistical method underforecasts the same peak by about 2 ft. While both methods hint at a second peak, this peak is also underforecast by both methods. This is an interesting case, in that the two peak surges are associated with only one storm system. The second peak appears to be related to the natural period of Lake Erie which is about 14 hours. The storm surge on December 25, 1977 is also underforecast by about 2.5 ft by both forecast methods. Storm surges that occurred on November 18, 1978 and December 5, 1978 are underforecast by about 5 ft by both methods. The December 21, 1978 event is underforecast by 3 ft by the dynamical method, while the statistical method underforecasts this event by 2 ft. Both methods forecast the peak surges to occur 1 to 4 hours too late.

The comparison of the Buffalo surge forecasts generated by the dynamical and statistical methods may be summarized as follows: In a number of cases, significant surges are underforecast by both methods. Negative surges are forecast very well by the dynamical method, while the statistical method overforecasts these surges by significant amounts. The statistical method sometimes overforecasts small positive surges. We therefore conclude that the dynamical method yields much better storm surge forecasts at Buffalo than the statistical method. The summary statistics, shown in table 1, reinforce this conclusion. The correlations between the dynamical forecasts and the observed water level fluctuations are about 5 to 15 percent higher than the correlations associated with the statistical method. The rmse's associated with the dynamical method are 0.3 to 1.0 ft lower (25% to 65% lower) than the rmse's associated with the statistical method.

4.2 Toledo

A comparison of observed peak surges with forecast peak surges for Toledo storm surge events when the magnitude of the observed or forecast peak surge was equal to or greater than 3 ft is depicted in figure 9. This figure points out the following:

1. The statistical method overforecasts minor positive surges by about 2 ft (4 cases).

2. Both methods are in fair agreement with the commonly observed negative surges (20 cases) and the single observed large positive surge.

The statistical method overforecasts minor positive surges. Examples are shown in figure 10. Minor positive surges are forecast very well by the dynamical method. Figure 11 shows the one observed large positive surge and three typical negative surges at Toledo. Both methods forecast the positive surge on December 5, 1977. On December 9, 1977 the dynamical method overforecasts the large negative surge. Both methods slightly overforecast the smaller negative surge on December 25, 1977. The statistical method overforecasts the negative surge on December 21, 1978. Both methods tend to forecast peak surges 3 to 6 hours too late.

For Toledo we conclude that the dynamical method is slightly better than the statistical. However, the superiority of one forecast method over the other is not nearly as clear as in the Buffalo comparison. The correlation coefficients and rmse's shown in table 2 also support the conclusion that the dynamical method works better. The correlations for the dynamical forecasts are 10 to 15 percent higher than for statistical forecasts. The rmse's for the dynamical forecasts are 0.3 to 0.5 ft lower (20 to 40 percent lower) than those for the statistical forecasts.

5. CONCLUSIONS AND RECOMMENDATIONS

As pointed out by Richardson and Pore (1969), the statistical method produces good forecasts for storm surge cases which are similar to cases used in development. The negative surge cases observed at Toledo and some positive surges at Buffalo were forecast well by the statistical method. However, the statistical method produces poor forecasts at both Buffalo and Toledo for small surges due to southwest winds, and for most surges generated by northeast winds. This is because the cases used to develop the statistical regression equations were usually large surges associated with southwest winds. Very few cases of northeast winds and no cases of small (less than 3 ft) surges were included in the development data. This often causes the statistical method to "cry wolf" by forecasting a large surge when none is observed. The infrequent case of northeast winds causes high water at the western end of Lake Erie which is highly susceptible to flooding; so an accurate forecast for these cases is important.

Both the statistical and dynamical methods underforecast peak positive surges at Buffalo (see figure 5). Note that during this test period the distribution of peak positive observed surges at Buffalo is bimodal (6 cases about 3 ft and 6 cases about 6 ft). Both the statistical and dynamical methods are in some sense "tuned" to average surge conditions (3 to 4 ft). The statistical method is "tuned" with the developmental data while the dynamical method is "tuned" by the choice of the drag coefficient. Because peak positive surges at Buffalo were higher than average, the forecasts tended to be too low.

The accuracy of the dynamical method is also directly affected by the accuracy of the wind forecasts. Figure 4 is an example of the results that can be obtained when hourly winds from seven stations around the lake are used to drive the dynamical model. Increased temporal and spatial resolution in the wind forecasts would result in even better storm surge forecasts by the dynamical method.

On the basis of this comparison and verification of dynamical and statistical storm surge forecasts at Buffalo and Toledo <u>we recommend that the dynamical forecast method be used in place of the currently operational statistical method</u>. We also recommend continued verification of the forecasts produced by the dynamical method once they become operational. Significant storm surge events that are not forecast adequately, or events that are forecast to be significant when they are not, should be investigated event-by-event to determine whether the inadequate forecasts are the fault of the method or the fault of the wind forecasts that serve as input to the method. These studies may give us insight into how the forecast method can be improved.

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Table 1.--Summary of correlation coefficients and rmse's associated with the dynamical and the statistical Buffalo storm surge forecasts for November and December 1977, and April, November, and December 1978.

	Dynamical method		Statistical method	
	Correlation coefficient	rmse (ft)	Correlation coefficient	rmse (ft)
November 20 - December 27, 1977	0.74	0.99	0.70	1.33
April 2-27, 1978	0.61	0.60	0.58	1.68
November 5 - December 31, 1978	0.71	0.74	0.62	1.39

Table 2.--As in table 1, except for Toledo.

