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A NEW EXTRATROPICAL STORM SURGE FORECAST EQUATION FOR CHARLESTON, SOUTH CAROLINA

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1. INTRODUCTION

The development of coastal communities and businesses along the east coast has increased the potential for serious damage resulting from extratropical storm surges. Storm surge (measured water level minus astronomical tide) is primarily caused by wind stress on the water surface. This surge, which is modified by the 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, coastal property may be seriously damaged.

2. BACKGROUND

At the request of the National Weather Service's Eastern Region, the Techniques Development Laboratory (TDL) developed automated extratropical storm surge forecast guidance for 12 tide gage locations along the U.S. east coast. Separate forecast equations were derived for each location with a multiple regression screening program. Forecasts of storm surge heights are made by interpolating sea-level pressure forecasts of the Limited-area Fine Mesh (LFM) model to Six-Layer Primitive Equation grid points. These interpolated values are the predictors in the storm surge forecast equations. Since September 1977, storm surge forecasts (National Weather Service, 1978) have been generated with sea-level pressure forecasts of the LFM-II model. Storm surge forecasts are made to 48 hours at 6-h intervals.

Verification of the automated surge forecasts by Richardson et al. (1979) showed that the surge forecasts for Charleston, S.C. were not as good as the surge forecasts at the other gage locations. They suggested that the poor Charleston forecasts may be due to an equation which was developed on too small a data sample. They also pointed out that the Charleston equation might be improved if it contained sea-level pressure with lag times as predictors.

With these suggestions as a guide, we have rederived the Charleston equation. This new equation, which was derived from a much larger development sample than the earlier one, contains sea-level pressures with lag times as predictors. This Office Note discusses this rederivation and presents an evaluation of the storm surge computations by this new equation.

3. REDERIVATION

As in the earlier derivation, the new Charleston equation was derived with a multiple regression screening program. The regression program is used to correlate measured surge heights (predictand) with observed predictors. This approach, where predictand data are correlated with observed predictors is called "perfect prog" in contrast to the MOS approach where predictand data are correlated with forecasts from a model.

A. Predictand

The predictand, storm surge height, is the meteorologically-generated water level fluctuation which does not include the astronomical tide height. Storm surge heights at 0000, 0600, 1200 and 1800 GMT were calculated by subtracting the astronomical tide heights from water level heights measured by the National Ocean Survey (NOS) tide gage at Charleston. The size of the development sample, 22 cases (288 measured storm surge heights) is more than double the size of the earlier development sample (nine cases, 105 pieces of data). All cases occurred during the 6-month period, November through April.

Storm surge cases varied in length from 1 to 7 days. During this period the magnitude of the peak surge (positive or negative) equaled or exceeded 1.5 ft. Surge cases were selected so that the peak surge was approximately in the middle of the surge case.

B. Predictors

We offered the regression screening program the following predictors:

1. analyzed sea-level pressure at 6-h intervals at National Meteorological Center (NMC) grid points,

2. astronomical tide heights,

3. air-sea temperature differences and ratios, and

4. first and second harmonics of the cosine of the day of the year.

Sea-level pressure at the 31 NMC grid points shown in Fig. 1 were offered as possible predictors of storm surge. This grid is a subset of the 75-point grid used in the derivation of storm surge equations for locations from Portland, Maine to Hampton Roads, Virginia (Pore et al., 1974). In addition to offering the sea-level pressure at the same time as the storm surge height, pressures were also offered at 6-h increments to 24 hours before the surge height. In the derivation of the earlier Charleston equation, the present operational equation, only the sea-level pressures valid at the time of the surge were offered as predictors. The first predictor selected for the new equation was the pressure with a 6-h lag at grid point 39. This predictor explained 53 percent of the variance of the surge height.

In an attempt to explain the relationship between the stage of the astronomical tide and storm surge, we offered the astronomical tide height as a predictor. However, this predictor had almost no correlation (0.01) with the surge height. For our development sample at Charleston, it appears that there is no relationship between the stage of the astronomical tide and the storm surge height. This may not be the case for extreme surge events at locations were the tide range is much greater than the tide range at Charleston.

