WEATHER BUREAU
Office of Systems Development
Techniques Development Laboratory
Silver Spring, Md.

August 1969

A Lake Erie Storm Surge Forecasting Technique

Technical Memorandum WBTM TDL 24

U.S. DEPARTMENT OF COMMERCE / ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION

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Environmental Science Services Administration
Weather Bureau

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A LAKE ERIE STORM SURGE FORECASTING TECHNIQUE

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OFFICE OF SYSTEMS DEVELOPMENT
TECHNIQUES DEVELOPMENT LABORATORY

SILVER SPRING, MD.
August 1969

UDC 551.465.755:551.509.313(285:71:73)

551.4	Oceanography
.465	Ocean currents
.755	Storm surges
551.5	Meteorology
.509	Synoptic forecasting
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(285)	Lakes
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A LAKE ERIE STORM SURGE FORECASTING TECHNIQUE

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ABSTRACT

Two methods for forecasting storm surge on Lake Erie at Buffalo, New York, and Toledo, Ohio, are presented. One method is for manual use at a Weather Bureau Forecast Office; the other is for use on a computer at a meteorological center where numerical weather forecasts are available as input. Both methods were derived by screening regression. Each method is tested with dependent and independent data. Hourly storm surge test forecasts 13 to 24 hours in advance for four storm surge cases at Buffalo and Toledo are forecast by the computer method with actual numerical forecasts of sea-level pressure as input.

INTRODUCTION

Storm surges on Lake Erie certainly do not constitute a new problem, but they have been gaining in importance with the growing population which is dependent on Lake Erie for electrical power production and transportation.

The Lake Erie storm surge has been the subject of numerous investigations. The problem was first considered by Henry [3] and Garriott [1] in 1902. The early study by Henry [3] dealt with the character and frequency of storm winds that prevailed on Lake Erie, the changes in water level produced by them, and the possibility of predicting the occurrences of the most pronounced changes in the level at the eastern end of the lake. The paper by Garriott [1] included charts that describe graphically over 200 of the more important storms that passed over the Great Lakes during the 25-year period from 1876 to 1900.

Lake Erie is nearly 240 miles long and almost 40 miles wide. The average depth of the lake is approximately 60 feet. Figure 1 shows that the major axis of Lake Erie is oriented in a west-southwest-east-northeast direction, a direction in which strong winds can develop and persist under normal meteorological conditions [6]. Previous studies by Irish and Platzman [4] have shown that storm surge on Lake Erie is caused primarily by the action of wind stresses on the lake surface. Other factors of less importance are the effect of atmospheric pressure, which causes higher water levels in areas of low pressure, and the modifying effects of shoreline configuration and bathymetry [8]. The southwest winds associated with low pressure systems that pass to the north of Lake Erie tend to push the water from the Toledo end toward the Buffalo end, while the winds associated with low systems which pass to the south of the lake have the opposite effect. The departures of the Buffalo and the Toledo lake levels from their respective monthly means are the storm surges at Buffalo and Toledo respectively.

High water at Toledo causes flooding, while low water poses a hazard to navigation. The change of the lake level at Buffalo has a significant effect on the power production on the Niagara River. A change of one foot produces a change of about 20,000 cubic feet per second in discharge, about 10 percent of the normal transport.

Irish and Platzman [4] refer to the storm surge at Buffalo minus the storm surge at Toledo as set-up. They have compiled frequency data on the incidence of extreme set-up on Lake Erie. Their study revealed that there were 76 cases in which the set-up exceeded 6.0 feet in magnitude in the 20-year period 1940 through 1959. Frequency intensity data for the 76 cases are presented graphically in figure 2. Figure 3 shows the frequency distribution by month for the 76 cases. Most of the set-up cases occurred in the six-month period October through March. More than 70 percent of the cases occurred in the three months November, December, and January.

All of the techniques developed to forecast Lake Erie storm surge may be classified as either dynamical models or statistical models. The models developed by Platzman are good examples of the dynamical approach. Several years ago Platzman [7] developed a two-dimensional dynamical model for predicting Lake Erie storm surge. More recently he developed a simplified one-dimensional model [6]. Input data for this model are observed and forecast winds issued by a Weather Bureau Forecast Office. The wind values are applied to a set of precomputed tables to obtain a forecast of the lake level at both ends of Lake Erie.

Reference is also made to Keulegan [5] for his work in determining the coefficient of wind stress and sea roughness over Lake Erie. These determinations were obtained by considering the deduced winds over Lake Erie, and the maximum wind set-up observed when severe westerly gales passed over the lake.

Harris and Angelo [2] applied the regression technique to Lake Erie storm surge with excellent results. Their regression equations were derived from hourly wind and pressure observations at six stations around Lake Erie. This technique was never used operationally because one of the reporting weather stations was closed, and the anemometers that furnished input data into the regression equations were changed soon after the derivation of the regression equations.

DEVELOPMENT

The Lake Erie storm surge studies previously mentioned have provided excellent background information. In fact, our approach to the task of developing a method for forecasting the storm surge at Buffalo and Toledo is patterned after the storm surge study by Harris and Angelo [2]. Two forecasting techniques were developed:

(1) A computerized technique that can use sea-level pressure as forecast by the National Meteorological Center's (NMC) Primitive Equation (PE) model and,

(2) A manual technique that can be used by a Weather Bureau Forecast Office.

The reason for developing the manual technique is that it will be a useful technique if it is not practical to implement the computerized technique.

The screening regression procedure was used to develop these two techniques. We chose the statistical approach for two reasons:

(1) The study by Harris and Angelo [2] demonstrated the excellent results that could be obtained through a statistical screening procedure.

(2) Platzman has already done a great deal of work using the dynamical approach. In fact a trial procedure for the operational prediction of storm surge at Toledo using his one-dimensional model was carried out by Weather Bureau Forecast Office, Chicago.

We applied the regression technique to the same lake level data used by Harris and Angelo [2]. This sample of data consists of 19 dependent storms and 11 independent storms which occurred during the period 1940 through 1959. Our approach differed from the approach by Harris and Angelo in that we represented the pressure and wind over Lake Erie by sea-level pressure at a network of grid points in the area of the lake rather than by observed winds at stations surrounding the lake. We did this in order to avoid the problems of weather stations being closed and anemometer heights being changed that were encountered by Harris and Angelo. Sea-level pressure values at the network of grid points were interpolated from sea-level pressure charts. Such data will be available regardless of changing density or patterns of weather observations.

Figure 4 shows the 25 NMC grid points at which sea-level pressure was recorded. The grid points are approximately 200 nautical miles apart. The grid, which has a heavier concentration of points to the west and to the north of Lake Erie, was designed to pick up the lows as they approached from the west, and to follow them as they passed to the north of the lake. The lower two rows of the grid were included to allow for southerly passages of lows. An examination by Irish and Platzman [4] of the track of each low associated with the 31 cases that occurred from 1940 through 1959 where Lake Erie set-up exceeded 8 feet showed that in 27 cases the storms originated west of the Mississippi River. The location of low centers for the 27 cases at the time of maximum set-up is shown in figure 5. Their study also pointed out that the mean position of low centers at the time of peak set-up, denoted by ▲ in figure 5, is located about 350 miles north and slightly east of the center of Lake Erie.

An examination of thirty storm cases during the period 1940 through 1959 showed that the change in lake level height at Buffalo during a one-hour period was 2 feet or greater in 14 of the storm cases. In 21 of the 30 storm cases, less than 3 hours elapsed between the time of the rise to the peak surge and the fall to normal water level. If the surge is not forecast every hour, the peak surge could easily be missed. We therefore made the decision to forecast the surge every hour.

Sea-level pressure charts are available every three hours. However, it would be more practical and economical if the computerized method used sea-level pressure as six-hour intervals, since regular NMC output of the PE model is for six-hour intervals.

Ten storms which occurred during the period 1940 through 1959 were used in deriving two sets of regression equations. A set of three regression equations was derived from sea-level pressure data at three-hour intervals, while a second set of six regression equations was derived from sea-level pressure data at six-hour intervals.

The set of regression equations which used pressure at three-hour intervals was derived in the following manner. Since the lake levels were recorded every hour, while the pressure data from sea-level pressure charts were available only at three-hour intervals, the lake level data were divided into three groups, namely:

(1) The lake levels that occurred at the same time as the pressure;

(2) The lake levels that occurred one hour after the pressure;

(3) The lake levels that occurred two hours after the pressure.

The pressures at three-hour intervals at the 25 NMC grid points, each with lag times 0 through 36 hours, were screened for each of the three lake level groups.

