

## IMPROVED AUTOMATED EXTRATROPICAL STORM SURGE FORECAST GUIDANCE FOR EAST COAST CITIES

William S. Richardson (1) and  
 Craig S. Gilman (2)  
 Techniques Development Laboratory  
 Office of Systems Development  
 National Weather Service, NOAA  
 Silver Spring, Maryland 20910

### ABSTRACT

Short range (6 to 24 hour) automated extratropical storm surge forecast guidance will be improved when the National Ocean Service's water level telemetry measurements become available to the National Weather Service's automated surge forecast method in real time. The projected improvement is based on a verification study which included 11 to 13 independent storm events.

### 1. INTRODUCTION

The development of coastal communities and businesses has increased the need for accurate and timely storm surge (measured water level minus astronomical tide) forecast guidance. In a continuing effort to improve this guidance, we have derived new forecast equations for Boston, Mass.; New York, N.Y.; Norfolk, Va.; and Charleston, S.C. (3); and Willets Point, N.Y. (4). These new equations use sea-level pressure forecasts and water level telemetry data from the National Ocean Service (NOS) to forecast surges to 24 hours in advance.

### 2. BACKGROUND

Automated guidance has been made for 10 tide gage sites (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.; and Norfolk, Va.) since the early 1970's. In the late 70's forecasts for Avon, N.C. and Charleston, S.C. were added (5). Fig. 1 shows the 12 locations for which surge guidance is made. Forecasts for additional sites (Cape Hatteras, Morehead City, and Southport) along the North Carolina coast are planned for the fall of 1984. For each location, separate equations were derived with a multiple regression screening program (6). The regression program was used to correlate observed storm surge heights with analyzed sea-level pressures. These pressures were

tabulated at grid point locations where forecasts from the National Meteorological Center's (NMC's) 6-Level Primitive Equation (6LPE) model (7) were made.

Forecasts from the 6LPE model were used to generate surge forecasts until the birth of the Limited-area Fine Mesh (LFM) model (8). 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 near future, observed storm surge heights at a number of east coast tide gage locations will become part of NMC's database via NOS's water level telemetry system. Since this database will be accessible to the automated storm surge forecast system, observed surge heights can 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 article addresses the derivation of the new equations and presents a statistical evaluation of the surge heights computed by these equations. For a complete discussion of the derivation, see Richardson and Gilman (3, 4).

### 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 (9) approach where predictand data are correlated with forecasts from a model.

### 3.1 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 NOS 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. Development samples varied in size from 53 storm surge events (597 6-h heights) at New York to 22 events (288 6-h heights) at Charleston. All storm surge events occurred from November through April and varied in length from 1 to 7 days.

### 3.2 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 with 6-, 12-, 18-, and 24-h lags. Heights with lags greater than 24 hours were not considered as predictors because the correlation fell off rapidly after that time. We did not offer stability predictors (differences between and ratios of air and water temperature, and harmonics of an annual cycle) since these predictors were not selected in an earlier rederivation of the Charleston storm surge equation (10).

During the derivation of the Willets Point equations, additional predictors were offered because observed surge heights at Willets Point with 6-, 12-, 18-, and 24-h lags were not selected. Additional predictors offered were the observed surge heights at Newport, R.I. and New York, N.Y. 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.

### 3.3 New Equations

New equations were derived for the following forecast hours:

Boston	- 12 and 24 hours,
Willets Point	- 6 and 24 hours,
New York	- 6, 12, and 24 hours,
Norfolk	- 6, 12, 18, and 24 hours, and
Charleston	- 12 and 24 hours.

Let's look at the Willets Point 24-h forecast equation.

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

where

$\text{LGA}_{24T}$  = Willets Point storm surge forecast in feet at verifying time T.

$\text{GP}(i)_T$  = sea-level pressure forecast in millibars at grid point  $i$  (see Fig. 3) at verifying time T, and

$\text{DIF}_{T-24}$  = storm surge at New York minus the storm surge at Willets Point in feet at T-24 hours.

