CHAPTER 53

AUTOMATED FORECASTING OF EXTRATROPICAL STORM SURGES

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ABSTRACT

The Atlantic coast of the United States is affected by extratropical storm surges several times each winter. The most devastating storm of this type on record is that of March 1962. This storm caused damage estimated at over $200 million. The National Weather Service has developed an automated technique for forecasting such storm surges. Statistical forecast equations have been derived for 11 locations from Portland, Me., to Charleston, S.C. Input data to these equations are values of sea-level pressure as forecast by an atmospheric prediction model of the National Meteorological Center. A sample forecast equation is shown.

The method was put into operation in 1971. Forecasts are transmitted via teletypewriter and extend to 48 hours at 6-hour intervals. A sample teletype message is shown. Forecasts of the devastating storm surge of Feb. 19, 1972, are discussed. These forecasts agreed reasonably well with observations of the storm surge. Experience with the method indicates it to be useful and therefore it will be expanded to include additional forecast locations.

INTRODUCTION

The extratropical storm of March 5-8, 1962, affected much of the east coast of the United States and caused record breaking high tides at locations between Long Island and Cape Hatteras. This storm was the most devastating on record, as it caused damage estimated to be over $200 million. Figures 1 and 2 show some of the damage at Virginia Beach, Va., and Rehoboth Beach, Del. It is fortunate that storms causing this much damage are rare. However, storms of lesser damage potential occur several times each winter. Accurate and timely forecasts of flooding caused by these storms are important. The crucial times to

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forecast these conditions are also the times when forecasters already have burdens brought on by poor weather conditions associated with coastal storms. Therefore, the National Weather Service has developed an objective forecast technique for forecasting extratropical storm surges. This technique has been automated and operates with meteorological input data from an atmospheric prediction model.

SURGE CHARACTERISTICS

Storm surge is defined as the meteorological effect on sea-level and is computed as the algebraic difference between observed tide and the normal astronomical tide. Figure 3 illustrates this definition with a 2-day length of tide record. Here the observed tide is shown by the upper solid curve, the normal (or predicted) astronomical tide by the dashed line, and the storm surge by the lower curve.

The principal factors involved in the generation and modification of the extratropical storm surge are as follows:

1. The rise of water caused by the action of the wind stress on the water surface. It can be thought of as consisting of two components. One component is the set-up of water by the onshore wind in which the slope of the water surface is directly proportional to the wind stress and inversely proportional to the water depth. The other component is the effect of the alongshore wind that generates a current parallel to shore. The effect of the earth's rotation is to have water piled up along the shore if the shore is to the right of the current.

2. The reduction of atmospheric pressure, generally called the inverted barometer effect that causes an increase in sea level in areas of low pressure.

3. The transport of water by waves and swell in the shallow water area near shore.

4. The modifying effects of coastline configuration and the bathymetry, such as convergence or divergence in bays.

The effect of the time of occurrence of the storm surge with respect to the stage of the normal astronomical tide is shown in Figure 4. Here, two identical storm surges are combined with different phases of the normal tide, one occurring at normal high tide and the other at normal low tide, with the one at high tide resulting in a higher actual tide. The time of occurrence of the storm surge with respect to the normal tide can mean the difference between serious and minor flooding.

The recurrence intervals in cases per year for storm surges of 2 ft or greater, 3 ft or greater, and 4 ft or greater for Portland, Boston, Newport, New York, Atlantic City, Breakwater Harbor, Baltimore, and Norfolk are shown in Figure 5. For example, New York City experiences a 2-ft or greater storm surge about six times a year. A 4-ft or greater surge would be expected to occur only once every 2 years.

DEVELOPMENT OF FORECAST EQUATIONS

The forecast technique is a statistical method based on actual storm surge data during the months of November through April from 1956 through 1969. Storm surge values were determined by subtracting hourly values of the astronomic tide from hourly values of observed tide as shown in Figure 3. Data were selected on the basis of storm surge occurrence. Those storms that produced surges of 2 ft or more at four or more of the stations considered were used. Sixty eight storms were selected in this manner.