The lake level data were divided into six groups for the derivation of the set of regression equations based on the pressure at six-hour intervals. The pressure at six-hour intervals at the 25 NMC grid points, each with lag times 0 through 36 hours, were screened for each of these six lake level groups.

The manner in which the predictors were screened is outlined below.

1) $SS = A_1 + B_1X_1$

2) $SS = A_2 + B_2X_1 + C_1X_2$

3) $SS = A_3 + B_3X_1 + C_2X_2 + D_1X_3$

$\vdots$

4) $SS = A_n + B_nX_1 + C_{n-1}X_2 + \dots\dots + NX_n$

where SS is storm surge, A_1, A_2, A_3, etc. are constants, X_1, X_2, X_3, etc. are predictors, and B_1, B_2, C_1, C_2, etc. are regression coefficients.

The procedure is to select the single predictor X_1 for equation 1 which is best in explaining the variance of the storm surge. The second regression equation contains the first predictor X_1 and the predictor X_2 that contributes most to explaining the residual variance of storm surge after the first predictor is considered. This process is continued until the reduction in variance attained by additional predictors is not significant or until the desired number of predictors is included [8]. We selected as our cutoff point the screening step where the additional reduction of variance was less than one percent.

The storm surge at Buffalo was computed by using pressure at three-hour and six-hour intervals. In all cases the computed storm surge for the two methods was about the same. Figure 6 shows the results of the two methods when applied to three storm surge cases. The following conclusion is based upon comparison of the results of the two methods. A set of six regression equations using pressure at six-hour intervals yields about the same results as a set of three regression equations using pressure at three-hour intervals. Since we do not lose significant information by using pressure at six-hour intervals, we decided to:

(1) Develop a computer technique that uses sea-level pressure data from the PE model at six-hour intervals as input into a set of six regression equations;

(2) Develop a manual technique that uses data from sea-level pressure charts at six-hour intervals as input into a set of six regression equations.

A new set of six regression equations was derived from a larger number of storm cases. The six regression equations were derived from hourly lake level data and six-hour pressure at 25 NMC grid points for 19 storms which occurred during the period 1940 through 1959. Separate computer runs clearly indicated that the computer run which used current pressure data specified the peak surge most accurately. Graphs of the observed and specified storm surge showed that the specification of peak surge was significantly better when the latest available pressure was used in the computations. Graphs of two of these storms are shown in figure 7.

The first variable selected in most computer runs was the pressure with 0 hour lag at a grid point to the north or northwest of the lake. One of the first variables selected lies in about the same position as the mean position of the low centers denoted by ▲ in figure 5. However, the pressures at grid points to the west and west-northwest of the lake were the first variables selected in computer runs that used pressure twelve hours earlier as the latest available pressure. The selection of these variables is in good agreement with the movement of the lows toward the northeast as they pass to the north of Lake Erie. The earlier pressures at points to the west of the lake are the best predictors of the pressure at points to the north and northwest of the lake. The second variable selected in all but one computer run was a pressure point to the southwest of the lake. The first and second variables selected defined a pressure gradient extending over the lake. This pressure pattern explained the winds, which earlier studies have shown to be the cause of storm surge on Lake Erie.

OPERATIONAL TECHNIQUE

We chose the set of six regression equations which used pressure with lag times of 0 through 36 hours as the set of regression equations to be used in the Buffalo computerized technique. The set of regression equations was derived from data of 19 storms, which included 148 six-hourly observations. Each variable selected in the equations reduced the variance by at least one percent.

A manual method, one that could be used by a Weather Bureau Forecast Office, was developed by deriving a set of six regression equations from the first six variables that were most often selected in the Buffalo screening runs. We chose the six regression equations which contained the first five variables selected by the screening run as the set of regression equations to be used in the manual method.

The sets of regression equations for the computer technique and the manual technique for Buffalo are given in Appendix A. The specified storm surge at Buffalo, obtained by using each of these methods with the sea-level pressure analyses, is shown with the observed storm surge at Buffalo for the 19 dependent and the 11 independent storms in figures 8 and 9. Included in table 1 are the statistics for each of these methods for the 19 dependent storms and the 11 independent storms.

Since the Toledo lake levels were tabulated only every even hour, only three regression equations were derived for the Toledo forecasting methods. The derivation of the set of Toledo regression equations was carried out in the same manner as the Buffalo derivation. We used 15 storms, 148 six-hourly observations in the derivation of the three equations. We chose the set of three regression equations which used pressure with lag times of 0 through 36 hours as the set of regression equations to be used in the Toledo computerized technique.

A manual method was developed by deriving a set of three regression equations from the first six variables that were most often selected in the Buffalo and Toledo screening runs. We chose the three regression equations which contained the first five variables selected by the screening run as the set of regression equations to be used in the manual method.

Appendix B contains the sets of regression equations for the computer technique and the manual technique for Toledo. The specified storm surge at Toledo, obtained by using each of these methods with the sea-level pressure analyses, is shown with the observed storm surge at Toledo for the 15 dependent and the 11 independent storms in figures 10 and 11. Statistics for each of these methods, for the 15 dependent and the 11 independent storms, are included in table 1.

The agreement between the specified storm surge for Buffalo and Toledo and the observed storm surge was very good in almost all cases.

TEST FORECASTS

Storm surge test forecasts for Buffalo and Toledo were made for four storm surge cases with sea-level pressure as forecast by NMC's PE model. The four storm cases were selected after reviewing lake level records for Buffalo and Toledo. In each of the four cases the lake level was at least three feet above the Buffalo monthly mean. All four cases occurred in December 1968 and January 1969. Sea-level pressure forecasts from NMC's archived data tapes were used to forecast the storm surge at Buffalo and Toledo.

We feel that the most important forecast period for the Buffalo and Toledo storm surge is the forecast period 13 to 24 hours in advance. Hourly storm surge test forecasts for Buffalo and Toledo 13 to 24 hours in advance, and the storm surge estimated by using sea-level pressure analyses for the four storm cases are shown in figures 12 and 13. Table 1 contains statistics for the four storm cases.

The maximum storm surge at Buffalo on December 5, 1968, was underforecast. The underforecasting of the storm surge is due primarily to the storm surge forecast equations, since the specified storm surge was also much lower than the observed storm surge. The storm surge forecast equations did not forecast the maximum storm surge because the low pressure system associated with the surge approached Lake Erie from the northwest. However, the test forecasts valid after 1400 on December 5 were much better since the path of the low then approached the paths of the lows in the developmental data.

The test forecasts for the December 29 storm surge were very good until 0800 December 29. At this time the equations forecast the surge to be 4.8 feet at Buffalo, while the observed surge was 0.1 feet. Since the surge specified by observed pressures at this time was 3.5 feet, we can attribute only part of the storm surge forecast error to the error in the sea-level pressure forecast. The remainder of the error is due to the storm surge forecast equations. In almost all of the developmental cases, the lows traveled between 30 and 40 mph in the six-hour period following the peak surge. In the December 29 case, the low traveled 65 mph during that six-hour period. The faster traveling low caused the lake level to return to normal much sooner than usual, and, therefore, the equations overforecast the surge during this period.

The best storm surge test forecasts were for the two cases which were most similar to the developmental data, December 23 and January 1. In the cases where the lows approached from a different direction (December 5) or moved at a different speed (December 28), the forecasts were not good. Although the maximum storm surge was not forecast well in two of the four cases, the trend of the storm surge was forecast. We feel that a forecast of the trend of the storm surge would be a very useful guide to a Weather Bureau Forecast Office.

CONCLUSION

Tests on the dependent sample, the independent sample, and the four case sample indicate that a meaningful storm surge forecast for Buffalo and Toledo could be made by computer. Input into this computer model would be sea-level pressure as forecast by the PE model. We feel that a forecast of the storm surge at Buffalo and Toledo 13 to 24 hours in advance would be useful to the Weather Bureau Office concerned with such forecasts. Therefore, we plan to make comparative tests of this method against other available methods to determine if implementation of this method is desirable.

ACKNOWLEDGMENTS

The authors express their gratitude to the U. S. Lake Survey for providing lake level data at Buffalo and Toledo. Appreciation is also expressed to Mrs. N. S. Foat, Miss W. Webster, Mr. H. Perrotti, Mrs. R. C. Lopresti, and Miss M. Torchinsky of Techniques Development Laboratory for their clerical and drafting assistance.

REFERENCES

1. Garriott, E. B., "Storms of the Great Lakes," U. S. Weather Bureau, Bulletin K, Washington, D. C., 1903, 9 pp., 968 charts.

2. Harris, D. L., and A. Angelo, "A Regression Model for Storm Surge Prediction," Monthly Weather Review, Vol. 91, Nos. 10-12,Oct.-Dec. 1963, pp. 710-726.