We also offered stability predictors in the form of differences and ratios of the air and sea temperatures. The air temperature was the measured air temperature at the Charleston Forecast Office at 0000, 0600, 1200, and 1800 GMT. The water temperature was extracted from a curve which was drawn from averaged monthly bucket temperatures (National Ocean Survey, 1972) measured at the Charleston Customhouse Wharf. Averaged bucket temperatures are based on 30 years of data (1942 through 1971). Our stability predictors were not selected. Two major shortcomings in our air and sea temperature data may explain why the stability predictors were not selected. First, the air and sea temperatures were not measured at the same location. The Charleston Forecast Office is approximately 10 mi. northwest of the Customhouse Wharf. And second, there is a great deal of variability from year to year between the maximum and minimum bucket temperatures for a month. For example, during the fall, winter, and early spring months, the maximum and minimum temperatures during a month may differ by as much as 25° F. In future work, we recommend that measured daily water temperatures be used to derive stability predictors.

In a further attempt to explain the relationship between atmospheric stability and storm surge, we offered the regression screening program the cosine(2πDoy/365) and cosine(4πDoy/365), where Doy is the day of the year. Neither of these predictors were selected.

C. New Equation

As a first step in developing a new operational equation, four equations were derived. While each equation contained only sea-level pressures as predictors, the equations differed from each other in that the maximum time lag of the pressure was different in each equation. All four equations were used to specify surge heights for 11 independent cases. That is, surge heights were computed with analyzed pressures. The surge heights specified by the equation which contained sea-level pressures with 00- and 06-h lags as predictors verified best (highest correlation, lowest RMSE) on independent data. This equation which is referred to as the "new" Charleston equation is:

$$SS\ (CHS)_t = 69.6 + 0.0276\ P(39)_{t-6} - 0.0884\ P(60)_t - 0.0432\ P(58)_{t-6} + 0.0359\ P(39)_t, \tag{1}$$

where $SS\ (CHS)_t$ is the storm surge height in feet at Charleston at time t and P is sea-level pressure in millibars at the indicated grid point. The negative number of the pressure subscript is the time lag in hours.

4. EVALUATION

Only the storm surge heights specified by the new equation, and the earlier derived operational equaton were evaluated. The operational equation is:

$$SS\ (CHS)_t = 52.8 + 0.0065\ P(31)_t - 0.0346\ P(60)_t - 0.0711\ P(50)_t + 0.0907\ P(40)_t - 0.0431\ P(54)_t. \tag{2}$$

The predictand and predictors in the operational equation have the same definitions as the predictand and the predictors in the new equation. Note that the 00-h lag is the maximum lag time of the predictors in the operational equation. Also notice that the operational equation contains one more predictor than the new equation. In the derivation of each equation, screening for potential predictors was stopped when a predictor explained less than one percent of the variance of the surge height.

Table 1 shows the verification scores (correlation coefficient and RMSE) associated with the new equation (1), and the operational equation (2), for 11 independent surge cases. Verification scores were computed from specified surge heights which were inflated. These heights are inflated by multiplying the specified surge heights by the reciprocal of the correlation coefficient which was calculated with dependent data. We use this same inflation procedure to produce the operational forecast guidance for Charleston. The inflation factor for the operational and new equation is 1.14. Scores in the top part of the table 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 ft.) data. Peak surge heights represent approximately 8 percent of the independent data.

For all data, the correlation coefficient associated with the new equation is .11 larger than the correlation coefficient associated with the operational equation. The RMSE associated with the new equation is 0.1 ft. lower than the RMSE associated with the operational equation. While the difference between correlation coefficients for the peak data is not as impressive as for the all data sample, the RMSE associated with the new equation is almost 0.1 ft. lower than the RMSE associated with the operational equation.