	Dynamical method		Statistical method	
	Correlation coefficient	rmse (ft)	Correlation coefficient	rmse (ft)
November 20 - December 27, 1977	0.63	1.22	0.54	1.50
April 2 - 27, 1978	0.69	0.73	0.64	1.23
November 5 - December 31, 1978	0.78	0.72	0.71	1.24

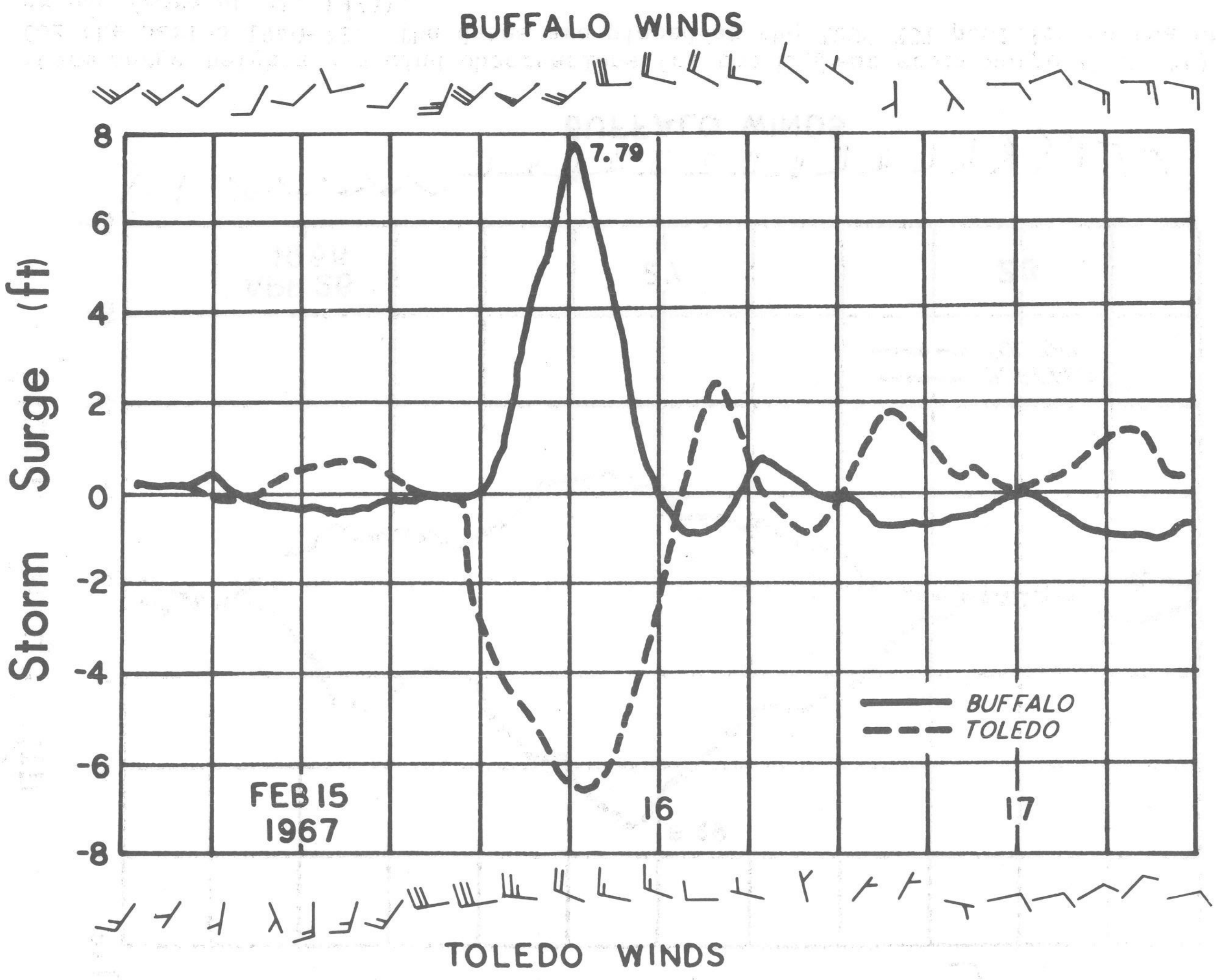

Figure 1.--Storm surge heights and wind observations for the highest storm surge (7.79 ft) at Buffalo for the period 1940-72. The dates are placed at the 1200 EST position on the storm surge graphs (Pore et al. 1975).