3. Henry, A. J., "Wind Velocity and Fluctuations of Water Level on Lake Erie," U. S. Weather Bureau, Bulletin J, Washington, D. C., 1902, 22 pp., 12 charts.

4. Irish, S. M., and G. W. Platzman, "An Investigation of the Meteorological Conditions Associated with Extreme Wind Tide on Lake Erie," Monthly Weather Review, Vol. 90, No. 2, Feb. 1962, pp. 39-47.

5. Keulegan, G. H., "Hydrodynamic Effects of Gales on Lake Erie," U. S. National Bureau of Standards, Journal of Research, Vol. 50, No. 2, Feb. 1953, pp. 99-109.

6. Platzman, G. W., "A Procedure for Operational Prediction of Wind Set-up on Lake Erie," Technical Report No. 11, The University of Chicago, ESSA Contract E-91-67(N).

7. Platzman, G. W., "The Dynamical Prediction of Wind Tides on Lake Erie," Meteorological Monographs, Vol. 4, No. 26, 44 pp.

8. Pore, N. A., "The Relation of Wind and Pressure to Extratropical Storm Surge at Atlantic City," Journal of Applied Meteorology, Vol. 3, No. 2, April 1964, pp. 155-163.

APPENDIX A

Sets of Regression Equations for Buffalo

Computer Technique

$$\begin{aligned}SS(1) = {} & 11.4 - 0.0390\ P(12)_{-6} - 0.0100\ P(3)_{0} + 0.1573\ P(12)_{-12} \\ & - 0.0644\ P(4)_{-24} - 0.1770\ P(11)_{0} + 0.0856\ P(2)_{0} + 0.0316\ P(22)_{-24} \\ & - 0.0542\ P(2)_{-24} - 0.0593\ P(13)_{-12} + 0.1190\ P(7)_{0}\end{aligned}$$

$$\begin{aligned}SS(2) = {} & -1.1 + 0.0150\ P(17)_{0} - 0.0614\ P(4)_{0} - 0.1874\ P(13)_{-6} \\ & + 0.1255\ P(9)_{-6} + 0.0140\ P(13)_{-12} - 0.0733\ P(5)_{-18} \\ & + 0.0179\ P(24)_{-36} - 0.0792\ P(2)_{-24} + 0.0753\ P(7)_{-12} \\ & - 0.1208\ P(11)_{0} + 0.0980\ P(12)_{-24} + 0.1443\ P(3)_{0} \\ & + 0.0966\ P(12)_{-6} - 0.0628\ P(11)_{-18}\end{aligned}$$

$$\begin{aligned}SS(3) = {} & -16.5 - 0.0015\ P(17)_{0} + 0.0022\ P(4)_{0} - 0.2265\ P(13)_{-6} \\ & + 0.0596\ P(13)_{-12} + 0.1377\ P(13)_{0} - 0.2436\ P(12)_{0} \\ & + 0.2078\ P(12)_{-6} + 0.1406\ P(7)_{0} - 0.0293\ P(24)_{-36} \\ & - 0.0814\ P(11)_{-6} - 0.0783\ P(5)_{-18} + 0.0706\ P(5)_{-12}\end{aligned}$$

$$\begin{aligned}SS(4) = {} & -23.3 - 0.0848\ P(17)_{0} + 0.0463\ P(23)_{-36} - 0.1101\ P(4)_{0} \\ & - 0.0727\ P(8)_{-6} + 0.2091\ P(3)_{0} + 0.2308\ P(12)_{-6} \\ & - 0.1106\ P(12)_{0} - 0.0597\ P(5)_{-24} + 0.0929\ P(18)_{0} \\ & - 0.1219\ P(13)_{-6} + 0.1001\ P(4)_{-6} - 0.0722\ P(11)_{0} - 0.0242\ P(21)_{-30}\end{aligned}$$

$$\begin{aligned}SS(5) = {} & -21.6 - 0.1072\ P(12)_{0} + 0.1085\ P(3)_{0} + 0.1800\ P(12)_{-6} \\ & - 0.0581\ P(5)_{-18} + 0.0248\ P(24)_{-36} - 0.1057\ P(13)_{-6} \\ & - 0.0865\ P(11)_{0} + 0.0656\ P(9)_{-6}\end{aligned}$$

$$\begin{aligned} SS(6) = {} & 7.1 - 0.1225\ P(12)_{0} + 0.1279\ P(4)_{0} + 0.0627\ P(12)_{-6} \\ & -0.0927\ P(5)_{-18} - 0.0432\ P(14)_{-6} + 0.0233\ P(24)_{-36} \\ & -0.0461\ P(2)_{-18} + 0.0840\ P(8)_{-12} \end{aligned}$$

Manual Technique

$$\begin{aligned} SS(1) = {} & 3.5 - 0.1040\ P(12)_{-6} + 0.1133\ P(3)_{0} + 0.0810\ P(12)_{-12} \\ & -0.0570\ P(4)_{-24} - 0.0367\ P(13)_{-6} \end{aligned}$$

$$\begin{aligned} SS(2) = {} & 0.3 - 0.0463\ P(17)_{0} + 0.0629\ P(4)_{0} - 0.1470\ P(13)_{-6} \\ & +0.0806\ P(13)_{0} + 0.0498\ P(17)_{-6} \end{aligned}$$

$$\begin{aligned} SS(3) = {} & -3.7 - 0.0031\ P(17)_{0} + 0.0710\ P(4)_{0} - 0.1986\ P(13)_{-6} \\ & + 0.0722\ P(13)_{-12} + 0.0624\ P(13)_{0} \end{aligned}$$

$$\begin{aligned} SS(4) = {} & 33.5 - 0.0060\ P(17)_{0} - 0.0309\ P(4)_{0} - 0.1353\ P(3)_{-6} \\ & + 0.2109\ P(3)_{0} - 0.0717\ P(12)_{0} \end{aligned}$$

$$\begin{aligned} SS(5) = {} & -10.1 - 0.1576\ P(12)_{0} + 0.1626\ P(3)_{0} + 0.1055\ P(12)_{-6} \\ & -0.0513\ P(5)_{-18} - 0.0493\ P(13)_{-6} \end{aligned}$$

$$\begin{aligned} SS(6) = {} & 1.2 - 0.1147\ P(12)_{0} + 0.1089\ P(4)_{0} + 0.1044\ P(12)_{-6} \\ & -0.0486\ P(5)_{-18} - 0.0510\ P(13)_{-6} \end{aligned}$$

Where SS(T) is the storm surge in tenths of feet, valid T hours after the verifying time of the latest pressure forecast used in the storm surge equation, and P is the sea-level pressure in millibars at the indicated grid point. The subscript is the time lag in hours.

APPENDIX B

Sets of Regression Equations for Toledo

Computer Technique

$$\begin{aligned} SS(2) = {} & 17.6 - 0.0124\,P(12)_{-6} - 0.0137\,P(5)_{0} + 0.1301\,P(13)_{-6} \\ & - 0.0812\,P(9)_{-6} + 0.0468\,P(8)_{-12} - 0.1967\,P(8)_{-18} \\ & - 0.0207\,P(21)_{-36} + 0.0597\,P(8)_{-24} + 0.1642\,P(9)_{-18} \\ & - 0.0408\,P(19)_{-18} - 0.0632\,P(5)_{-12} \end{aligned}$$

$$\begin{aligned} SS(4) = {} & 19.2 + 0.1347\,P(13)_{-6} - 0.1074\,P(4)_{0} - 0.1236\,P(17)_{-6} \\ & - 0.0224\,P(21)_{-36} + 0.0599\,P(21)_{0} + 0.0394\,P(9)_{-18} \end{aligned}$$

$$\begin{aligned} SS(6) = {} & 9.5 + 0.0616\,P(13)_{-6} + 0.0396\,P(5)_{0} - 0.1102\,P(13)_{-12} \\ & - 0.0213\,P(21)_{-36} + 0.0347\,P(9)_{-24} - 0.1222\,P(4)_{0} \\ & + 0.0943\,P(9)_{-12} + 0.0758\,P(13)_{0} - 0.0625\,P(10)_{-6} \end{aligned}$$

Manual Technique

$$\begin{aligned} SS(2) = {} & -18.5 - 0.0453\,P(12)_{-6} + 0.0111\,P(5)_{0} \\ & + 0.1027\,P(13)_{-6} - 0.1244\,P(4)_{0} + 0.0732\,P(3)_{-12} \end{aligned}$$

$$\begin{aligned} SS(4) = {} & 18.3 + 0.1108\,P(13)_{-6} - 0.1199\,P(4)_{0} - 0.0378\,P(17)_{-6} \\ & - 0.0154\,P(17)_{-36} + 0.0435\,P(3)_{-6} \end{aligned}$$

$$\begin{aligned} SS(6) = {} & 9.8 + 0.1784\,P(13)_{-6} - 0.0773\,P(5)_{0} - 0.1426\,P(13)_{-12} \\ & + 0.0494\,P(13)_{-18} - 0.0182\,P(12)_{-36} \end{aligned}$$

Where $SS(T)$ is the storm surge in tenths of feet, valid T hours after the verifying time of the latest pressure forecast used in the storm surge equation, and P is the sea-level pressure in millibars at the indicated grid point. The subscript is the time lag in hours.