Earlier studies related surface wind conditions at coastal weather stations to the storm surge Pore (1964, 1965). In the operations of the National Meteorological Center (NMC), meteorological information at computational grid points is more readily available than at weather stations. For that reason, sea-level pressure forecasts at specific grid points were used to represent the generating winds off the east coast in the storm surge generation process. Every 12 hours the NMC runs their numerical atmospheric model (primitive equation model) that produces forecasts for most of the northern hemisphere. Figure 6 shows the grid points where sea-level pressure was considered in this study. Sea-level pressure at these grid points was obtained at 6-hour intervals from analyzed weather charts for the 68 storm cases. These pressure values, with appropriate lag times, were considered as possible predictors of storm surge.

Forecast regression equations were derived by the statistical screening procedure that has been described by Klein (1965) as follows:

> "The object of the screening procedure is to select from a large set of possible predictors only those few which contribute significantly and independently to the forecast of a predictand. This is accomplished by a forward method of multiple regression in which significant predictors are picked in a stepwise fashion, one by one. As a result, a small number of predictors can be selected which contain practically all the linear predictive information of the entire set with respect to a specific predictand. The importance

of using a small set of predictors to prevent redundancy and instability of the multiple regression equation and to insure good results when applying it to new data has been emphasized by Lorenz (1956, 1959), Grant (1956), Panofsky and Brier (1958), and others."

A detailed description of the selection of predictors by screening is given by Miller (1958). The manner in which predictors of storm surge are screened is shown below:

$$SS = A_1 + B_1X_1 \quad \ldots \quad (1)$$

$$SS = A_2 + B_2X_1 + C_1X_2 \quad \ldots \quad (2)$$

$$SS = A_3 + B_3X_1 + C_2X_2 + D_1X_3 \quad \ldots \quad (3)$$

$$\vdots$$

$$SS = A_n + B_nX_1 + C_{n-1}X_2 + NX_n \quad \ldots \quad (n)$$

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_2, etc., are regression coefficients.

The procedure is to first select the best single predictor (X_1) for regression Eq. 1. The second regression equation contains the first predictor (X_1) and the predictor (X_2) that contributes most to reducing the residual after the first predictor is considered. This screening procedure is carried out until the desired number of predictors is included.

A separate forecast equation was derived for each of the locations shown in Figure 7, so that local effects at each location are considered. The locations extend from Portland, Me., on the north to Charleston, S.C. on the south. These locations were chosen because they are in densely populated areas that are frequently threatened by extratropical storm surges. Also, accurate tide observations, necessary for verification of forecasts, are available from the National Ocean Survey and U.S. Army Corps of Engineers for these locations.

Figure 8 shows, as an example, the forecast equation derived for storm surge at New York. Predictors are the sea-level pressure expressed in millibars at the indicated grid points. The subscripts on these terms indicate the time lags in hours. In this case, nearly all the predictors have time lags of 6 hours. Similar equations were derived for the other 10 locations.

APPLICATION TO THE MARCH 1962 STORM

The waves and storm tides generated by the storm of March 5-8, 1962, caused unprecedented damage to coastal areas from southern New England to Florida. The very persistent strong northeast winds blowing over an extremely long fetch were responsible. Another important factor is that the storm occurred at a time of very high astronomical tide. Articles by Stewart (1962) and Cooperman and Rosendal (1962) give details of the storm.

At 7 a.m. EST on March 5th there was an ill-defined low pressure area with a frontal wave northeast of the Bahamas. Low pressure also extended northwestward through the Carolinas and Virginia. By 7 a.m. EST on the 6th, the entire low pressure area had deepened, resulting in a long easterly fetch over the western Atlantic north of Cape Hatteras. The storm continued to intensify and resulted in an elongated low with strong northeast wind over a very long fetch. Four pressure analyses for the storm are shown in Figure 9.

Since the automated method described in this paper did not become operational until Oct. 8, 1971, automated forecasts were not made for the 1962 storm. However, we have made calculations of the storm surge for this storm based upon actual sea-level pressure analyses.

Curves of observed storm surge and calculated storm surge are shown in Figure 10 for the eight locations, for which we have data, for the period March 5-8, 1962. The heavy solid curves show the observed storm surges based on hourly values. The dashed lines connect the computed values of the storm surge made at 6-hour intervals.

We feel there is considerable skill in the calculation of surge for this storm, even though it was a very intense, record-breaking storm.