In addition to the statistics shown in Table 1, we have also included a discussion of two independent storm surge events (November 24-26, 1950 and December 2-5, 1971). The meteorological setting (Figs. 2 and 3), measured winds at the Charleston Forecast Office, storm surge heights, and inflated specified heights (Fig. 4) are shown for each event. The inflated surge heights specified by the new equation and the operational equation are plotted with measured surge heights. Solid lines connect measured surge heights which are plotted every hour. Inflated surge heights specified by the operational equation are denoted by circles while inflated heights specified by the new equation are shown as squares. Dates are placed at 1200 EST. The measured winds at the Charleston Forecast Office are plotted above each surge event.

The November 1950 storm was considered by some to be the worst storm on record for the eastern United States (Bristor, 1951 and Smith, 1950). While this storm occurred near the time of spring tides and caused record breaking tides from Maryland to New York, it caused only low water levels at Charleston. Fig. 2 (sea-level pressure patterns from November 24-26, 1950) shows that the general wind flow along the South Carolina coast is offshore by 0130 EST November 25. Approximately 12 hours after this time, Charleston experienced about a 3 ft negative surge with winds from west to west-northwest at 20 kt (upper portion of Fig. 4). The surges specified by the operational and new equation are also negative. However, the surge specified by the new equation is in better agreement with the measure peak negative surge than the surge specified by the operational equation. The measured surge remained negative for about 2 days while specified surges returned to zero after 1 day.

In contrast to the November 1950 event, the December 1971 event was associated with a positive surge at Charleston. This event began as a low pressure system developed in the Gulf of Mexico on December 2, 1971 (Fig. 3). The system deepened and moved in a northeasterly direction until it was located off the South Carolina coast on the evening of December 3 . The peak surge which occurred during the evening of December 3 is specified to be positive by both equations (lower graphs of Fig. 4). Six hours before the peak surge the Charleston Forecast Office recorded 15 kt winds from the northeast. Again the peak surge height specified by the new equation is in better agreement with the measured surge than the peak height specified by the operational equation. Notice the peak surge is followed by secondary oscillations which occur at approximately 12-h intervals. The peaks of the oscillations occur about the same time as the astronomical low tide.

5. RECOMMENDATION

Based upon this evaluation, the Weather Service's Committee on Analysis and Forecast Technique Implementation recommended that the operational equation be replaced by the new equation. This replacement was made on September 10, 1980.

6. FUTURE PLANS

We have derived a storm surge equation which uses the observed storm surge heights with lag times in addition to sea-level pressures as predictors. This equation will allow forecasters to update the automated storm surge forecasts by considering the latest storm surge observations. Preliminary tests with this updatable equation have shown that short range forecasts (12 hours or less) can be improved by offering recent storm surge observations as predictors. This update method, which is being tested at Charleston, South Carolina, Hampton Roads, Virginia, and Boston, Massachusetts, will be presented and discussed in a forthcoming Office Note.