TABLE 1. STORM SURGE STATISTICS FOR BUFFALO AND TOLEDO.

BUFFALO

	DEPENDENT SAMPLE		INDEPENDENT SAMPLE		*FOUR CASE SAMPLE	
	Computer Method	Manual Method	Computer Method	Manual Method		
PRESS	Analyses	Analyses	Analyses	Analyses	Analyses	+12 and +18
CORR	0.83	0.79	0.81	0.82	0.80	0.76
RMSE	0.77	0.81	0.84	0.82	1.00	1.10
N	1596	1596	864	864	211	211

TOLEDO

	DEPENDENT SAMPLE		INDEPENDENT SAMPLE		*FOUR CASE SAMPLE	
	Computer Method	Manual Method	Computer Method	Manual Method		
PRESS	Analyses	Analyses	Analyses	Analyses	Analyses	+12 and +18
CORR	0.84	0.81	0.76	0.78	0.80	0.71
RMSE	0.80	0.86	1.30	1.31	1.28	1.39
N	630	630	456	456	106	106

*The forecasts valid at the following times were used in determining the statistics for the four case sample:

(1) 0200 Dec. 4, 1968 through 0100 Dec. 6, 1968,

(2) 1200 Dec. 22, 1968 through 1500 Dec. 24, 1968,

(3) 0600 Dec. 27, 1968 through 0600 Dec. 29, 1968,

(4) 0100 Dec. 31, 1968 through 0500 Jan. 2, 1969.

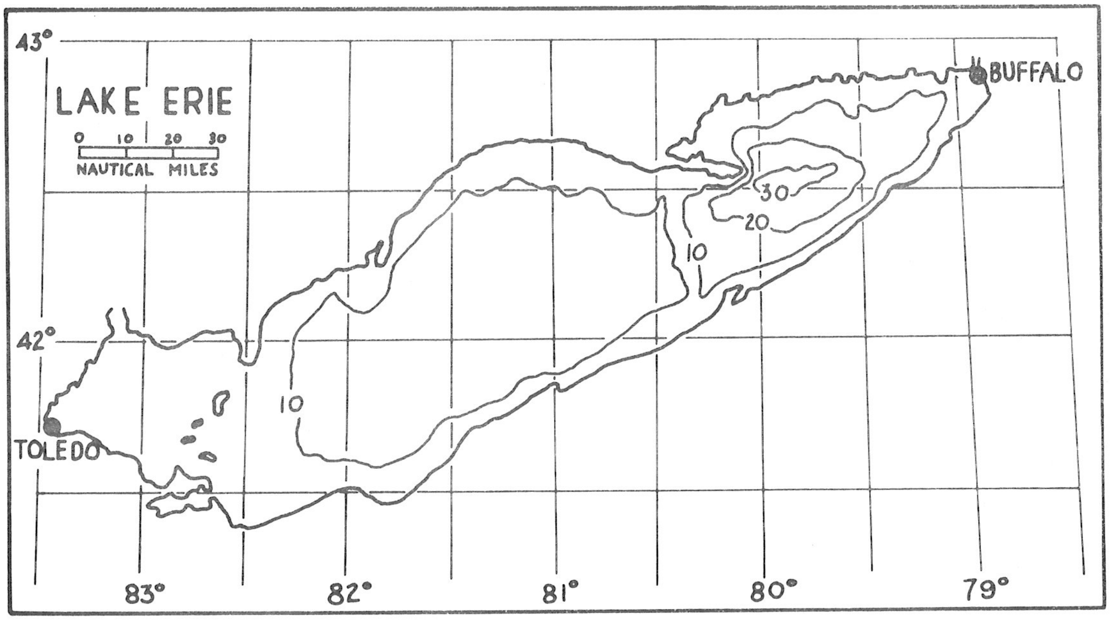


Figure 1.--Configuration of Lake Erie. Depth contours are shown at 10-fathom intervals (1 fathom = 6 feet).

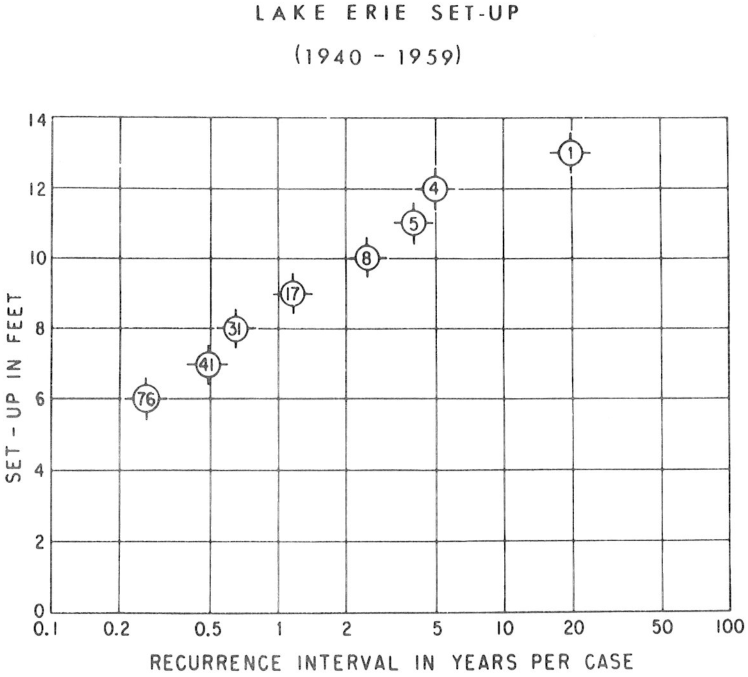


Figure 2.--Recurrence interval. The circled numbers give the number of cases for which set-up exceeded 6, 7, 8, 9, 10, 11, 12, and 13 feet. (From Irish and Platzman (4))

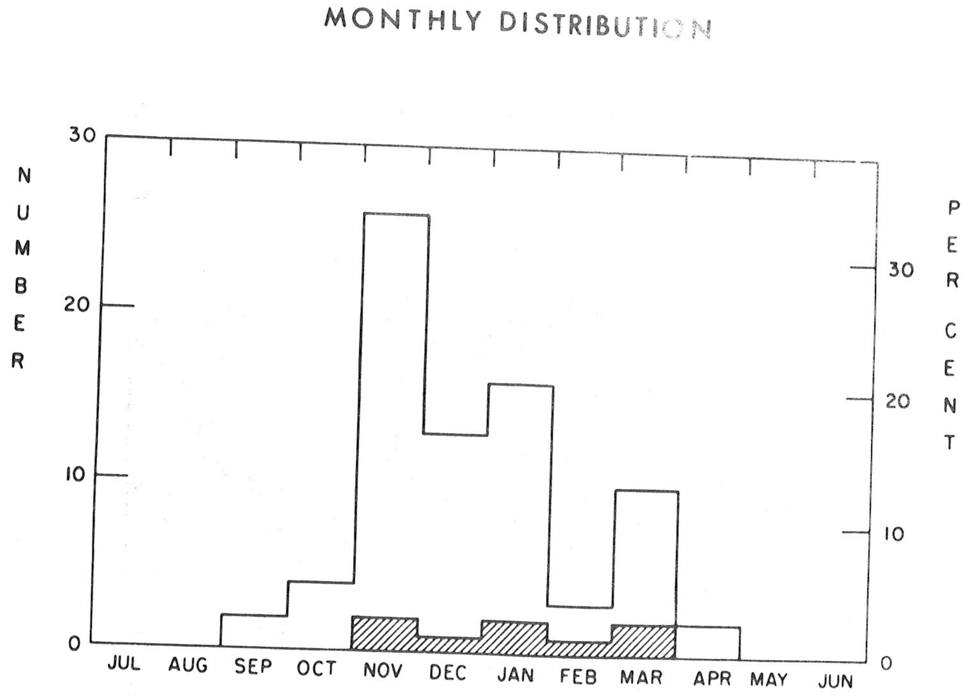


Figure 3.--Monthly distribution of 76 cases in which the set-up exceeded 6 feet during the period 1940-59. Hatching shows distribution of 8 cases in which set-up exceeded 10 feet (4).

