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IMPROVED 6-, 12-, 18-, AND 24-H EXTRATROPICAL STORM SURGE FORECAST GUIDANCE FOR WILLETS POINT, N.Y.

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1. INTRODUCTION

In a continuing effort to improve east coast extratropical storm surge forecast guidance, we have derived new forecast equations for Willets Point, N.Y. The derivation of these equations is similar to the derivation of new equations for Boston, Mass; New York, N.Y.; Norfolk, Va.; and Charleston, S.C. (Richardson and Gilman, 1983).

The meteorologically generated storm surge (measured water level minus astronomical tide) is primarily caused by wind stress on the water surface. This surge, which is modified by nearshore bathymetry and the shoreline, is superimposed on the astronomical tide. When significant storm surges and associated wave action occur at the same time as high astronomical tides, serious flooding and beach erosion may occur.

2. BACKGROUND

The Techniques Development Laboratory has developed automated extratropical storm surge forecast guidance for 12 tide gage locations (Portland, Maine; Boston, Mass.; Newport, R.I.; Stamford, Conn.; Willets Point, N.Y.; New York, N.Y.; Atlantic City, N.J.; Breakwater Harbor, Del.; Baltimore, Md.; Norfolk, Va.; Avon, N.C.; and Charleston, S.C.) along the east coast (National Weather Service, 1978). For each location (see Fig. 1), a separate equation was derived with a multiple regression screening program (Pore et al., 1974). The regression program was used to correlate observed storm surge heights with analyzed sea-level pressures at 6-Level Primitive Equation (6LPE) model grid points.

Forecasts from the 6LPE model were used to generate surge forecasts until the birth of the Limited-area Fine Mesh (LFM) model. Forecasts for the 12 tide gage locations are now made by interpolating sea-level pressure forecasts of the LFM model to 6LPE grid points. These interpolated values are the predictors in the storm surge forecast equations. This interpolation step eliminated the time consuming job of retabulating 80,000 analyzed sea-level pressure values (predictors) at LFM grid points. This would have been necessary if surge equations were derived with predictors at those points. Storm surge forecasts at 6-h intervals (Fig. 2) are made twice each day to 48 hours.

In the very near future, observed storm surge heights at a number of east coast tide gage locations will become part of the National Meteorological Center's (NMC's) data base. Since this data base will be accessible to the automated storm surge forecast system, observed surge heights could be used as predictors in the storm surge forecast equations. In the short term, storm surge observations should be very good predictors of future surge heights.

This paper discusses the derivation of 6- and 24-h forecast equations for Willets Point N.Y. These new equations use storm surge observations (measured water levels minus astronomical tides) in addition to sea-level pressures to forecast surge heights. An evaluation of surge heights computed by these new equations is also presented.

3. DERIVATION

The new equations were derived with a multiple regression screening program. This regression program was used to correlate predictand data (measured surge heights) with observed predictors. This approach, where predictand data are correlated with observed predictors is called "perfect prog" in contrast to the Model Output Statistics (Glahn and Lowry, 1972) approach where predictand data are correlated with forecasts from a model.

A. Predictand

The predictand, storm surge height, is a meteorologically-generated water level fluctuation. Storm surge heights at 0100, 0700, 1300, and 1900 EST were calculated by subtracting the astronomical tide heights from water levels measured by National Ocean Service tide gages. From these calculated heights, we selected storm surge events. Each event, which began and ended with observed surge heights near zero, contained at least one observed height with a magnitude equal to or greater than 2 feet. The development sample was 51 storm surge events (409 6-h heights). All storm surge events occurred from November through April and varied in length from 1 to 7 days.

B. Predictors

For each height, we offered the regression program analyzed sea-level pressures at 6-h intervals at 75 NMC grid points (Fig. 3) with time lags of 0, 6, 12, 18, and 24 hours. Also offered as predictors were the observed surge heights at Willets Point, Newport, and New York with 6-, 12-, 18-, and 24-h lags. At these same lag times, differences between storm surge heights (New York-Willets Point and Newport-Willets Point) were also offered as predictors. Heights and differences in heights with lags greater than 24 hours were not considered as predictors because the correlation fell off rapidly after that time.