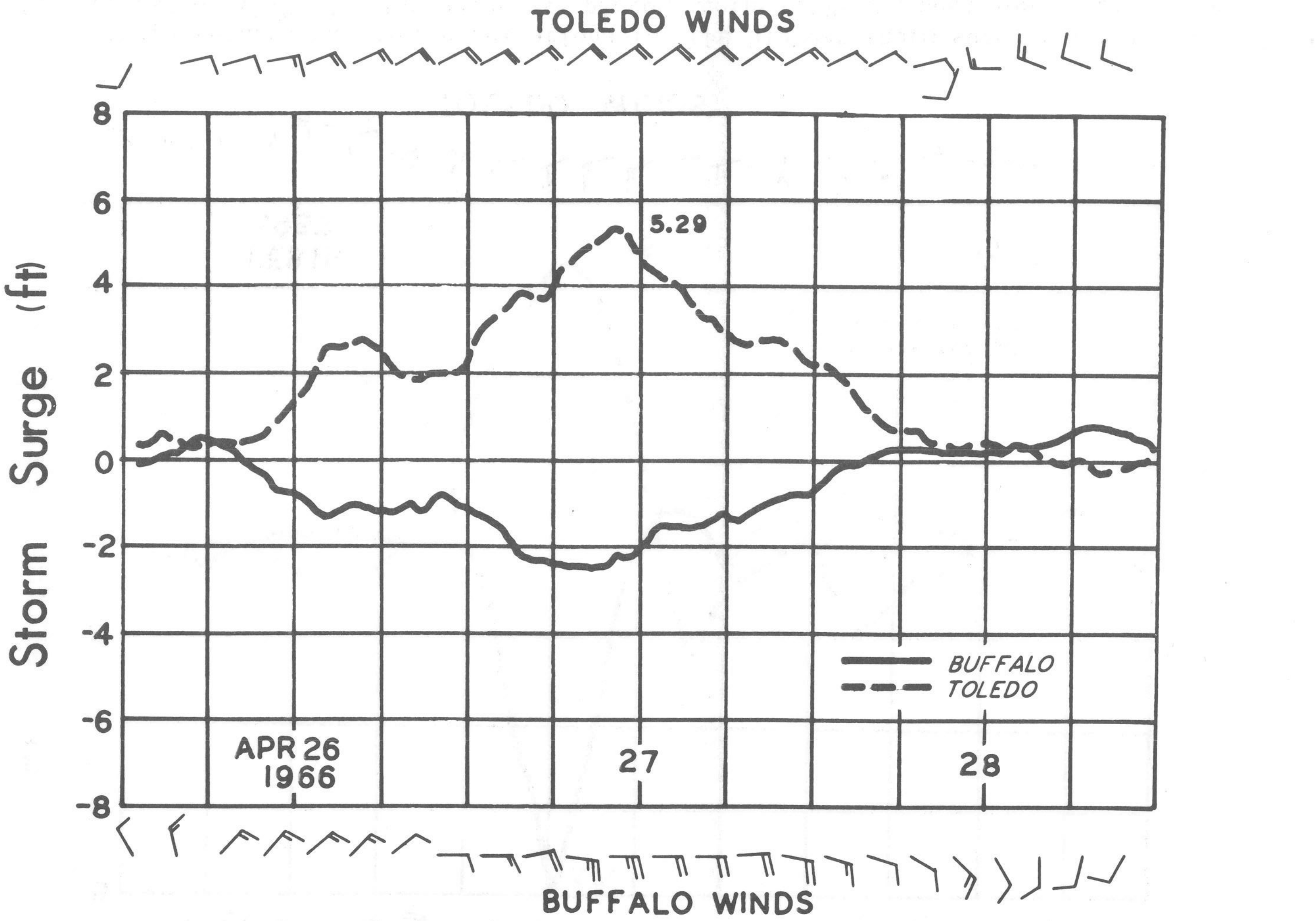

Figure 2.--Storm surge heights and wind observations for the highest storm surge (5.29 ft) at Toledo for the period 1940-72. The dates are placed at the 1200 EST position on the storm surge graphs (Pore et al. 1975).

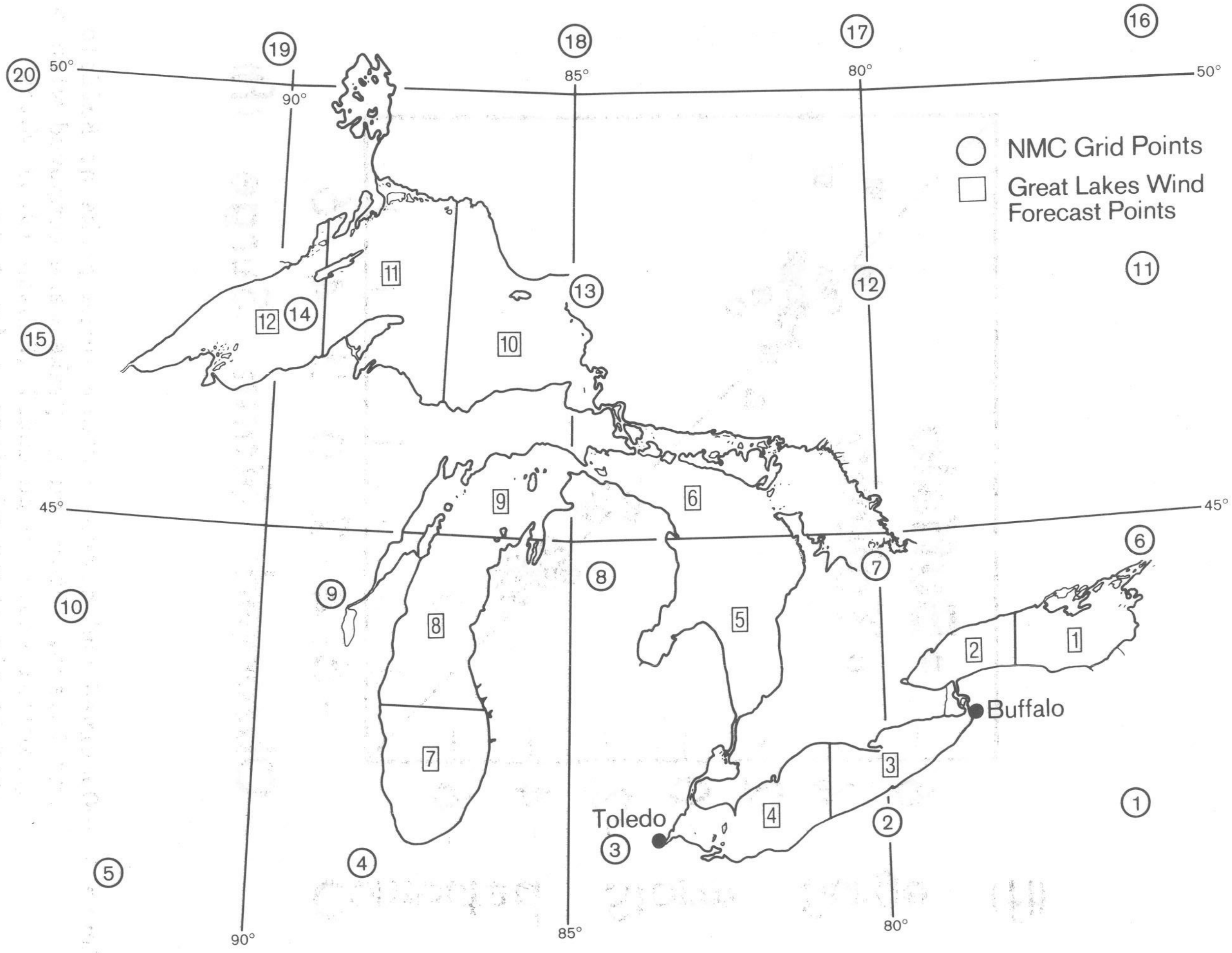

Figure 3.--Location of National Meteorological Center (NMC) Primitive Equation Model grid points which surround the Great Lakes and Great Lakes wind forecast points (Feit and Barrientos 1974).