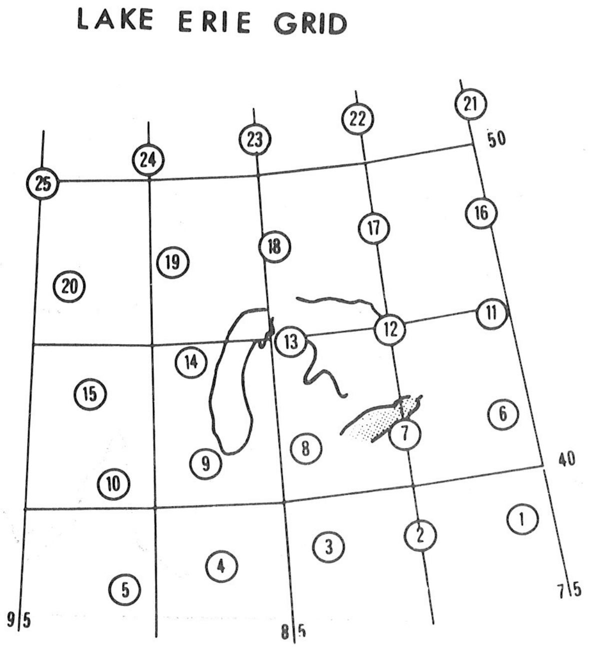


Figure 4.--Lake Erie Grid.

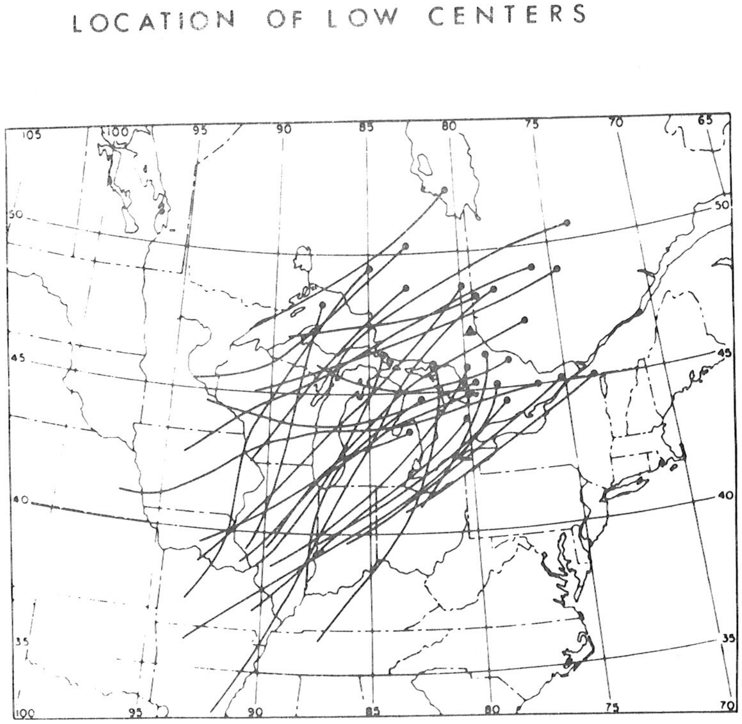


Figure 5.--Location of low centers (heavy dots) at time of maximum set-up for 27 cases in which set-up exceeded 8 feet during the period 1940-59. (Irish and Platzman (4))

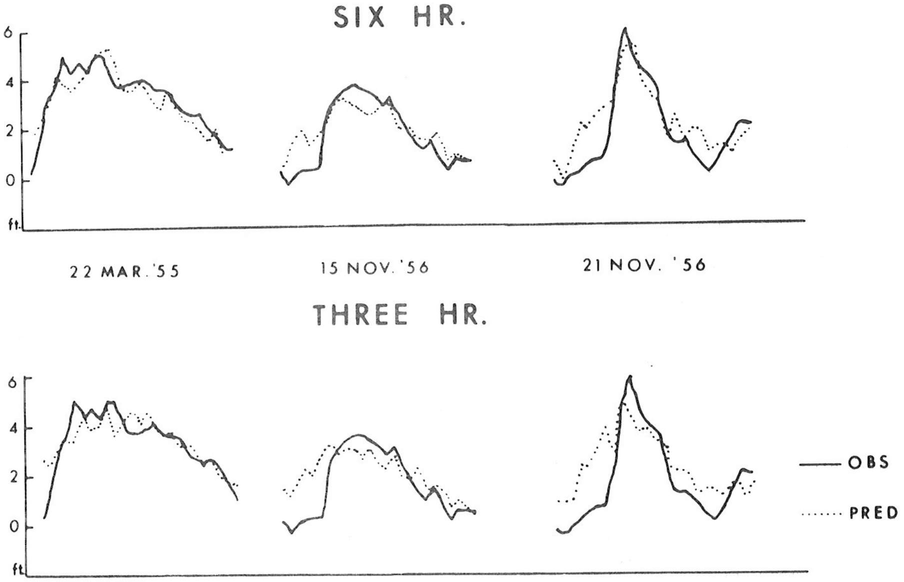


Figure 6.--Specified storm surge at Buffalo computed using sea level pressure at 6-hour and 3-hour intervals.

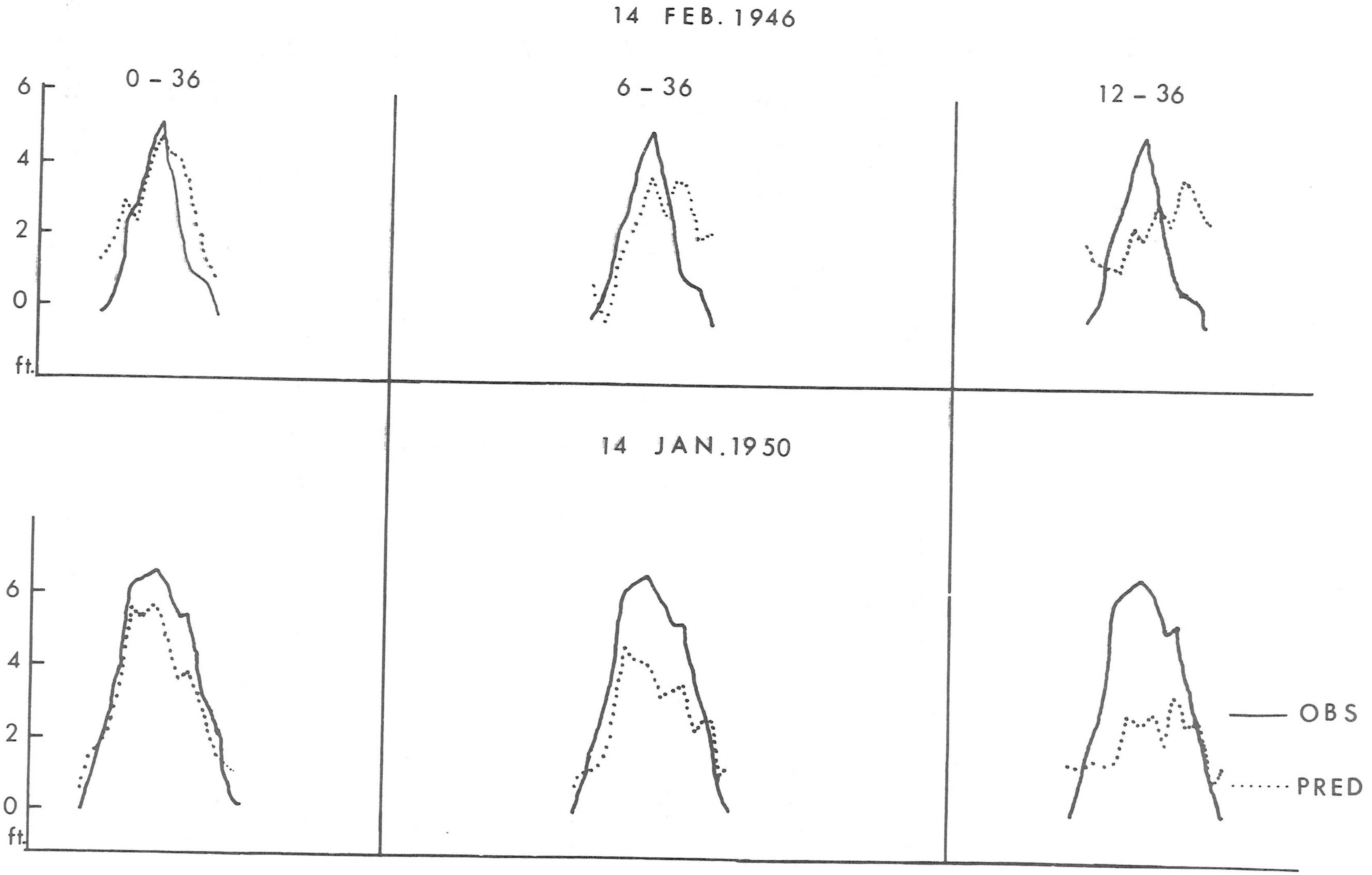


Figure 7.--Specified storm surge at Buffalo computed from equations containing sea level pressure with 0-, 6-, and 12-hour minimum lags.