C. New Equations

The first predictor selected in the derivation of the 6-h equation was the observed surge height at New York with a 6-h lag. Neither storm surge heights nor height differences were selected as predictors in the derivation of the 12- and 18-h equations. For the 24-h equation, a storm surge difference (New York-Willets Point) was selected as the sixth predictor.

New equations are shown in the appendix. All constants and coefficients in all equations have been inflated. This inflation procedure partially corrects for underforecasting magnitudes of peak surge heights by multiplying surge heights by the reciprocal of the correlation coefficient which was calculated with the development sample. The average value of inflation factors is approximately 1.2. This same inflation procedure is used to produce the operational surge forecast guidance.

4. EVALUATION

Storm surge heights specified (computed with analyzed, not forecast, sea-level pressures) by the new equations and the operational equation were evaluated in two ways. First, verification scores were computed and evaluated for independent events for each location. Second, comparisons of observed and specified surges were made for two significant storm surge events.

A. Verification Scores

Table 1 shows the dates of independent events which were used in the evaluation. Table 2 shows the verification scores (correlation coefficient, RMSE, and weighted RMSE) associated with independent data. 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 magnitude of the observed surge height is 1 foot or less. For heights with magnitudes greater than 1 foot, the error (observed minus specified) is weighted by multiplying the error by the observed surge. The mathematical expression for WRMSE is:

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

where

n = number of observations in the surge event,

O_i = i-th observed surge height,

S_i = i-th specified surge height, and

W_i = i-th weight, where $W_i = 1$ if $|O_i| \leq 1$, or $W_i = O_i$ (numerical value without units) if $|O_i| > 1$.

This statistic gives a heavier weight to an error that occurs when the magnitude of the surge is greater than 1 foot. Errors associated with high surge heights are more critical and are therefore given more weight.

Scores in the upper part of Table 2 are based on all independent data. The scores shown in the lower part of the table were computed from peak (magnitude of measured surge equaled or exceeded 1.5 feet) data or 25 percent of the data. Scores associated with the 06- and 24-h equations are listed under the headings LGA06 and LGA24, respectively.

For all data, the correlation coefficient associated with the 6-h equation is only slightly larger than the correlation coefficient associated with the operational equation. Keep in mind that only one operational equation is used to make forecasts for all projections. Verification statistics for 6- and 12-h persistence are shown under the headings 6h and 12h. The RMSE associated with the 6-h equation is a little lower than the RMSE for the operational equation. The opposite is the case for the 24-h equation. The new equations have the lower WRMSE's. Persistence at 12 hours is not nearly as good a predictor as persistence at 6 hours. For peak data, in the lower half of Table 2, the RMSE's associated with the new equations are better than the one associated with the operational equation. The new equations also have much better WRMSE's than the operational equation.

B. Significant Storm Surge Events

Two events (November 24-27, 1950 and November 4-8, 1953) were chosen by selecting the two events with the highest observed storm surge height. Meteorological settings, measured surge heights, and heights specified by the 24-h equation and the operational equation are shown for each event. The inflated surge heights specified by the 24-h equation and the operational equation are plotted at 6-h intervals while solid lines connect hourly measured surge heights. Inflated surge heights specified by the 24-h equation are denoted by dots while inflated heights specified by the operational equation are shown as squares. The WRMSE's associated with the 24-h equation and the operational equation are given for each independent event. Dates are placed at 1200 EST.

The November 1950 storm was considered by some to be the worst storm on record for the eastern United States (Bristor, 1951). This storm caused record-breaking tides all along the northern east coast. Fig. 4 shows the sea-level pressure pattern associated with this event. The upper graph in Fig. 5 shows that the new 24-h equation specified the surge more accurately except for the peak value. The WRMSE associated with the new 24-h equation is slightly better than the WRMSE associated with the operational equation.