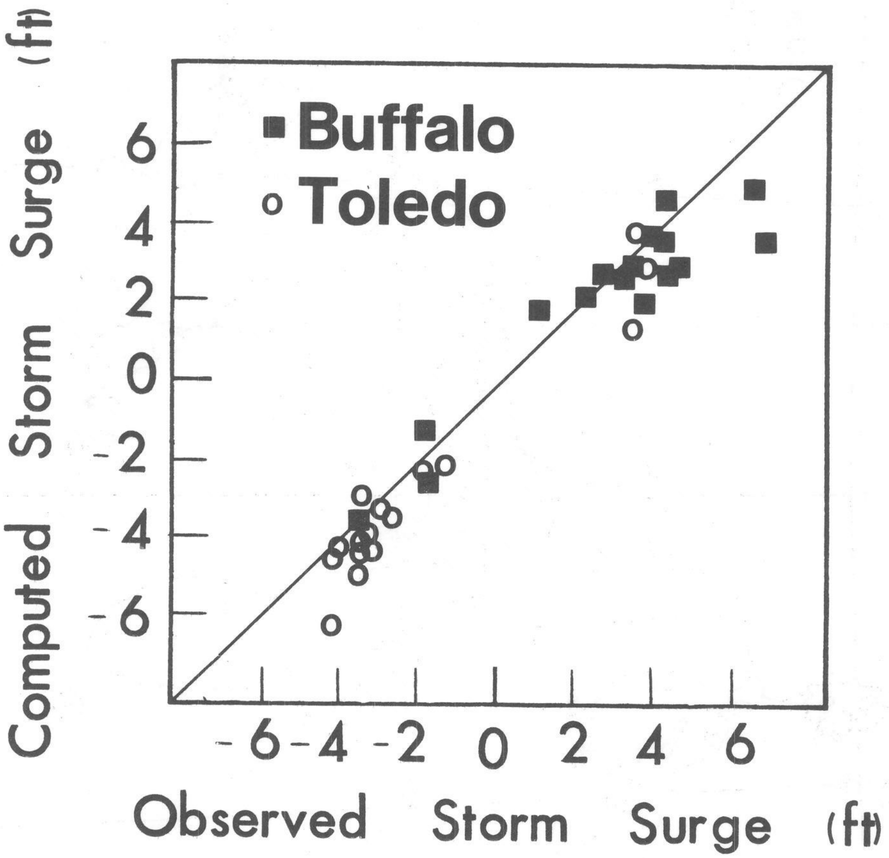

Figure 4.--Observed and computed storm surge peaks at Buffalo and Toledo. Storm surge peaks were computed with a dynamical storm surge model (Schwab 1978) which used hourly observed winds as input data.

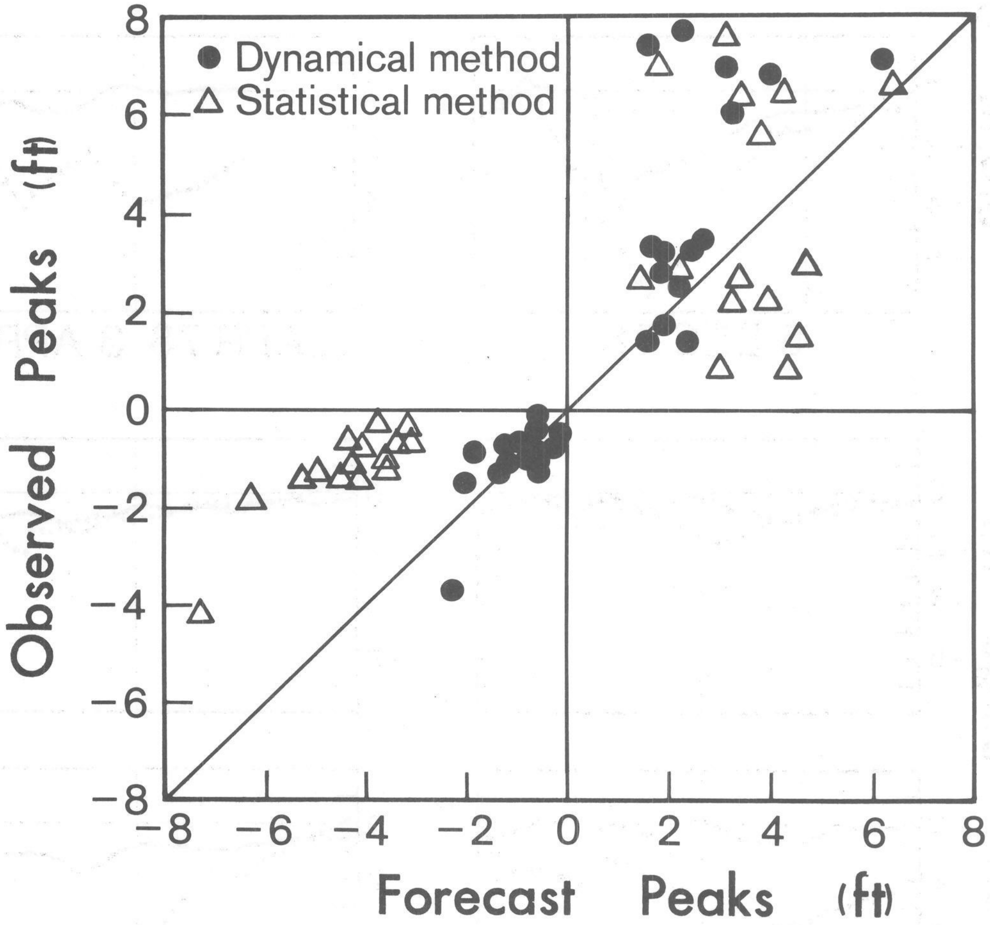

Figure 5.--Comparison of observed and forecast storm surge peaks at Buffalo for cases when the magnitude of either the observed or forecast peak surge equaled or exceeded 3 ft. Peak surge forecasts generated by the dynamical method are denoted by dots. Forecasts generated with the statistical method are depicted with triangles.

