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The Relation of Wind and Pressure to Extratropical Storm Surges at Atlantic City

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ABSTRACT

The relationship of certain meteorological parameters to the extratropical storm surge is investigated empirically. Multiple regression equations are determined which relate the onshore wind components, alongshore wind components, and atmospheric pressure distribution with various time lags to the storm surge. The alongshore component of wind is found to be more important than the onshore component in the generation of extratropical storm surges. Calculations using as predictors the components of both wind speed and wind speed squared show both systems to be about equally satisfactory for practical predictions. Comparison is made between a one-station model which uses weather parameters at Atlantic City, and a three-station model which includes information from Nantucket and Norfolk as well as Atlantic City. A practical forecast equation which contains five predictors is presented for possible operational use.

1. Introduction

The high tides and wave action of the infamous storm of March 1962 brought tremendous destruction to coastal areas along much of the United States East Coast. Preliminary damage reports were in excess of $200 million. The destructive action at Atlantic City was evident by the bisection of the Steel Pier accompanying the loss of a large portion. This storm was of the same general type as the more common, less damaging, winter extratropical coastal storms. Even though storms with the damage potential of the March 1962 storm occur infrequently, the damage and flooding caused by the more common storms makes the pursuit of extratropical storm surge forecasting methods worthwhile.

The principal factors involved in the generation and modification of storm surges are:

1) The rise of water caused by the action of wind stresses on the water surface;
2) The reduction of atmospheric pressure, generally called the inverted barometer effect, which causes an increase in sea level in areas of low pressure;
3) The transport of water by waves and swells in the shallow water area near the shore;
4) The modifying effects of coastline configuration and bathymetry.

This study was designed to develop empirical prediction models by determining the relationship of the wind and pressure fields to the extratropical storm surge. Such effects as 3 and 4 are kept reasonably systematic with respect to the wind field by considering the tide data at only one station.

Some definitions are desirable at this point and will be made with reference to Fig. 1. The predicted tide is the normal astronomical tide caused by the gravitational attraction of the moon and sun and climatological factors. The storm surge is the algebraic difference between the observed and predicted tides and is considered to be the meteorological effect on sea level.

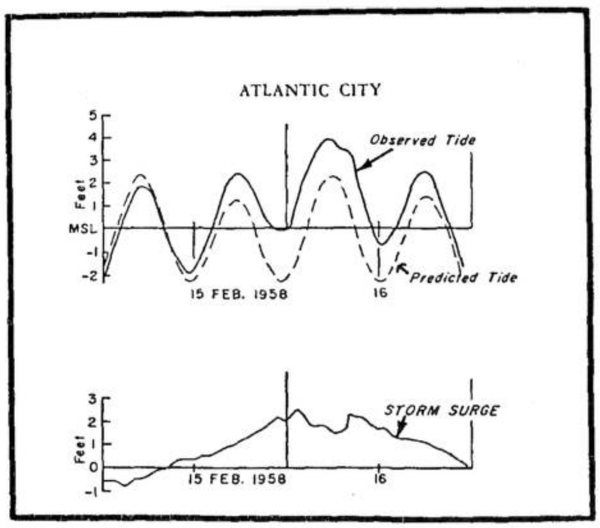

FIG. 1. Example of Atlantic City tide data showing the observed tide, the predicted astronomical tide and the storm surge.

2. Related studies

Hustead[1] related the 2-hr northeast wind movement at Norfolk to the storm surge and obtained a parabolic

[1] Hustead, A. D., 1955: An empirical method of forecasting meteorologically produced tidal departures from the normal astronomical tide in the Norfolk, Va., tidal basin for a specific wind direction. Manuscript of the U. S. Weather Bureau, 5 pp.

prediction curve. Extratropical storms and hurricanes which were offshore and moving northward were included in this study.

Miller (1957) studied the effect of geostrophic wind over an offshore circular area 300 miles in diameter on the Atlantic City storm surge during a six-month period. He concluded that the surge is nearly proportional to the wind speed, that in general there is a time lag of about twelve hours between the wind and the surge, and that maximum setup occurs with east-northeast winds.