The storm associated with the November 1953 event caused strong onshore winds at many coastal locations. Fig. 6 contains 12-h surface pressure charts from 0130 EST November 6 through 0130 EST November 8. At 0130 EST November 6, the low was located just off the Georgia-Florida coast. It progressed to the Cape Hatteras area by 1330 EST on the 6th, and to the Delaware area by 0130 EST on the 7th. The pressure gradient resulting from the low pressure of the storm and the high located over the Great Lakes area caused extremely high winds north of the storm center. The graph (lower graph of Fig. 5) for this event shows that the 24-h equation specified the surge much more accurately than the operational equation. This is also shown by the much lower (1.79 feet lower) WRMSE.

5. CONCLUSIONS

The statistical evaluation clearly shows that the surge heights specified by the new equations are significantly more accurate than heights specified by the operational equation. Evaluations of storm surge graphs, with the WRMSE statistic, also indicate the new equations specified the storm surge heights more accurately than the operational equation for the two storm surge events.

When storm surge observations at Willets Point become a part of the NMC data base, we suggest that:

(1) The 6-h forecasts for Willets Point be made with the new 6-h equation. The 12- 18- and 24-h forecasts be made with the new 24-h equation.

(2) Observed storm surge observations at the time of initial data (0000 or 1200 GMT) at Willets Point be transmitted in place of the calculated surge heights.

(3) Storm surge forecasts for 30, 36, 42, and 48 hours continue to be made with the operational equation.

ACKNOWLEDGMENTS

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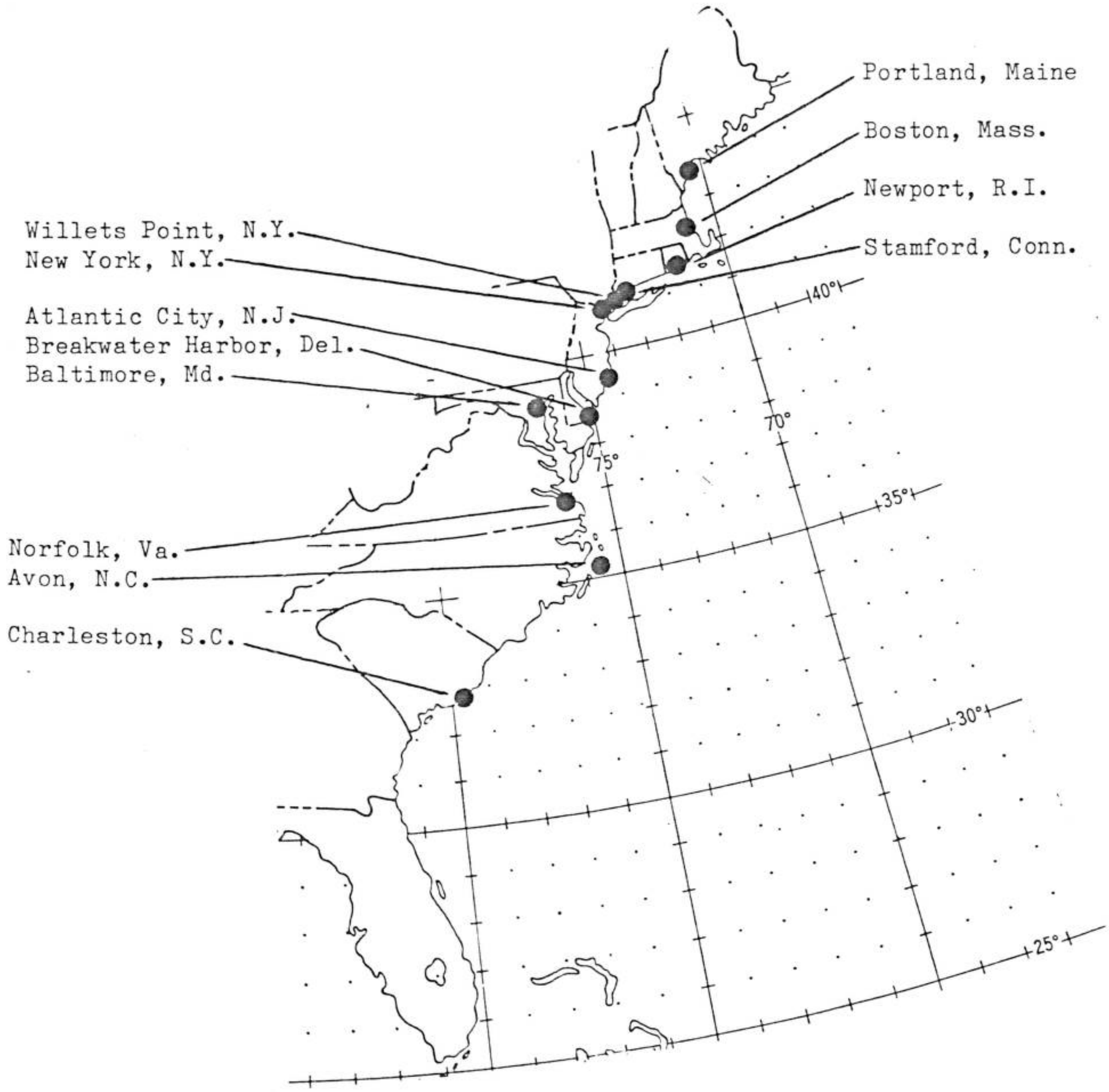