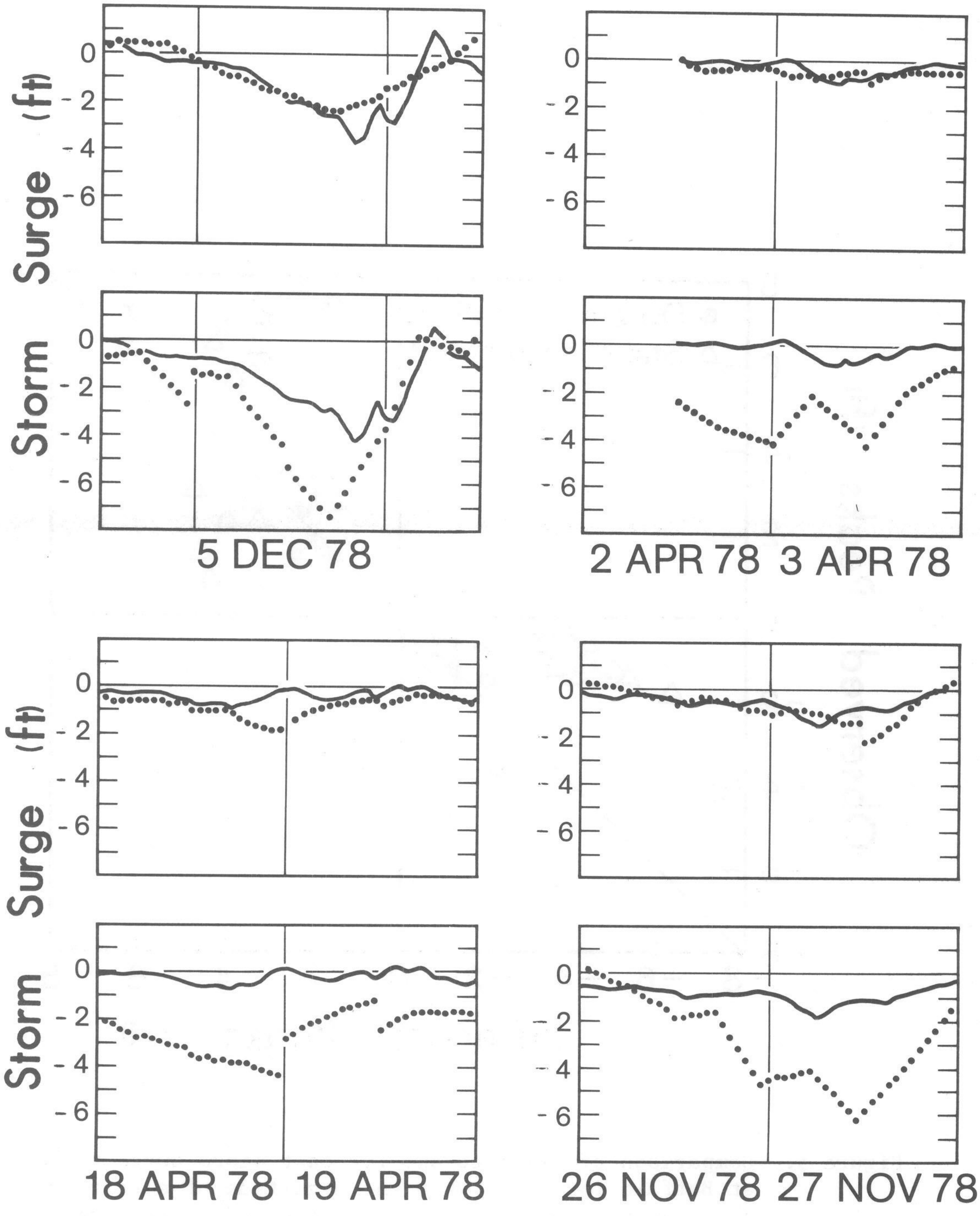

Figure 6.--Dynamical (upper panel) and statistical (lower panel) storm surge forecasts (dots) and observed storm surges (solid) for Buffalo on December 5, 1978, April 2-3, 1978, April 18-19, 1978, and November 26-27, 1978. Time is GMT.