7. ACKNOWLEDGMENTS

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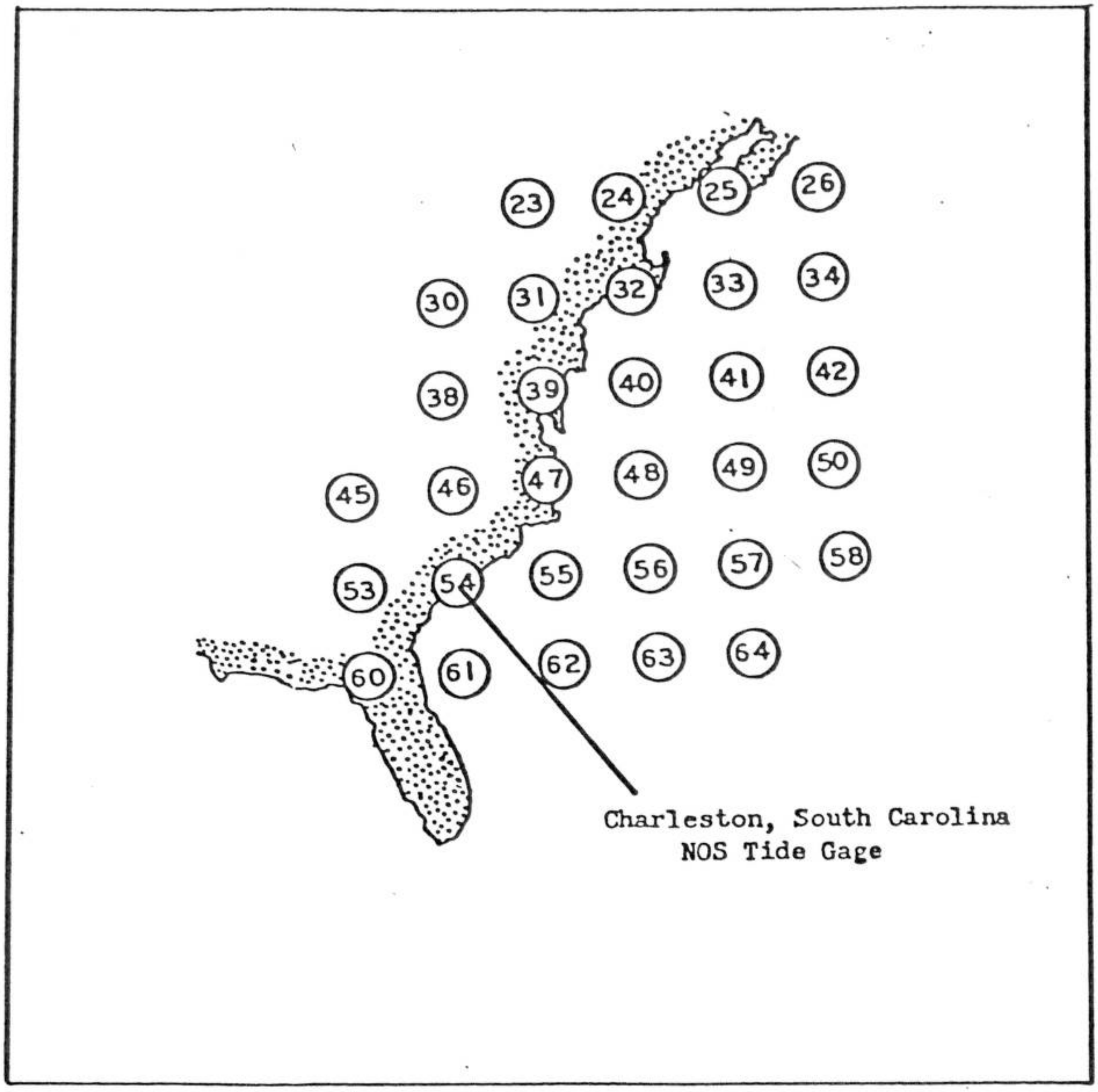

Figure 1. The locations of 31 NMC grid points where analyzed sea-level pressures were tabulated. Also shown is the approximate location of the Charleston NOS tide gage.