Figure 1. The 12 east coast locations for which automated extratropical storm surge forecasts are made.

FZUS3 KWBC 090000

STORM SURGE FCST FEET (INVALID FOR TROPICAL STORMS)

	00Z	06Z	12Z	18Z	00Z	06Z	12Z	18Z	00Z
PWM	0.1	0.6	0.9	1.5	1.6	1.8	1.6	1.4	1.0
BOS	-0.0	0.7	1.2	1.7	2.0	2.1	1.9	1.6	1.2
NWP	0.4	1.2	1.4	2.0	2.0	1.9	1.7	1.5	1.3
SFD	1.8	2.6	3.5	3.9	3.8	3.6	2.9	2.2	1.3
LGA	0.3	1.3	1.8	2.4	1.9	1.9	1.5	1.3	0.8
NYC	0.8	1.6	2.0	2.5	2.4	2.0	1.3	1.0	0.6
ACY	0.8	1.4	1.7	2.1	2.2	2.0	1.7	1.4	1.1
BWH	0.8	1.3	1.5	2.0	2.0	1.7	1.4	0.9	0.8
BAL	-0.0	0.2	0.4	0.2	-0.4	-1.0	-1.5	-1.4	-0.8
ORF	0.3	0.2	0.9	0.9	1.1	1.2	1.3	0.8	0.5
AVN	0.2	1.0	1.5	1.0	0.5	0.3	0.2	0.2	0.2
CHS	0.2	0.1	-0.6	-0.8	-1.3	-1.4	-0.9	-0.9	-0.2

Figure 2. A sample of the storm surge forecast message which is transmitted on Request/Reply twice each day. The storm surge height forecasts for Portland, Maine (PWM), Boston, Mass. (BOS), Newport, R.I. (NWP), Stamford, Conn. (SFD), Willets Point, N.Y. (LGA), New York, N.Y. (NYC), Atlantic City, N.J. (ACY), Breakwater Harbor, Del. (BWH), Baltimore, Md. (BAL), Norfolk, Va. (ORF), Avon, N.C. (AVN), and Charleston, S.C. (CHS) are made to 48 hours in advance at 6-h intervals. These forecasts, which are in feet, are based on sea-level pressure forecasts of the LFM model.