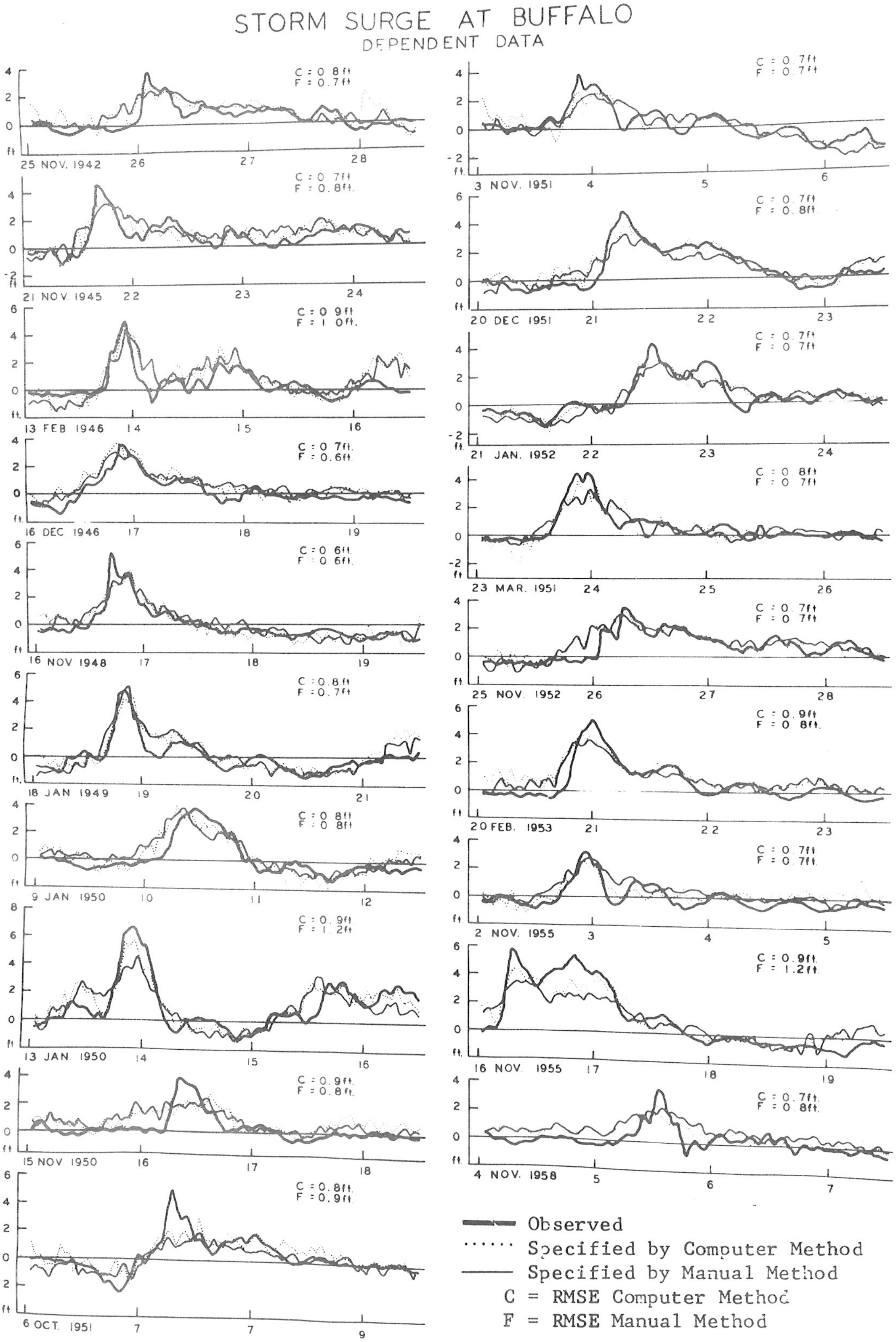


Figure 8.--Specified and observed storm surge at Buffalo for dependent data cases.

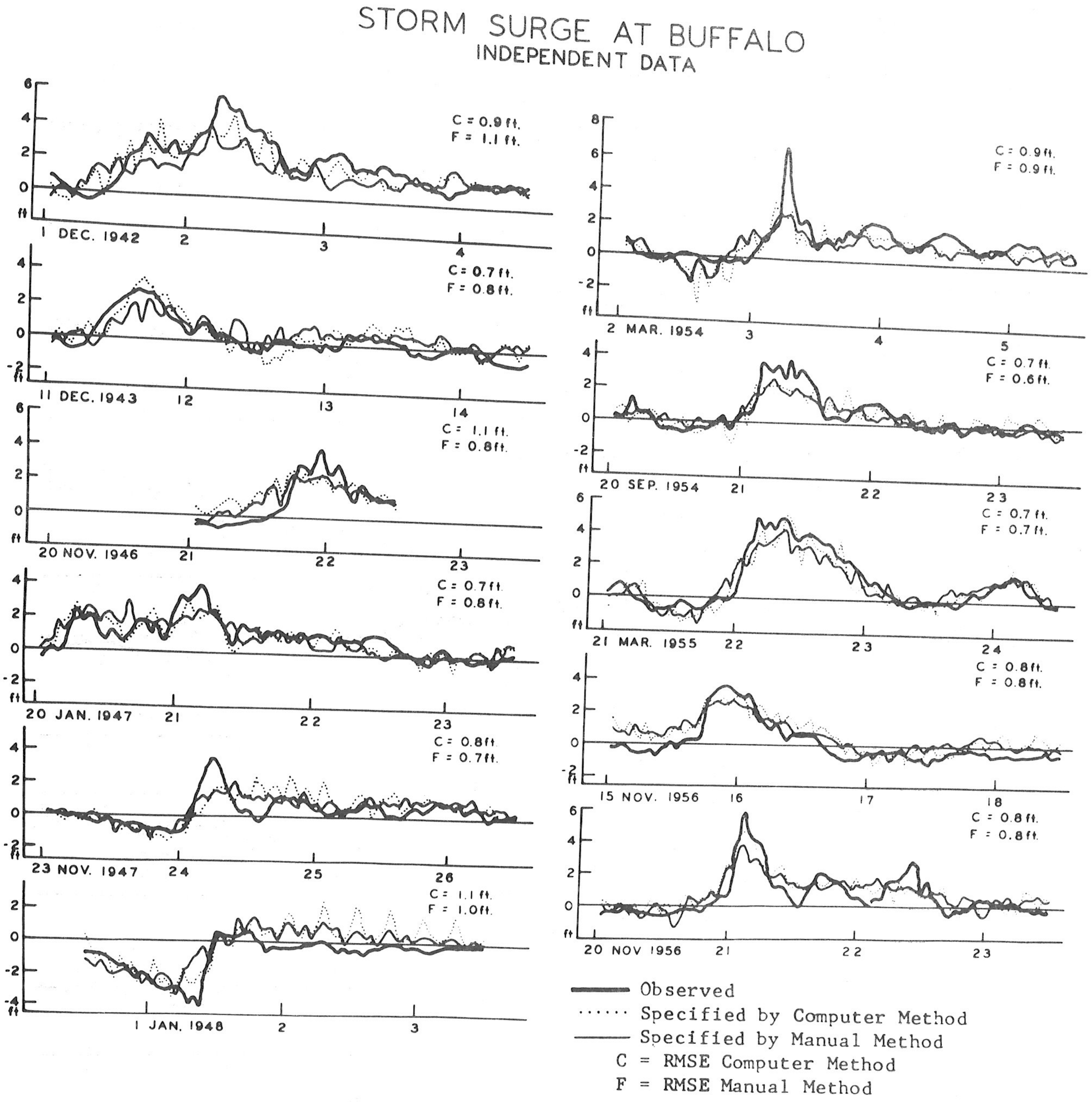


Figure 9.--Specified and observed storm surge at Buffalo for independent data cases.