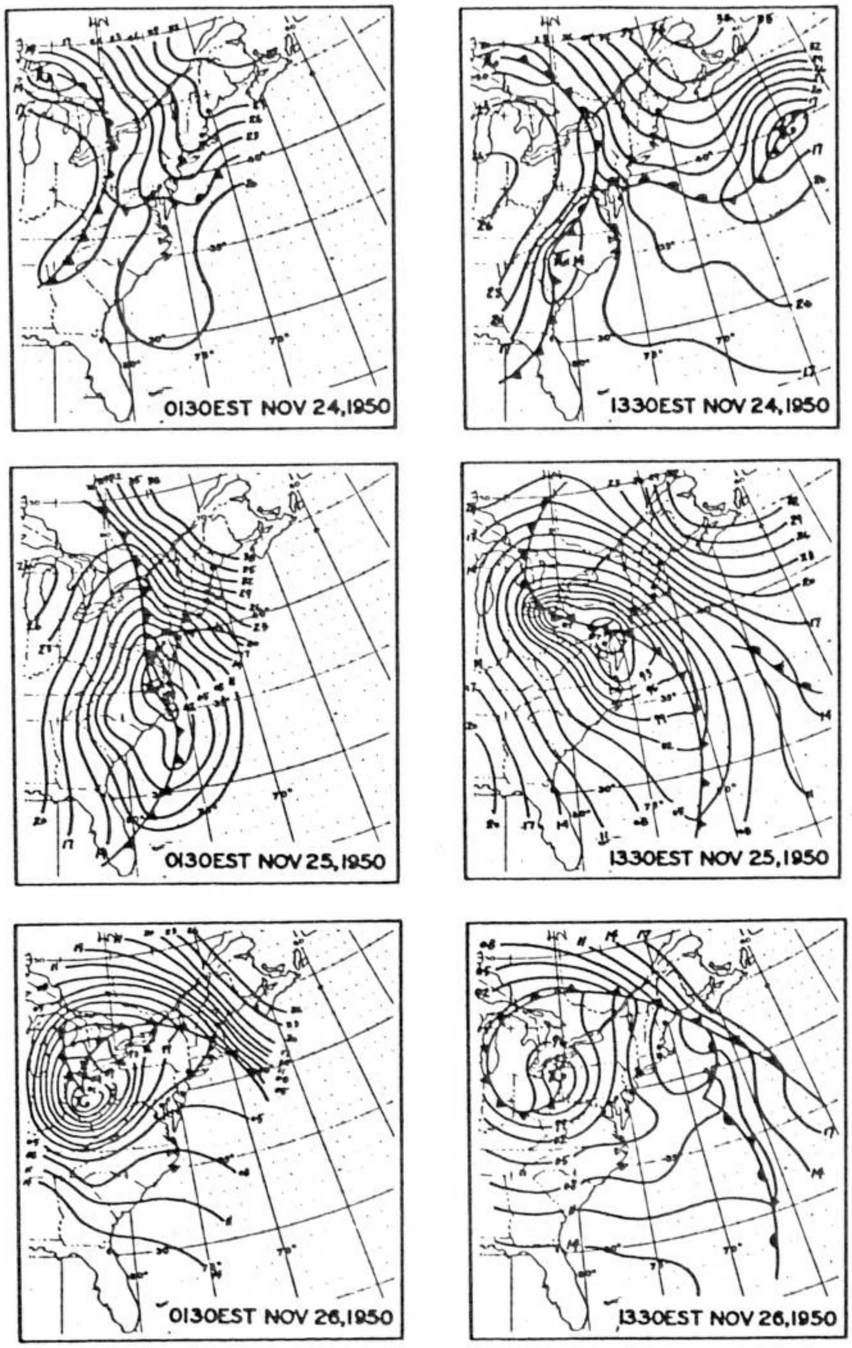

Figure 2. Sea-level pressure charts from 0130 EST November 24, 1950 to 1330 EST November 26, 1950 (Pore et al., 1974).