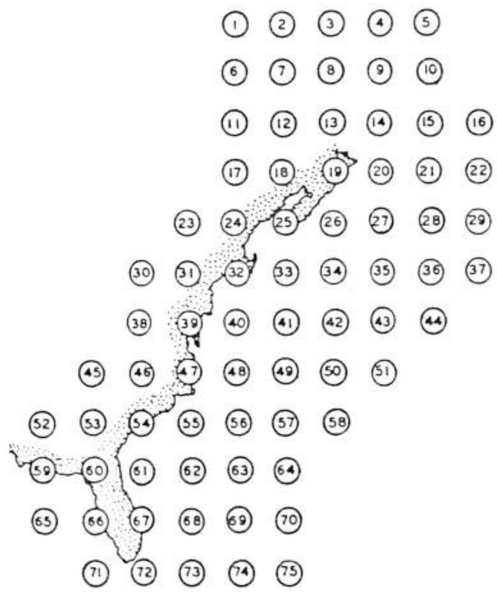

Figure 3. The location of the 75 NMC 6LPE grid points where analyzed sea-level pressures were available as predictors (from Pore et al., 1974).

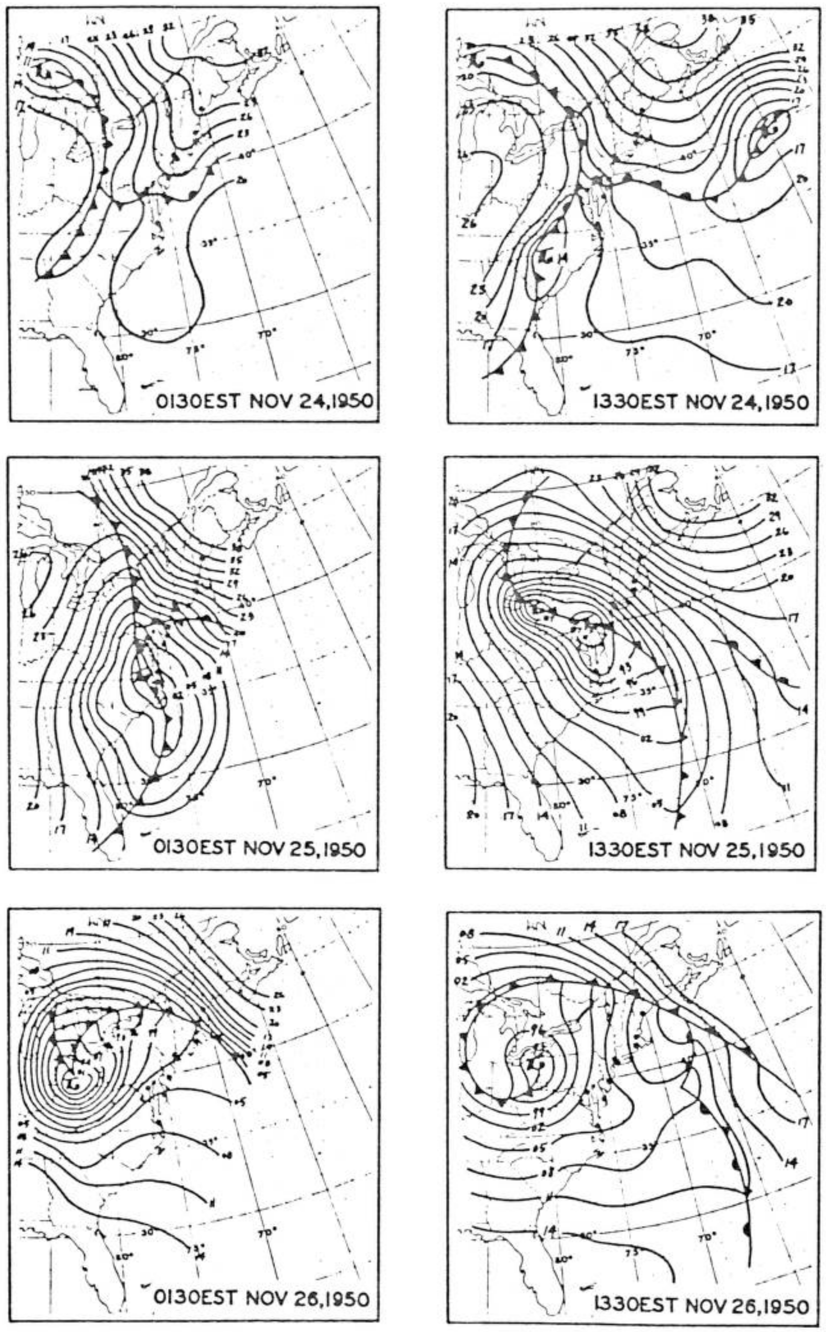

Figure 4. Sea-level pressure charts from 0130 EST November 24, 1950 to 1330 EST November 26, 1950.