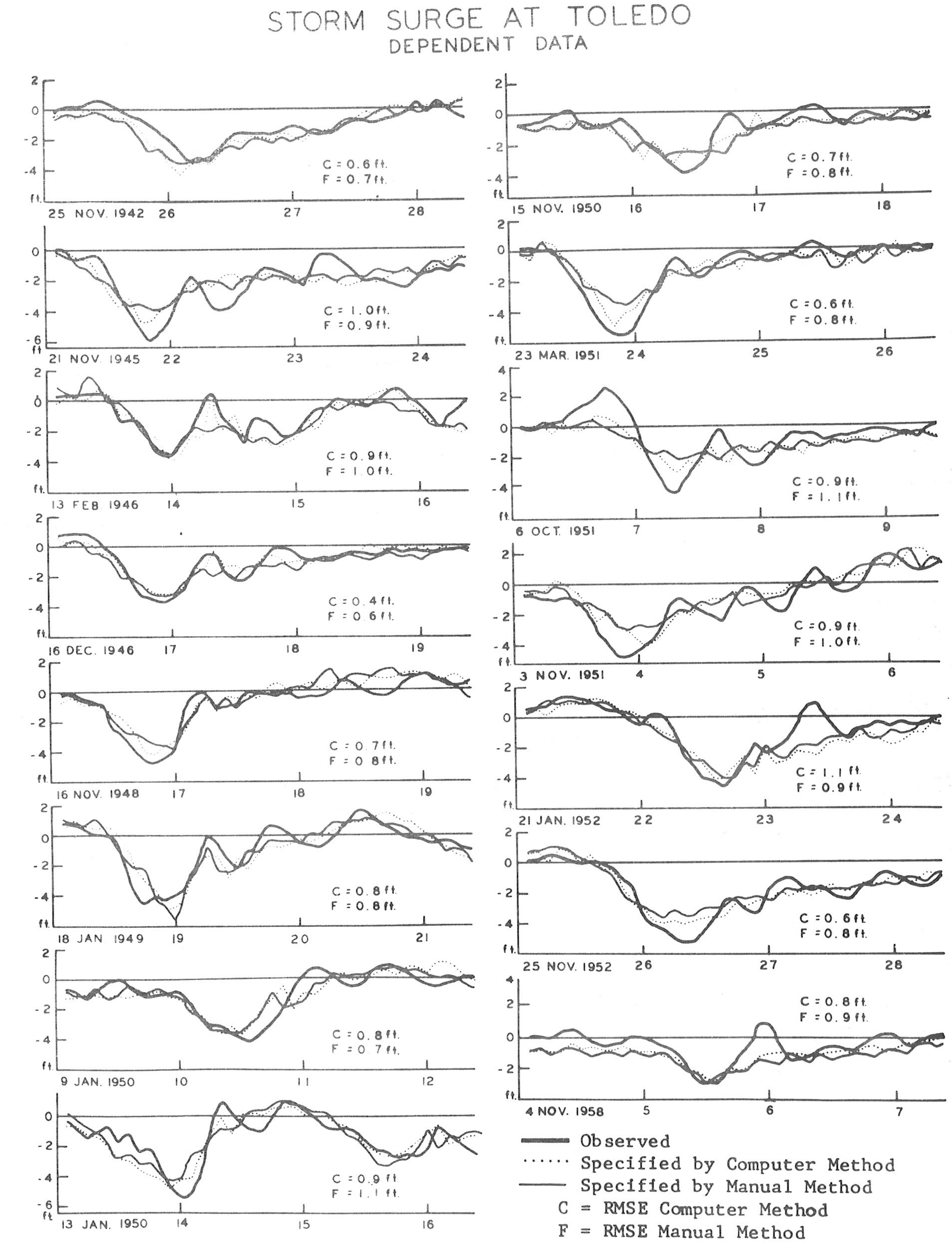


Figure 10.--Specified and observed storm surge at Toledo for dependent data cases.

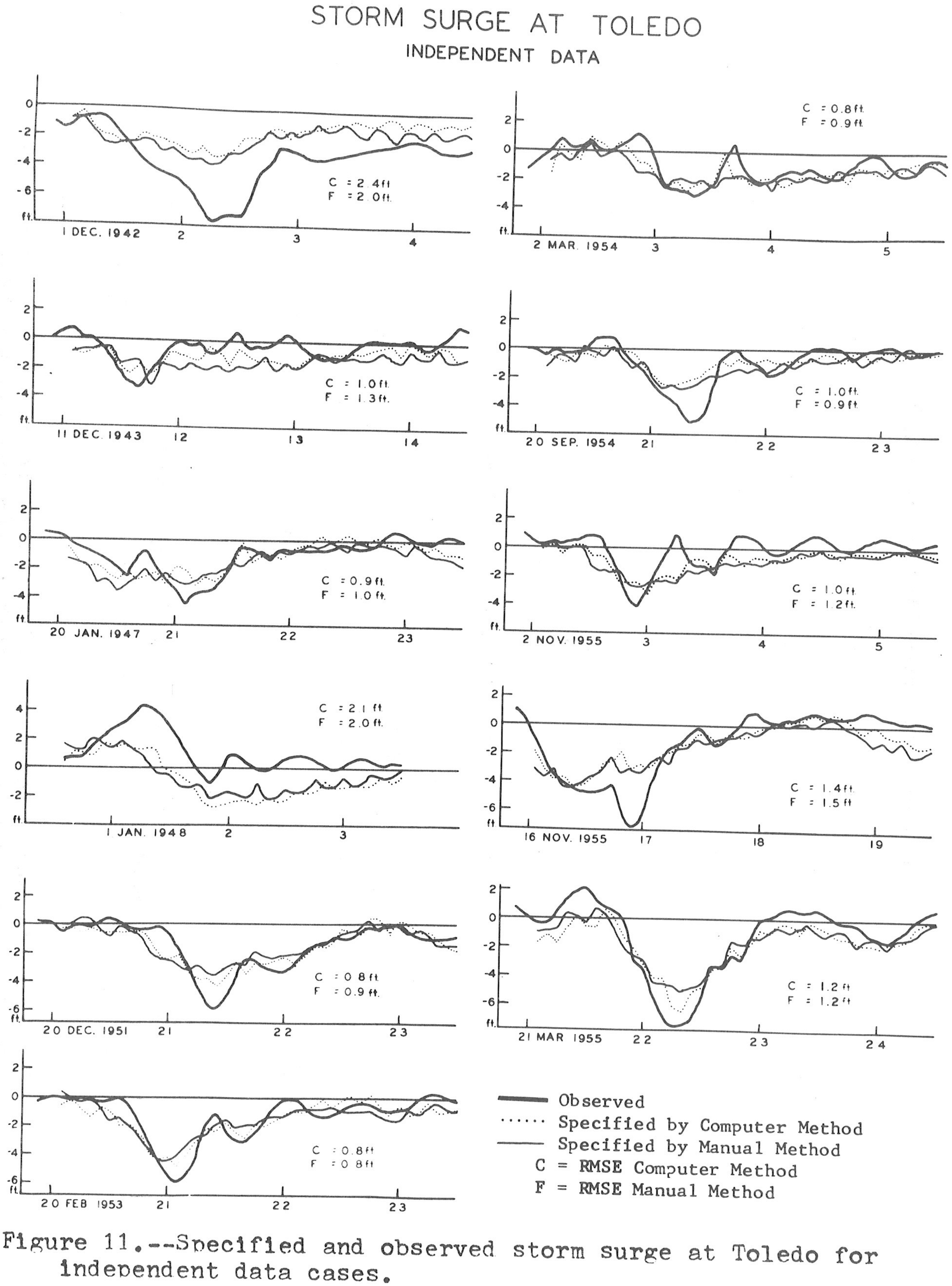
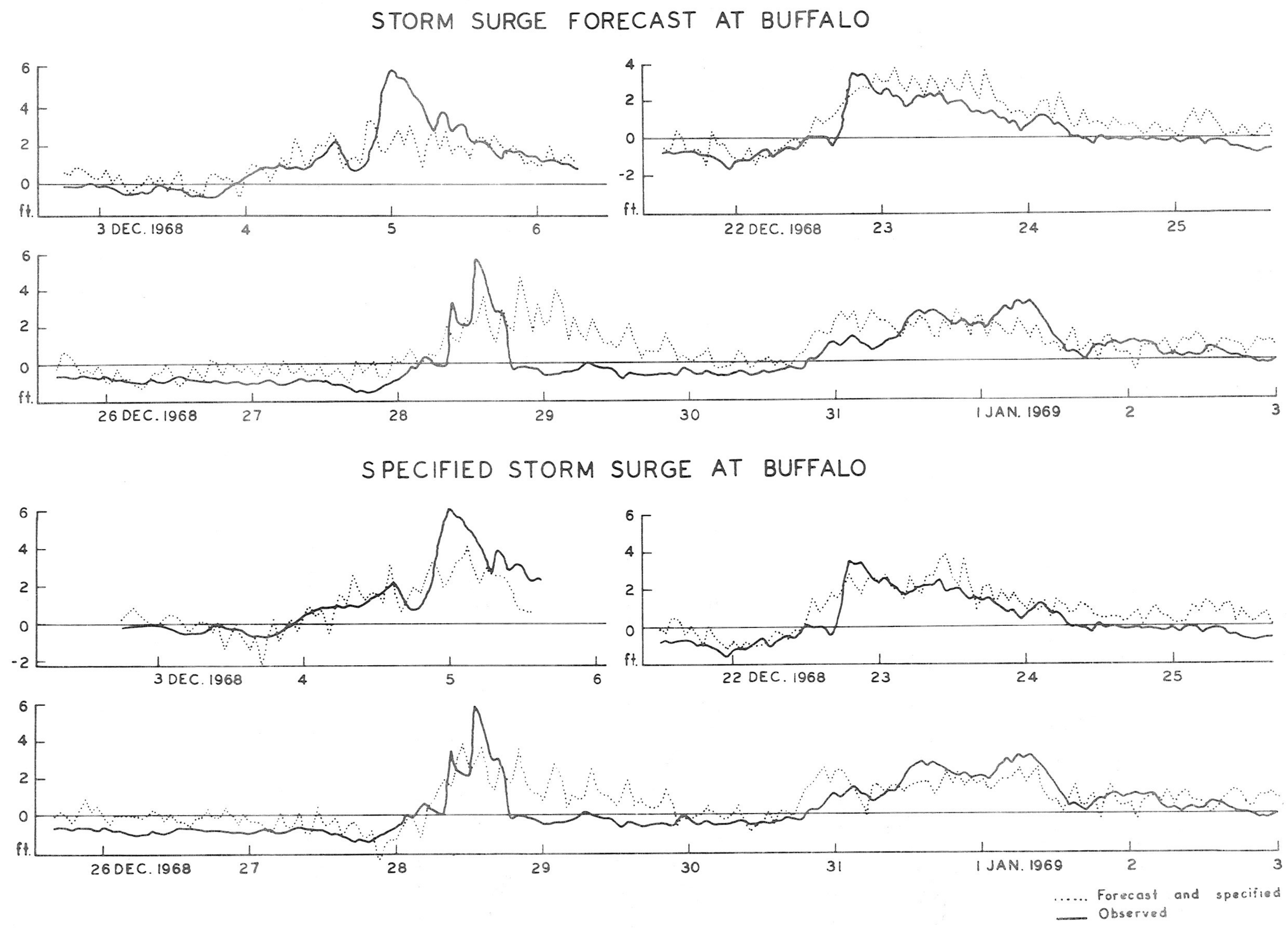