OPERATIONAL FORECASTING

In operational use, sea-level pressure forecasts at the appropriate grid points are used as input to the storm surge equations. The pressure forecasts are available twice daily from the numerical weather model of the NMC. Pressure forecasts to 48 hours at 6-hour intervals are used.

A sample teletype bulletin of storm surge height forecasts for the 11 locations is shown in Figure 11. The forecasts are expressed in feet at time intervals of 6 hours for the 48-hour forecast period. Such messages are transmitted on a Weather Service teletype circuit to forecast offices along the east coast where they are used as guidance in preparing the official storm tide bulletins.

AN ACTUAL FORECAST CASE

A very severe coastal storm, to which the automated storm surge method was applied during its first year of operation, was the storm of Feb. 18-20, 1972 (Pore, 1973). The northern portion of the U.S. Atlantic Coast suffered extensive damage and beach erosion. Conditions were very bad as the time of maximum storm surge was near the time of astronomical high tide.

A low pressure system centered over the Great Lakes at 7 a.m. EST on Feb. 18th had a frontal system extending southward over eastern Tennessee, Georgia, Alabama, and into the Gulf of Mexico. Subsequent developments, as depicted on the Northern Hemisphere surface charts of NMC, are shown in Figure 12. By 1 p.m. EST, a closed low had developed over Georgia. Further development occurred and the storm moved rapidly toward the north-northeast, to a position just north of Cape Cod at 1 a.m. EST on the 20th.

Some of the numerical weather model forecasts of storm position and central pressure are shown in Figure 13. The storm center positions and central pressures, taken from the NMC Northern Hemisphere surface charts can be compared to these 12-hour, 24-hour, and 36-hour forecasts. The shorter-range numerical forecasts of the track were very consistent with the longer-range forecasts and are considered to be quite good.

The numerical weather sea-level pressure forecasts, valid about the time of maximum storm surge, can be compared to the NMC pressure analysis in Figure 14. Here it is seen that the longer-range forecasts, such as the +30-hour forecast, did not have the storm intense enough. The shorter-range forecasts, such as the +6-hour forecast, look quite good, both for storm intensity and position.

Calculations of the storm surge based on sea-level pressure analyses and forecasts are shown in Figures 15 through 18. Storm surge calculations, based on sea-level pressure analyses of the NMC Northern Hemisphere surface charts, are shown in Figure 15. Here the observed storm surges, based on hourly values, are shown by the solid curves. Maximum values of observed surge are printed near the peak of each curve. Calculations of storm surge, based on pressure analyses, are shown by dots at 6-hour intervals. It is felt that these storm surge calculations agree fairly well with the observations. Figures 16 through 18 show, in the same manner, actual forecasts of surge based on the sea-level pressure forecasts. Figure 16 shows 6- and 12-hour forecasts of the surge. Two forecast intervals are combined on one chart so that there is a forecast value every 6 hours rather than every 12.

The actual forecasts of storm surge, of course, are not as accurate as the calculations based on the pressure analyses. The underforecasting of storm intensity of the numerical weather model in the longer-range forecasts was discussed earlier and is reflected in the longer-range forecasts of storm surge, as shown in Figure 18. The 6- and 12-hour surge forecasts were closer to the observed surge than the longer-range 30- and 36-hour forecasts. It is felt that the automated storm surge forecasts provided useful guidance material, especially on the timing of the surge.

CONCLUSION

The statistically derived extratropical storm surge forecast method uses the meteorological forecasts of the NMC as input to provide guidance material for Weather Service coastal forecast offices. The accuracy of the surge forecasts depends greatly upon the accuracy of the meteorological forecasts. Experience, so far, has shown the method to be useful and for that reason it is being expanded to include more locations.

ACKNOWLEDGMENTS

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Figure 1.-Damage at Virginia Beach, Va., caused by the Severe March 1962 storm.

Figure 2.-Boardwalk at Rehoboth Beach, Del., destroyed by the March 1962 storm.

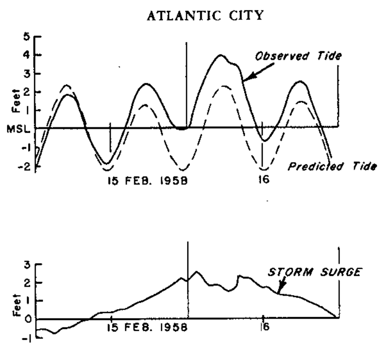


Figure 3.-Tide data showing the observed tide, predicted astronomical tide, and the storm surge.