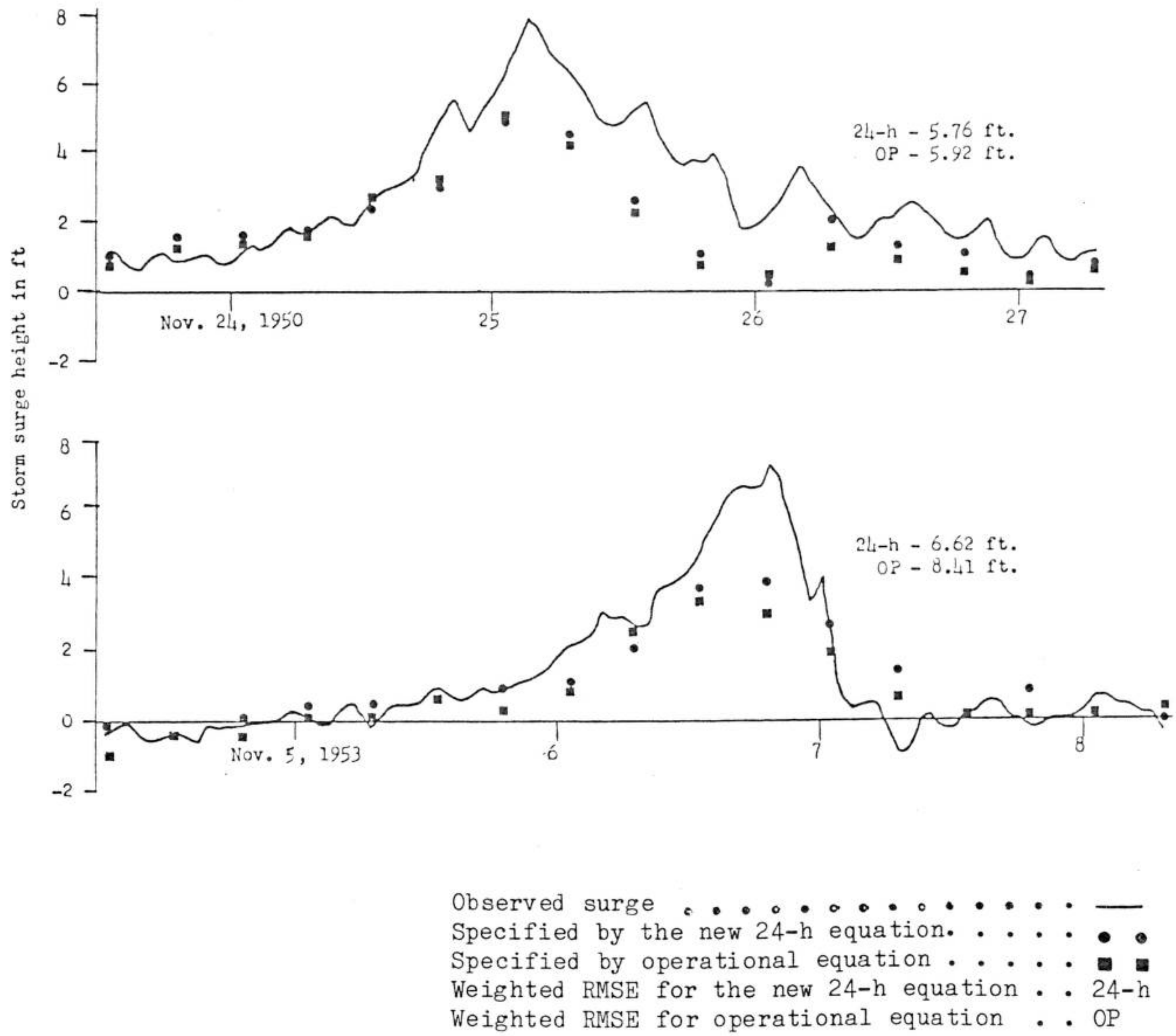

Figure 5. Two independent Willets Point storm surge events which occurred on November 24-27, 1950 (top graph) and November 5-8, 1953 (lower graph). Observed surges are shown as solid lines, while surges specified by the new 12-h equation and the operational equation are denoted by dots and squares, respectively. Coincident specifications are depicted by squares. Dates are placed at 1200 EST. Weighted RMSE's are given for the new 12-h equation and the operational equation from each event.