A 24-h forecast can be made if we have sea-level pressure forecasts for the indicated grid points at T, T-6 hours, and T-12 hours, and the measured surge at New York and Willets Point at T-24 hours. Forecast equations for hours 12 and 18 were not derived because storm surge heights predictors were not selected by screening process. However, the 24-h forecast equation can be used for 12- and 18-h forecasts. To make an 18-h forecast from initial time I ( $T = I + 18$  hours), we will use 6-, 12-, and 18-h sea-level pressure forecasts and the observed surge heights at New York and Willets Point at I-6 hours.

## 4. EVALUATION

Storm surge heights specified (computed with analyzed, not forecast, sea-level pressures) by the new equations and the operational equation were evaluated. Verification scores were computed and evaluated for independent events for each location. Computed heights were inflated by multiplying specified surge heights by the reciprocal of the correlation coefficient which was calculated with the dependent sample. The average value of the inflation factors is approximately 1.2. This inflation procedure, which partially corrects for under-forecasting magnitudes of peak surge heights, is the same inflation procedure used to produce the operational surge forecast guidance.

A new verification score introduced by Richardson and Gilman (3), a weighted RMSE (WRMSE), was used to evaluate the new forecast equations. The WRMSE 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.

To get a better feel for this statistic, let's look at an extreme surge event which occurred at Willets Point in November 1953. This event began with a low pressure system which was located just off the Georgia-Florida coast on November 6. See Fig. 4. The low moved off the Delaware coast on the 7th. The pressure gradient resulting from the low pressure of the storm and a high located over the Great Lakes area caused very high winds north of the center. The surge heights specified by the Willets Point 24-h equation and operational equation are plotted with the measured surge heights in Fig. 5.

Specified surge heights are plotted at 6-h intervals while solid lines connect hourly measured surge heights. Surge heights specified by the 24-h equation are denoted by dots while heights specified by the operational equation are shown as squares. Dates are placed at 1200 EST.

The peak surge which occurred on the 7th is greatly underspecified by both the new 24-h equation and the operational equation. This underspecification is emphasized in the larger WRMSE, 6.62 ft. for the new equations and 8.41 ft. for the operational equation. The respective RMSE's are 1.18 ft. and 1.30 ft. The large difference between the WRMSE's and the RMSE's can be accounted for by looking at the last measurement (2 ft.) and associated specifications on the 6th and the first two measurements (5 and 7.5 ft.) and specifications on the 7th. WRMSE's, associated with the independent surge events listed in Table 1, are shown in Table 2. Errors associated with

the new 6-, 12-, 18-, and 24-h equations are listed under the headings NO6, N12, N18, and N24. Scores for 6- and 12-h persistence are shown under the headings 6h and 12h, respectively. Keep in mind that only one operational equation is used at each location.

The scores shown in Table 2 indicate that the new equations perform better than the operational equation at all locations. We therefore feel that 6- to 24-h automated surge forecast guidance can be improved if water level telemetry measurements are used in real time.

## 5. PLANS

When NOS's water level telemetry data are included in the NMC database on a regular basis, we will change the automated surge program to calculate surge forecasts in the following manner:

- (1) The 6- and 12-h forecasts for Boston will be made with the new 12-h equation. Forecasts for the 18- and 24-h projections will be made with the new 24-h equation.
- (2) At Willets Point, the 6-h forecasts will be made with the new 6-h equation. The 12-, 18-, and 24-h forecasts will be made with the new 24-h equation.
- (3) For New York, the 6- and 12-h forecasts will be made with the new 6- and 12-h equations. The new 24-h equation will be used to make the 24-h forecast.
- (4) At Norfolk, the 6-, 12-, 18-, and 24-h forecasts will be made with the new 6-, 12-, 18-, and 24-h Norfolk equations, respectively.
- (5) The new Charleston 12-h equation will be used to make the 6- and 12-h forecasts for Charleston. Forecasts for 18 and 24 hours will be made with the new 24-h equation.
- (6) Observed storm surge observations at the time of initial data (0000 or 1200 GMT) at Boston, Willets Point, New York, Norfolk, and Charleston will be transmitted in place of the calculated surge heights.
- (7) Storm surge forecasts for 30, 36, 42, and 48 hours will continue to be made with the operational equation.