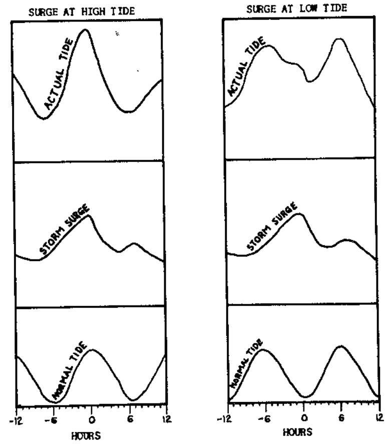


Figure 4.-The actual tide and its components.

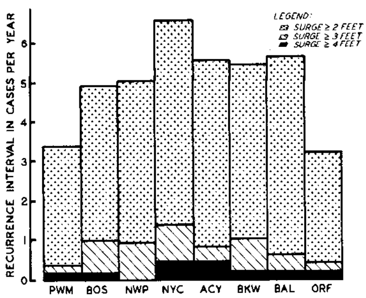


Figure 5.-Frequency of extratropical storm surges of 2, 3, and 4 ft or greater. Stations locations are shown in Figure 7.

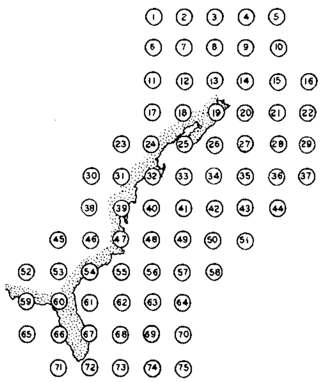


Figure 6.-Grid points where values of sea-level pressure were considered as predictors of storm surge.

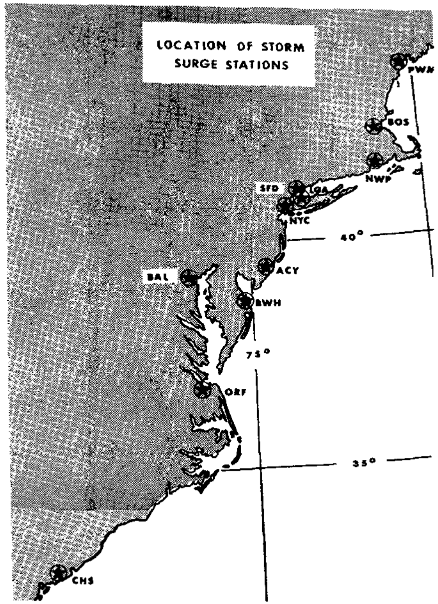
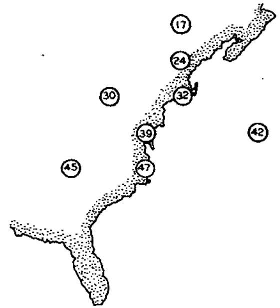


Figure 7.-The 11 forecast locations for which storm surge equations were derived.



$$SS(NYC)_t = A - B(47)_{t-6} + C(17)_{t-6} - D(42)_{t-6} - E(30)_{t-6} + F(24)_{t-6} - G(39)_{t-6} + H(32)_{t-6} + I(45)_t$$

Figure 8.-Storm surge forecast equation for New York. SS is storm surge, the number in parentheses of each term is the grid point for which sea-level pressure is used as a predictor, and the subscript on each term is the time lag of the predictor in hours.

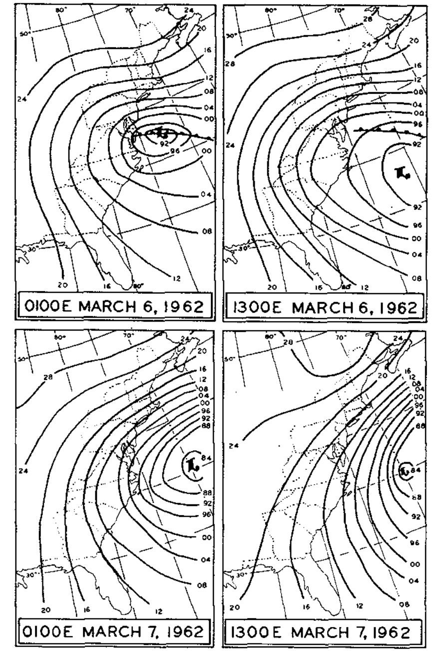


Figure 9.-Sea-level pressure charts for the coastal storm of March 1962.