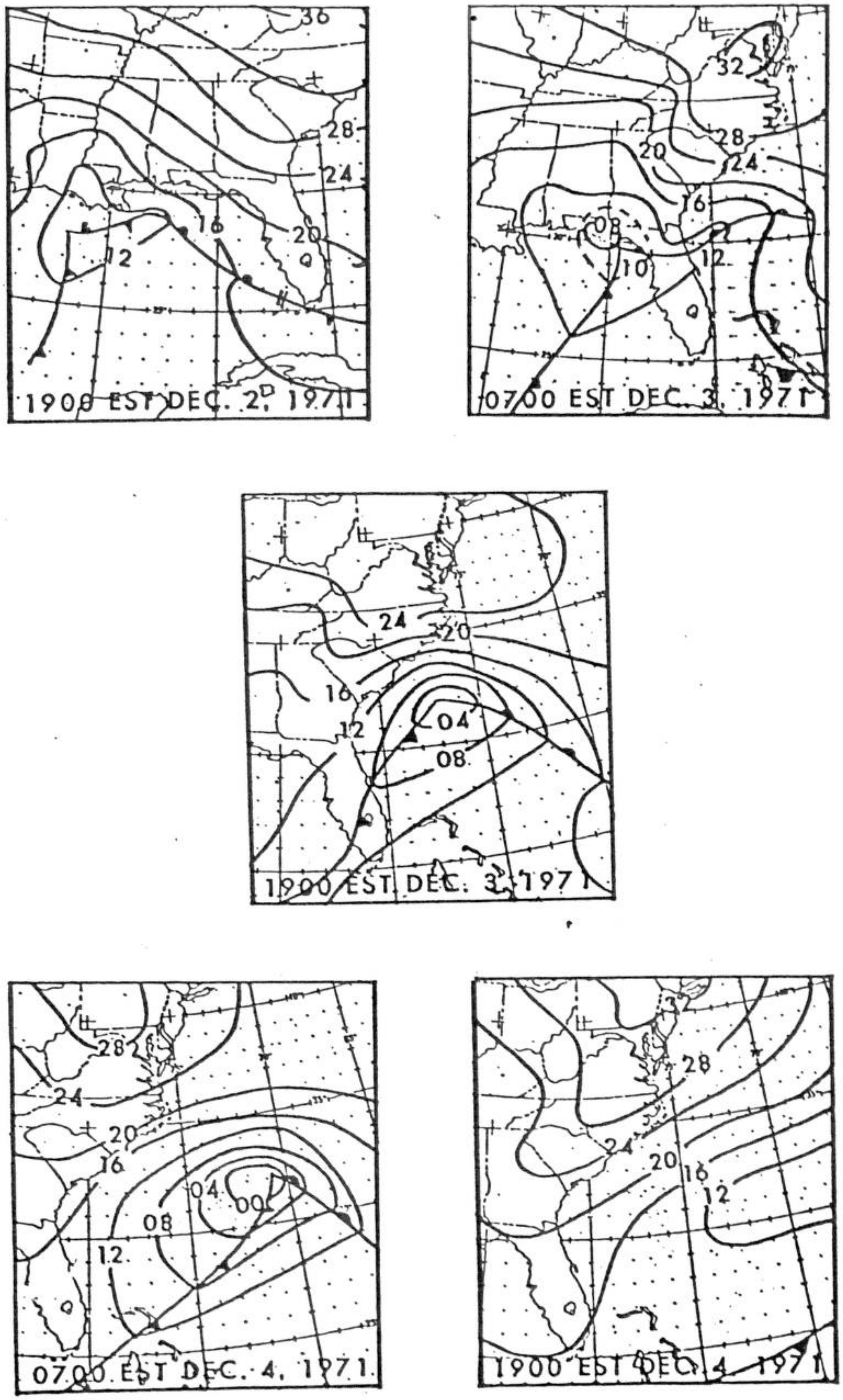

Figure 3. Sea-level pressure charts from 1900 EST December 2, 1971 to 1900 EST December 4, 1971.