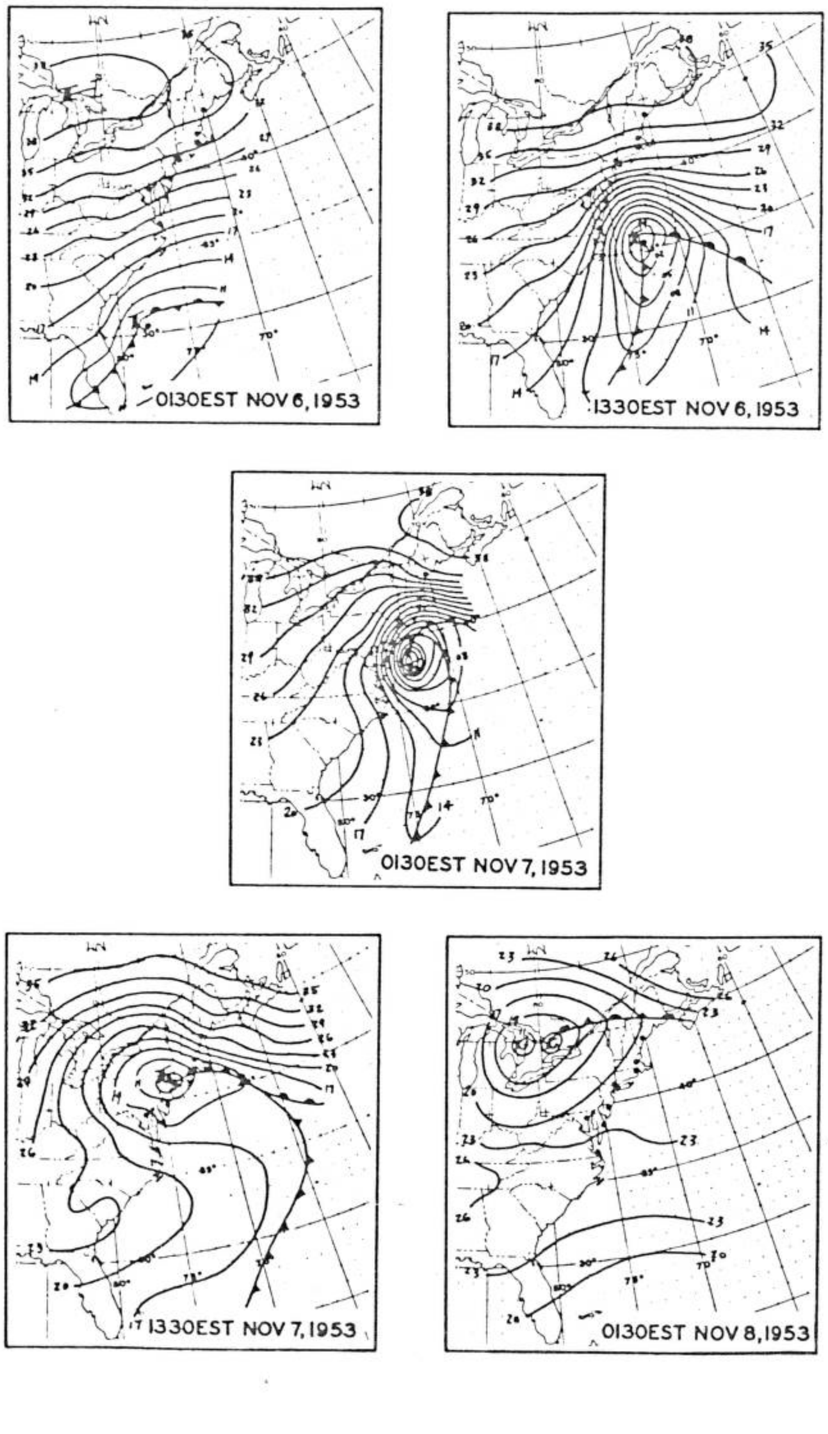

Figure 6. Sea-level pressure charts from 0130 EST November 6, 1953 to 0130 EST November 8, 1953.

Table 1. Dates of independent storm surge events which were used in the verification.

Dates of Independent Cases
Nov. 21-28, 1950
Nov. 3-8, 1953
Jan. 31-Feb. 6, 1972
Feb. 15-21, 1972
Nov. 6-9, 1974
Mar. 12-21, 1975
Apr. 3-6, 1975
Apr. 15-17, 1975
Jan. 29-Feb. 3, 1976
Mar. 14-18, 1976
Apr. 23-30, 1978

Table 2. Verification scores associated with the new equations, persistence, and the operational equation for 11 independent events. The new 6- and 24-h equations are denoted by LGA06 and LGA24. Six- and 12-h persistence are denoted by 6h and 12h. Scores tabulated in the top part of the table are based on all independent data (182 6-h heights). The lower part of the table shows the scores computed from peak data (46 6-h heights).

	New Equations		Persistence		Operational
	LGA06	LGA24	6h	12h	Equation
All Data					
Correlation coefficient	0.90	0.85	0.75	0.53	0.85
RMSE (feet)	0.78	0.95	1.13	1.57	0.86
WRMSE (feet)	2.48	3.08	3.68	5.27	3.46
Peak Data					
Correlation coefficient	0.94	0.90	0.77	0.52	0.91