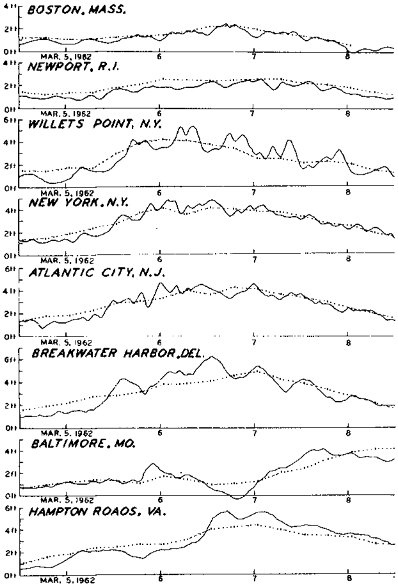


Figure 10.-Observed storm surge and calculated storm surge for seven locations during the March 1962 storm. Solid curves are observed storm surge. The dashed lines connect storm surge calculated at 6-hour intervals, based upon analyses of sea-level pressure.

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FZUS3 KWBC 070000
STORM SURGE FCST FEET INVALID FOR TROPICAL STORMS
       00Z  06Z  12Z  18Z  00Z  06Z  12Z  18Z  00Z
 PWM   0.6  0.4  0.6  0.5  0.8  1.1  1.5  1.9  1.7
 BOS   0.1  0.1  0.2  0.2  0.5  0.9  1.3  1.7  1.3
 NWP   0.7  0.6  0.6  0.5  0.9  1.4  1.7  1.6  1.1
 SFD   1.5  1.2  1.2  1.5  2.2  2.7  2.5  1.9  0.4
 LGA   0.2 -0.2  0.0 -0.2  0.4  0.8  1.1  0.3 -0.9
 NYC   0.3  0.3  0.4  0.5  1.0  1.4  1.5  0.6 -0.4
 ACY   0.1  0.1  0.1  0.2  0.7  1.0  0.8  0.5 -0.0
 BWH  -0.2 -0.3 -0.1 -0.2  0.4  0.6  0.5  0.1 -0.5
 BAL   0.5  0.2  0.5  0.9  0.8  1.4  1.4  0.2 -0.8
 ORF  -0.3 -0.3 -0.0 -0.1 -0.1 -0.4 -0.9 -0.5 -0.7
 CHS  -0.3 -0.6  0.0 -0.3 -0.5 -1.1 -0.7 -0.5 -0.3
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Figure 11.-Storm surge forecast teletype message. Forecast heights are in feet. Valid times are indicated above each column of heights. Forecast point locations are shown in Figure 7.

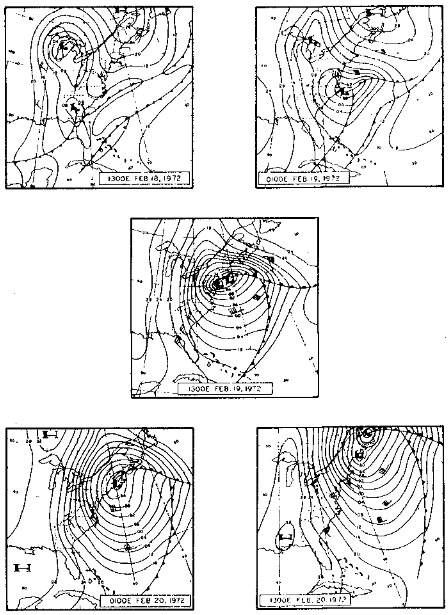

Figure 12.-Sea-level pressure analyses as shown on the Northern Hemisphere surface charts of the National Meteorological Center for Feb. 18-20, 1972.