Dates of Independent Cases	Tide Gage Locations				
	Boston	Willetts Point	New York	Norfolk	Charleston
Nov. 21-28, 1950	X	X	X	X	X
Nov. 3-8, 1953	X	X	X	X	X
Dec. 13-19, 1970	X		X	X	X
Dec. 1-7, 1971					X
Jan. 31-Feb. 6, 1972	X	X	X	X	
Feb. 15-21, 1972	X	X	X	X	
Nov. 6-9, 1974		X	X	X	X
Nov. 30-Dec. 4, 1974	X				
Mar. 12-21, 1975	X	X	X	X	X
Apr. 3-6, 1975	X	X	X	X	X
Apr. 15-17, 1975	X	X	X	X	X
Jan. 29-Feb. 3, 1976	X	X	X	X	X
Mar. 14-18, 1976	X	X	X	X	X
Feb. 5-11, 1978	X			X	X
Apr. 23-30, 1978		X	X	X	

Table 1. Dates of independent storm surge events which were used in the verification. Events used at each location are designated by the letter "X".

Gage Location	New Equations				Persistence		Operational Equation
	NO6	N12	N18	N24	6h	12h	
Boston		0.90		0.98	1.58	2.02	0.99
Willetts Point	2.48			3.08	3.68	5.27	3.46
New York	1.17	1.46		1.68	1.70	2.69	1.95
Norfolk	0.54	0.56	0.65	0.89	0.74	1.13	0.92
Charleston		0.46		0.55	0.72	0.91	0.67

Table 2. Weighted RMSE's (ft) associated with new equations, persistence, and the operational equation at each location for the independent surge events listed in Table 1.

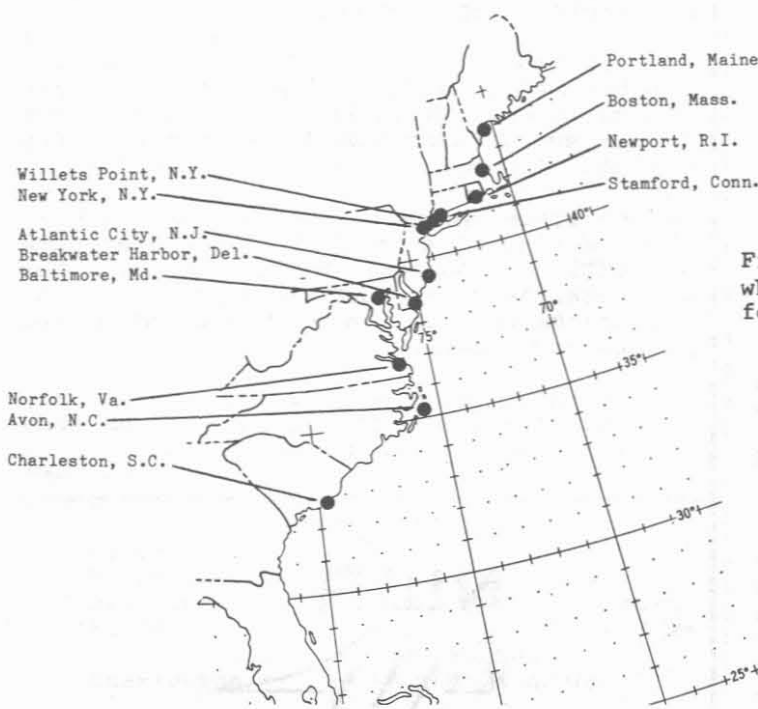


Figure 1. The 12 east coast locations for which automated extratropical storm surge forecasts are made.