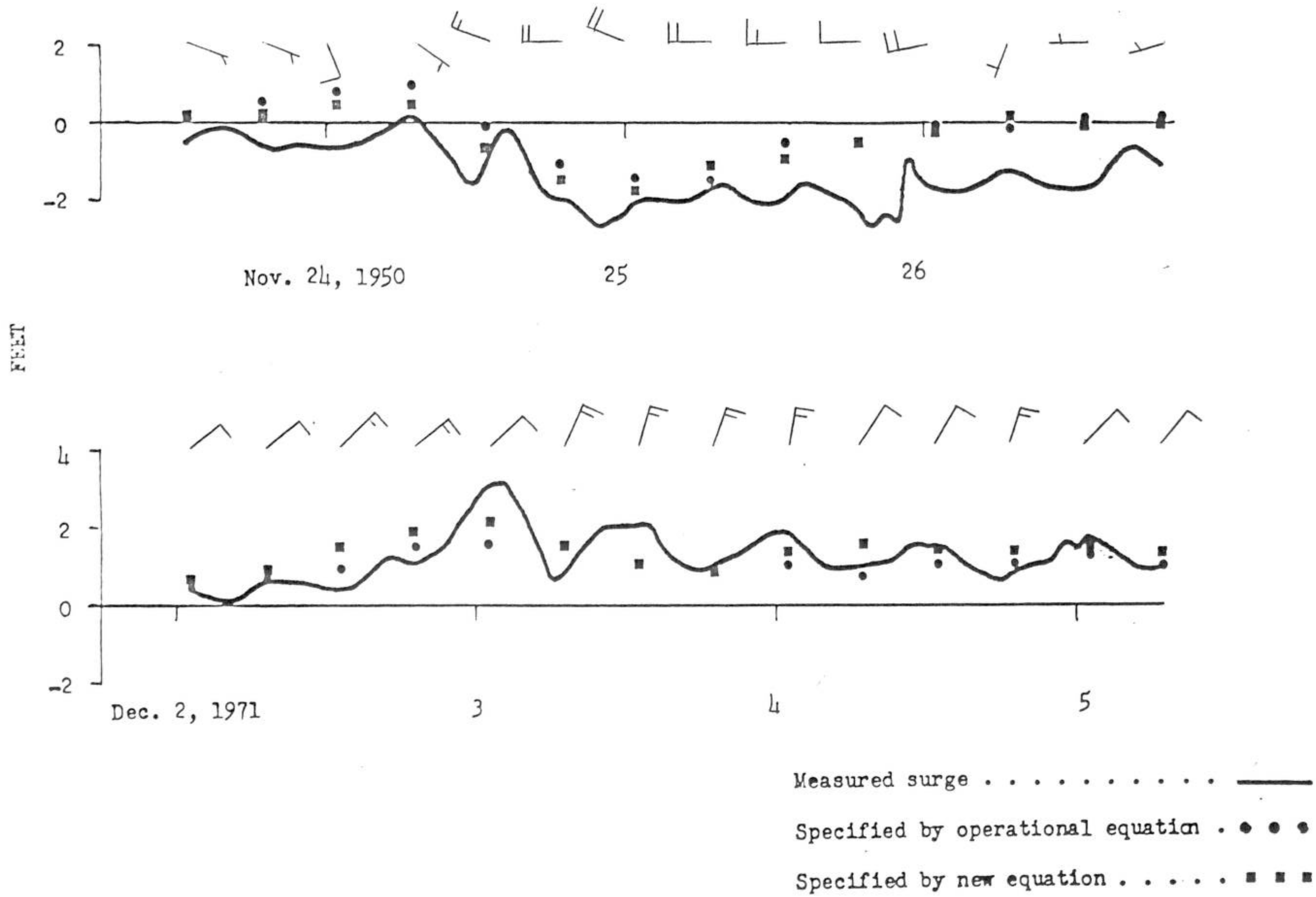

Figure 4. Two independent storm surge events which occurred on November 24-26, 1950 (top graphs) and December 2-5, 1971 (lower graphs). Measured surges are shown as solid lines, while surges specified by the operational equation and the new equation are denoted by circles and squares respectively. Coincident specifications are depicted by squares. Dates are placed at 1200 EST. Measured winds at the Charleston Forecast Office are plotted above each surge event.

Table 1. Verification scores associated with the new equation (1), and the operational equation (2), for 11 independent surge cases. Scores tabulated in the top part of the table are based on all independent data. The scores shown in the lower part of the table were computed from peak data.

ALL DATA

	New Equation (Equation 1)	Operational Equation (Equation 2)
Number of cases	11	11
Number of sets of data	203	203
Correlation coefficient	0.66	0.55
RMSE (ft)	0.63	0.73

PEAK DATA

	New Equation (Equation 1)	Operational Equation (Equation 2)
Number of sets of data	17	17
Correlation coefficient	0.92	0.89
RMSE (ft)	1.00	1.08