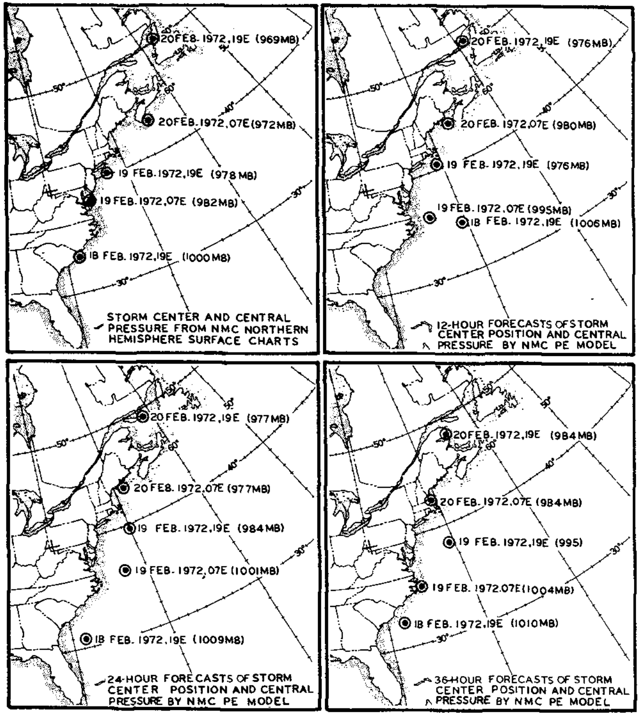

Figure 13.-Analyzed and forecast values of storm center position and central pressure. Data obtained from National Meteorological Center analyzed surface pressure charts and grid point values of sea-level pressure forecasts.

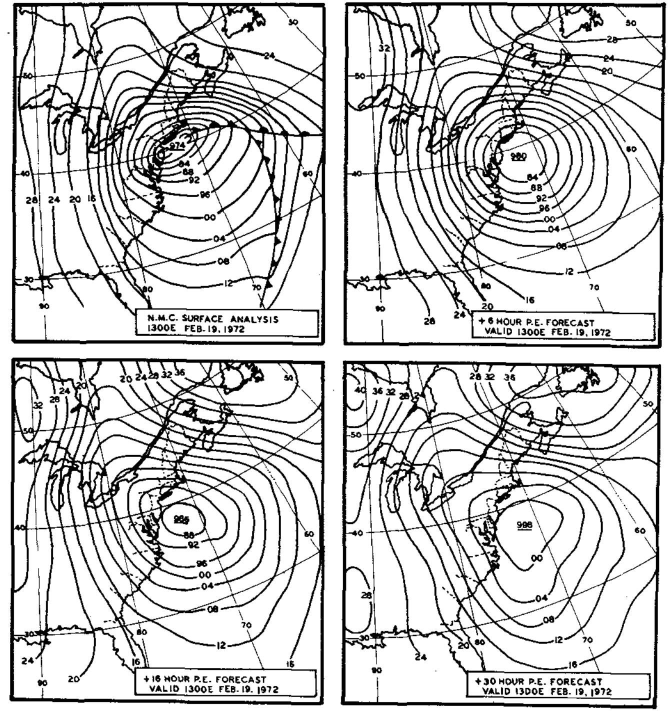

Figure 14.-Sea-level pressure analysis for 1300 EST on Feb. 19, 1972, and the 6-, 18-, and 30-hour forecasts by the numerical weather model of the National Meteorological Center.

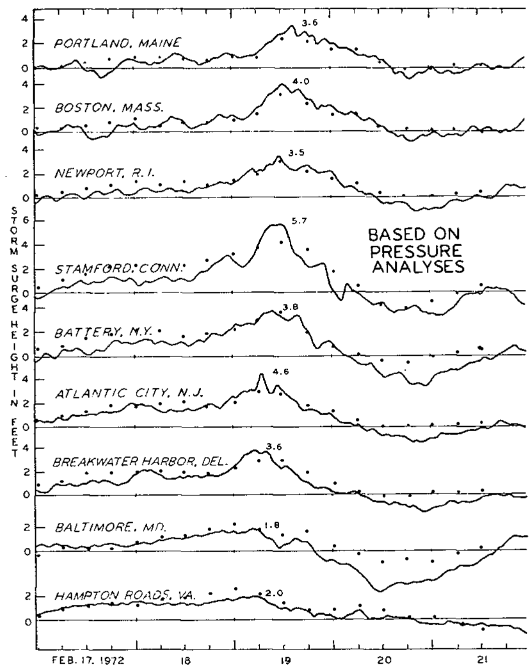

Figure 15.-Observed (solid curves) and calculated (dots) storm surges. Calculated values are based on sea-level pressure analyses. Maximum value (ft) of observed surge is placed near the peak of each curve and the date is placed at the 1200 EST position.