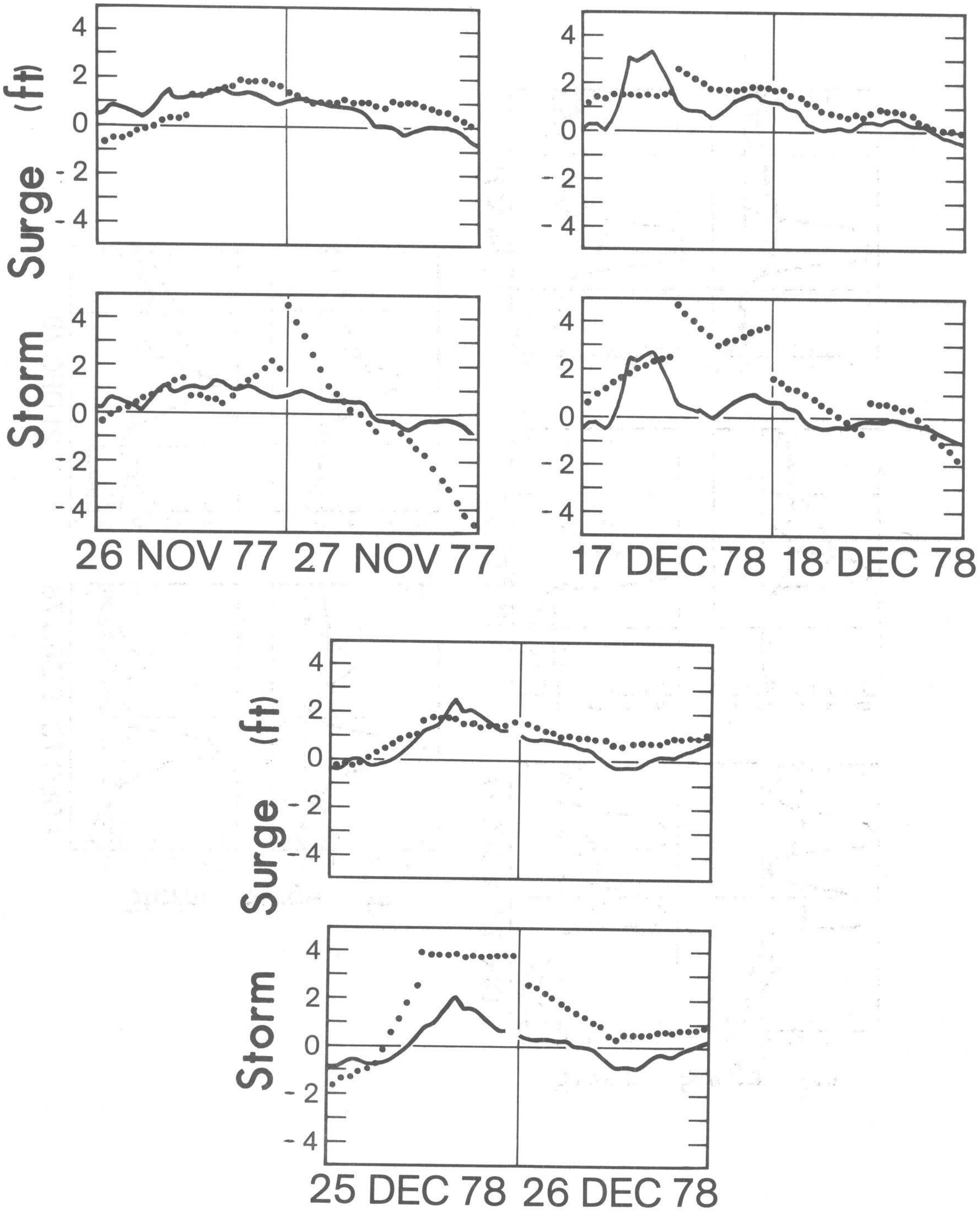

Figure 7.--As in figure 6 except for November 26-27, 1977, December 17-18, 1978, and December 25-26, 1978.

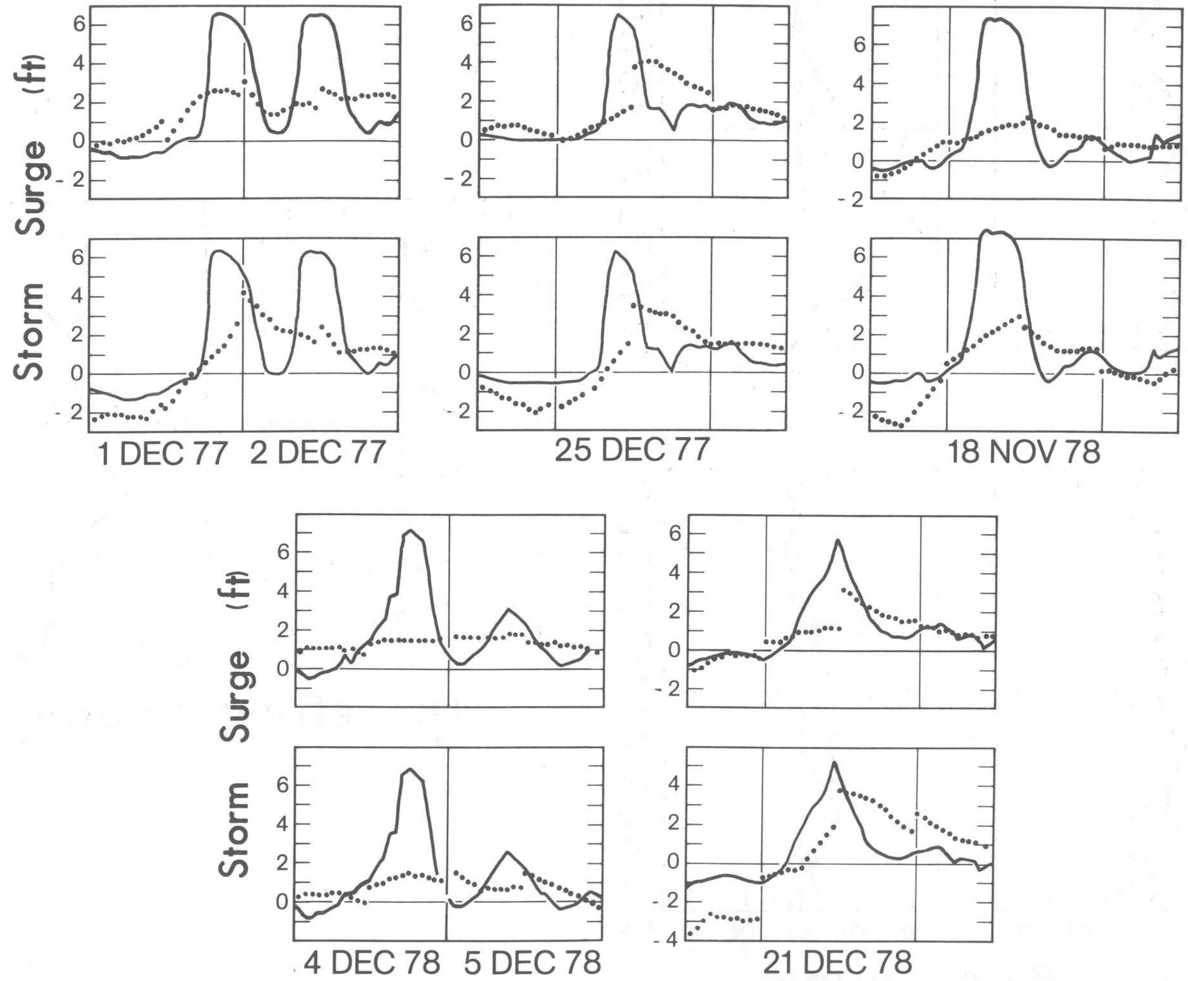

Figure 8.--As in figure 6 except for December 1-2, 1977, December 25, 1977, November 18, 1978, December 4-5, 1978, and December 21, 1978.