RMSE (feet)	1.05	1.23	1.77	2.43	1.31
WRMSE (feet)	4.80	5.97	7.17	10.29	6.79

APPENDIX

NEW WILLETS POINT EQUATIONS

$$
\begin{aligned}
LGA06_T = 12.53 &+ 0.6836\ NYC_{T-6} - 0.1900\ NYC_{T-18} \\
&- 0.0875\ GP(40)_T + 0.1417\ GP(24)_{T-6} \\
&- 0.0800\ GP(24)_{T-12} + 0.0528\ GP(48)_T \\
&- 0.3560\ DIF_{T-24} - 0.0390\ GP(39)_{T-6}
\end{aligned}
$$

$$
\begin{aligned}
LGA24_T = 17.79 &- 0.0765\ GP(40)_T + 0.1330\ GP(24)_{T-6} \\
&- 0.1456\ GP(39)_{T-6} - 0.0265\ GP(27)_{T-6} \\
&+ 0.0625\ GP(46)_{T-12} - 0.3430\ DIF_{T-24} \\
&+ 0.0736\ GP(48)_T - 0.0372\ GP(50)_T
\end{aligned}
$$

The term to the left of the equal sign is the storm surge forecast in feet at verifying time T. The three left most characters of this term designate gage location LGA (Willets Point). The number following the locations designator is the lag time in hours of the storm surge predictor. NYC is the New York storm surge height in feet. DIF is the storm surge at New York minus the storm surge at Willets Point in feet. GP is the sea-level pressure in millibars at the indicated grid point (see Fig. 3). The negative numbers of the pressure and surge subscripts are time lags in hours.