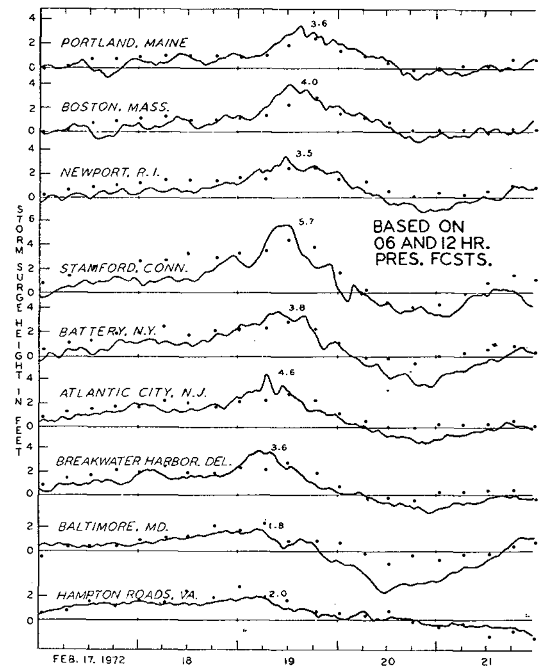

Figure 16.-Same as Figure 15 except dots indicate forecast storm surges. Forecast values are based on 6- and 12-hr sea-level pressure forecasts of the numerical weather model of the National Meteorological Center.

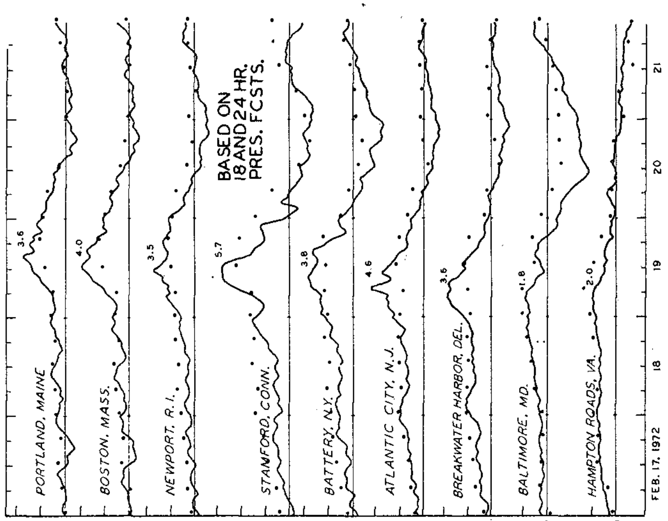

Figure 17.-Same as Figure 16 except forecast values are based on 18- and 24-hr sea-level pressure forecasts.

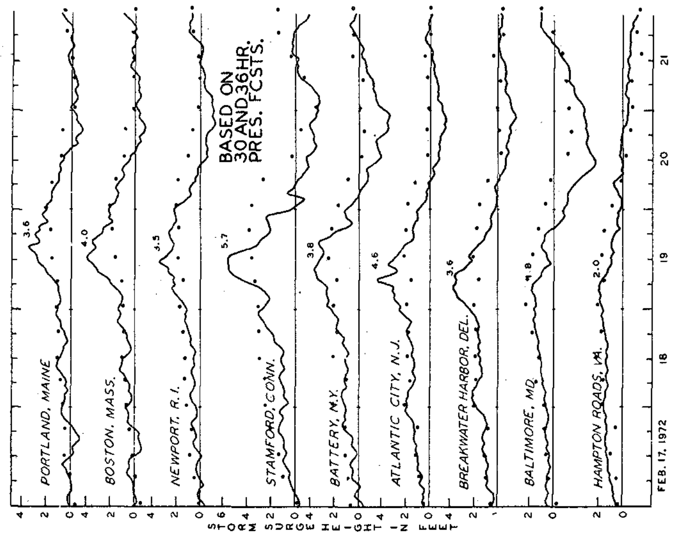

Figure 18.-Same as Figure 16 except forecast values are based on 30- and 36-hr sea-level pressure forecasts.