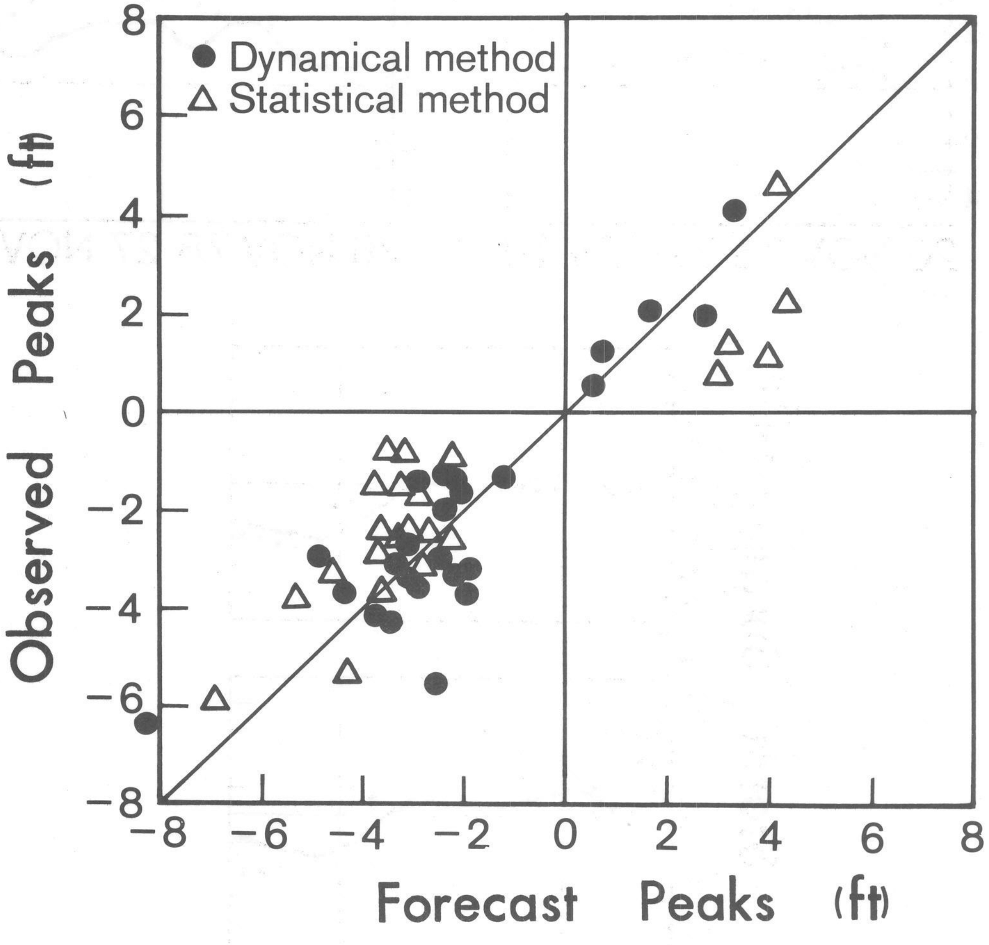

Figure 9.--Comparison of observed and forecast storm surge peaks at Toledo for cases when the magnitude of either the observed or forecast peak surge equaled or exceeded 3 ft. Peak surge forecasts generated by the dynamical method are denoted by dots. Forecasts generated with the statistical method are depicted with triangles.