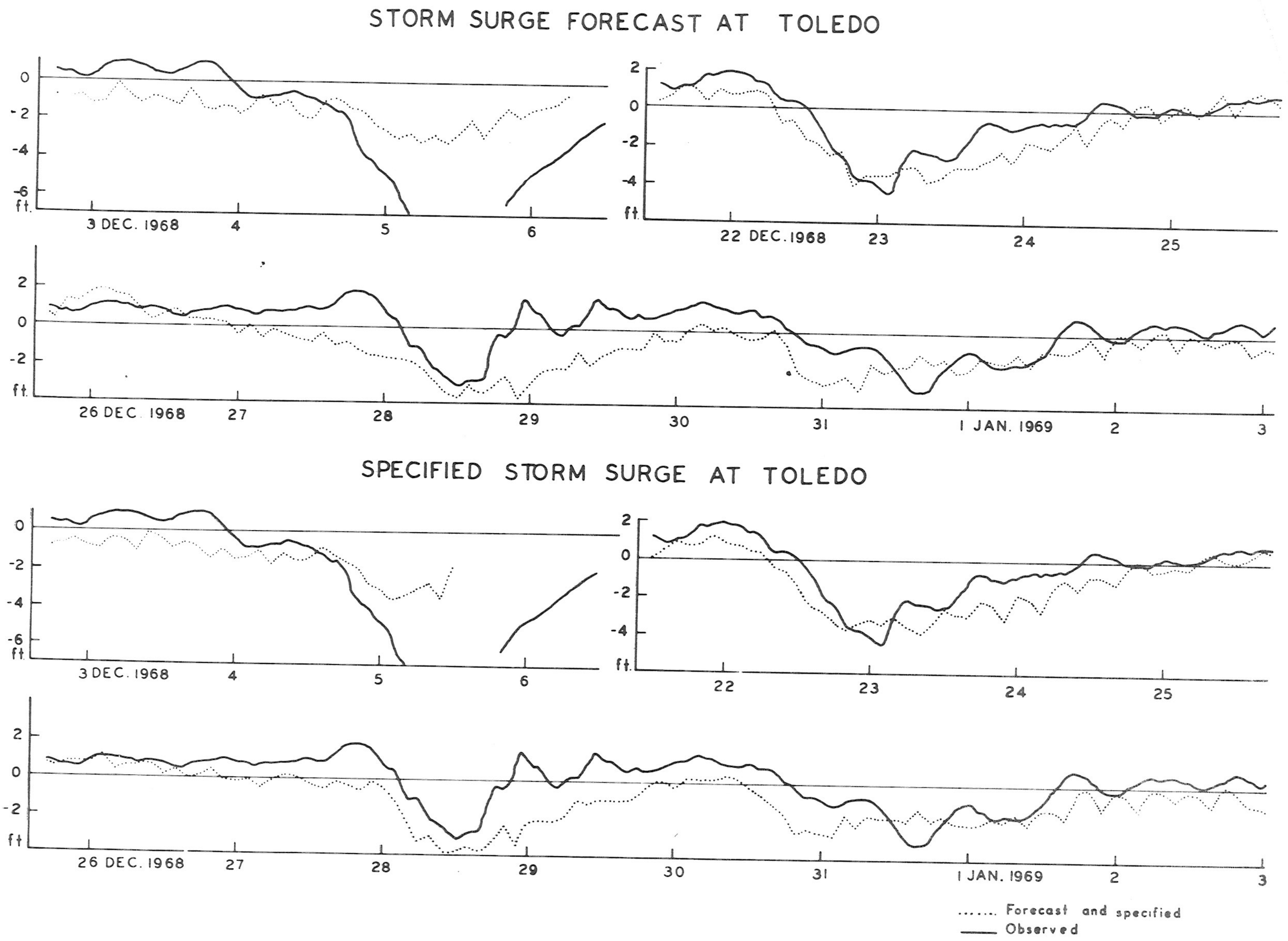
Figure 11.--Specified and observed storm surge at Toledo for independent data cases.



STORM SURGE FORECAST AT BUFFALO

SPECIFIED STORM SURGE AT BUFFALO

Figure 12.--Hourly storm surge forecasts 13-24 hours in advance and specified storm surge at Buffalo for four storms, December 1968 and January 1969.



STORM SURGE FORECAST AT TOLEDO

SPECIFIED STORM SURGE AT TOLEDO

Figure 13.--Hourly storm surge forecasts 13-24 hours in advance and specified storm surge at Toledo for four storms, December 1968 and January 1969.

(Continued from inside front cover)

WBTM TDL 16 Objective Visibility Forecasting Techniques Based on Surface and Tower Observations. Donald M. Gales, October 1968. (PB-180 479)

WBTM TDL 17 Second Interim Report on Sea and Swell Forecasting. N. A. Pore and Lt. W. S. Richardson, USESSA, January 1969. (PB-182 273)

WBTM TDL 18 Conditional Probabilities of Precipitation Amounts in the Conterminous United States. Donald L. Jorgensen, William H. Klein, and Charles F. Roberts, March 1969. (PB-183 144)

WBTM TDL 19 An Operationally Oriented Small-Scale 500-Millibar Height Analysis. Harry R. Glahn, March 1969.

WBTM TDL 20 A Comparison of Two Methods of Reducing Truncation Error. Robert J. Bermowitz, May 1969. (PB-184 741)

WBTM TDL 21 Automatic Decoding of Hourly Weather Reports. George W. Hollenbaugh, Harry R. Glahn, and Dale A. Lowry, July 1969.

WBTM TDL 22 An Operationally Oriented Objective Analysis Program. Harry R. Glahn, George W. Hollenbaugh, and Dale A. Lowry, July 1969.

WBTM TDL 23 An Operational Subsynoptic Advection Model. Harry R. Glahn, Dale A. Lowry, and George W. Hollenbaugh, July 1969.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