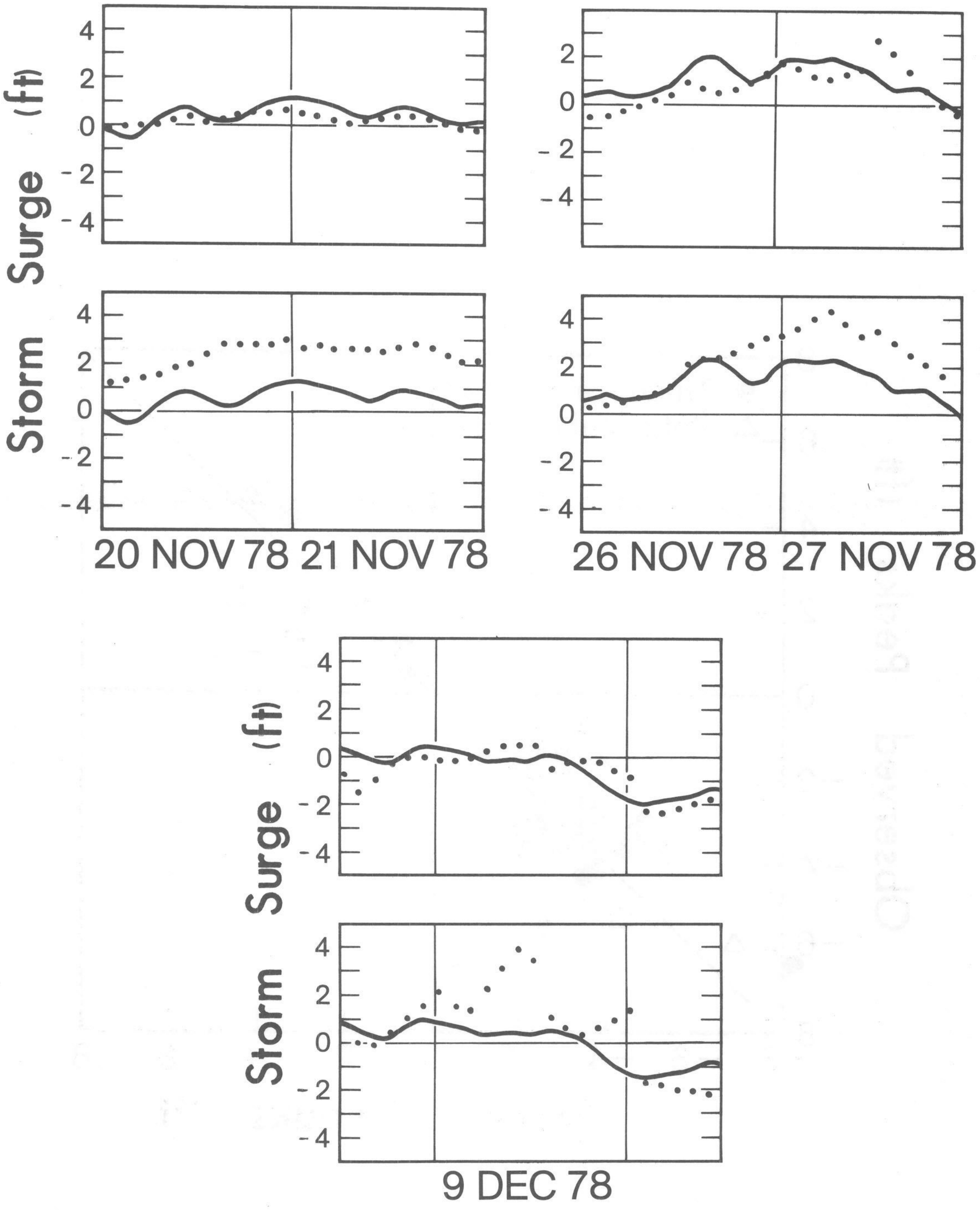

Figure 10.--Dynamical (upper panel) and statistical (lower panel) storm surge forecasts (dots) and observed storm surges (solid) for Toledo on November 20-21, 1978, November 26-27, 1978, and December 9, 1978. Time is GMT.

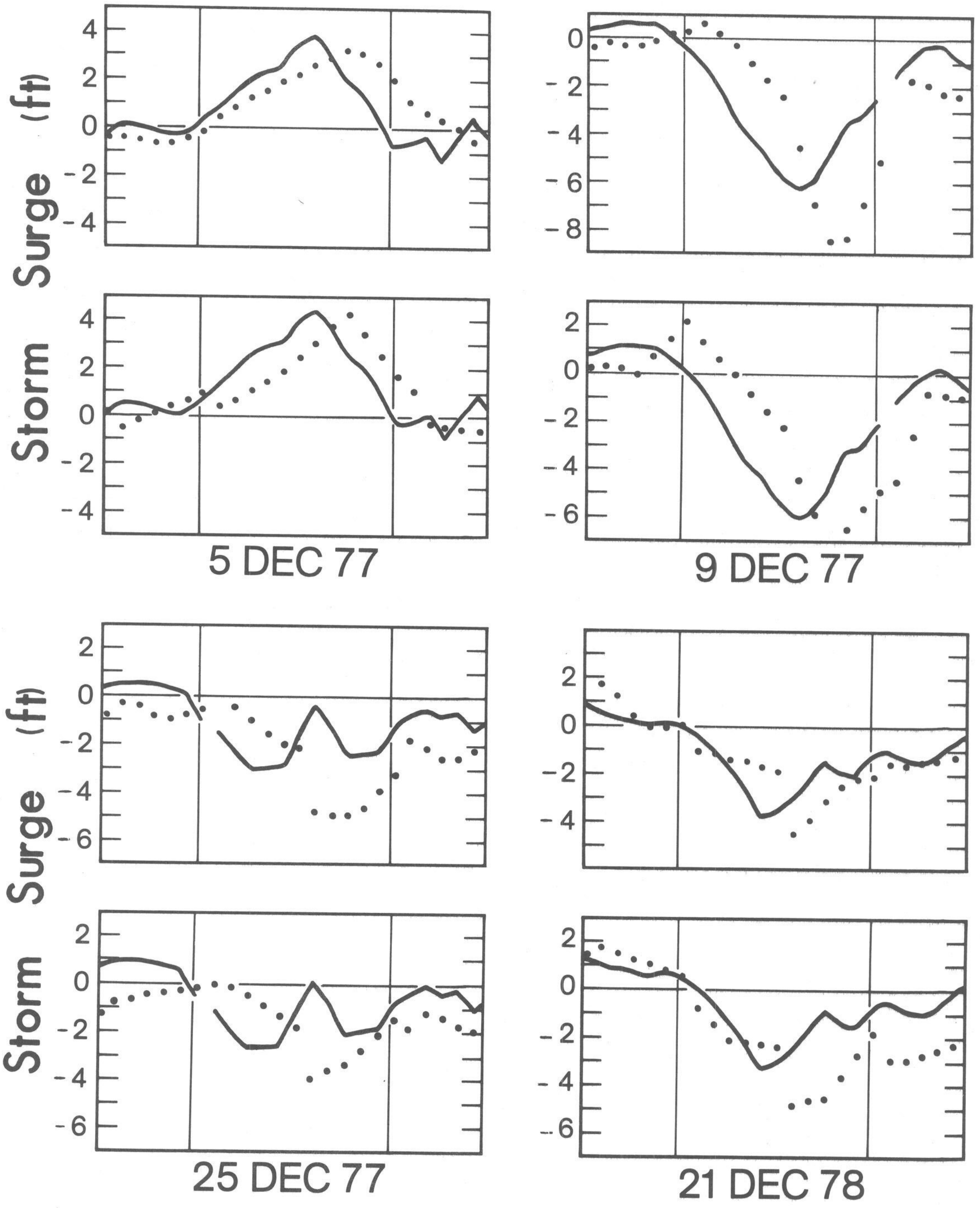

Figure 11.--As in figure 10 except for December 5, 1977, December 9, 1977, December 25, 1977, and December 21, 1978.

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