The effect of extratropical storms on the tide at several Atlantic Coast stations was studied by Donn (1958), who generally agreed with Miller that the relationship between wind speed and surge seems to be linear, that there is a time lag between the wind and the storm surge, and that winds from the northeast quadrant are favorable for generating storm surges at Atlantic City.

Tancreto (1958) related the computed significant wave height determined by the Sverdrup-Munk-Bretschneider method to the maximum storm surge at Boston. The significant wave height is a measure of the storm size, intensity and duration, and therefore, is related to the storm surge. The barometric effect was estimated, but within the range of the Boston data its contribution could not be detected.

The principal differences and similarities between the dynamic and statistical numerical methods of storm surge computations have been discussed by Harris (1962). In the dynamic method the numerical integration of the hydrodynamic equations is carried out to reveal information about the physical processes involved even though a practical prediction scheme may not be determined. The statistical approach, although not designed to disclose the physical processes to the extent of the dynamic method, is likely to make more efficient use of the available observational data and lead to relatively simple, easy to use prediction schemes such as a set of regression equations. It was shown that a solution for the linearized hydrodynamic equations for storm surges can be obtained as an integral of the product of the atmospheric forcing function and an influence function which approaches zero with increasing time lags. This solution can be approximated for a given time as the weighted sum of the atmospheric forces during a recent time period. The weighting factors can then be determined as regression coefficients in a multiple correlation problem.

Most of the research on wind stress has led to the conclusion that stress is proportional to the square of the wind speed. Defant (1961) has summarized the views of many writers, some of whom have preferred other exponents of the wind to represent stress. In this study two approximations for wind stress as a function of wind speed are investigated; namely, that stress is a linear function and that stress is a quadratic function of wind speed.

3. The data and predictors

Tide and weather data for the years 1956–1961 made up most of the data collection of this study. The storm surge was determined by subtracting the hourly astronomical tide from the hourly observed tide as recorded by the Coast and Geodetic Survey tide gage at Atlantic City. The meteorological data were extracted from hourly observations taken at the National Aviation Facilities Experimental Center at Atlantic City, and Weather Bureau Airport Stations at Norfolk, Va., and Nantucket, Mass.

Storm surge values of two feet or more were searched for to determine typical extratropical storm conditions. The dates of these storms were first approximated by examining the daily totals of hourly tide observations as tabulated by the Coast and Geodetic Survey. Daily weather maps were then examined to determine specific time periods of the storms. The resulting set of dependent data consisted of data from 18 storms with a total of 1910 hourly observations. Thirteen storms made up the independent data with a total of 1752 hourly observations. Fig. 2 shows surface weather charts for four of the storms. All of the dependent storms were typical extratropical storms, most of which passed through the southeastern part of the country and then moved offshore. A few approached from the ocean off the southeast coast. Maximum wind speeds in these storms as indicated by the hourly observations ranged from 22 to 50 knots. The properties of the dependent storms were such that the derived prediction equations are applicable to the winter extratropical storms which move through the southeast United States or approach the Middle Atlantic coastal area from offshore of our southeast coast.

Post storm surveys as compiled by Harris[2] indicate that tides are generally higher at nearby beach locations than at tide gage sites. These variations place a limit on the precision with which a tide gage can represent the tide conditions of a coastal area.

The extratropical storm surge at Atlantic City has a general pattern; however, it does vary for individual storms. Usually the surge begins to rise as the storm approaches and the wind offshore comes from the east quadrant. The peak surge occurs when the storm is in the latitudes of the northern Chesapeake Bay and then falls as the storm moves off to the northeast or north. Two distinct patterns occur after the peak: one is a gradual fall; the other is a rapid drop in the storm surge after the peak followed by a secondary surge peak several hours later. Several possible causes of this rapid drop and secondary peak have been investigated. None of them explain all cases. The secondary peak, although lower than the main peak, can result in higher actual

[2] Harris, D. L., 1963: Characteristics of the hurricane storm surge. U. S. Weather Bureau, Technical Paper No. 48, Washington, 139 pp.

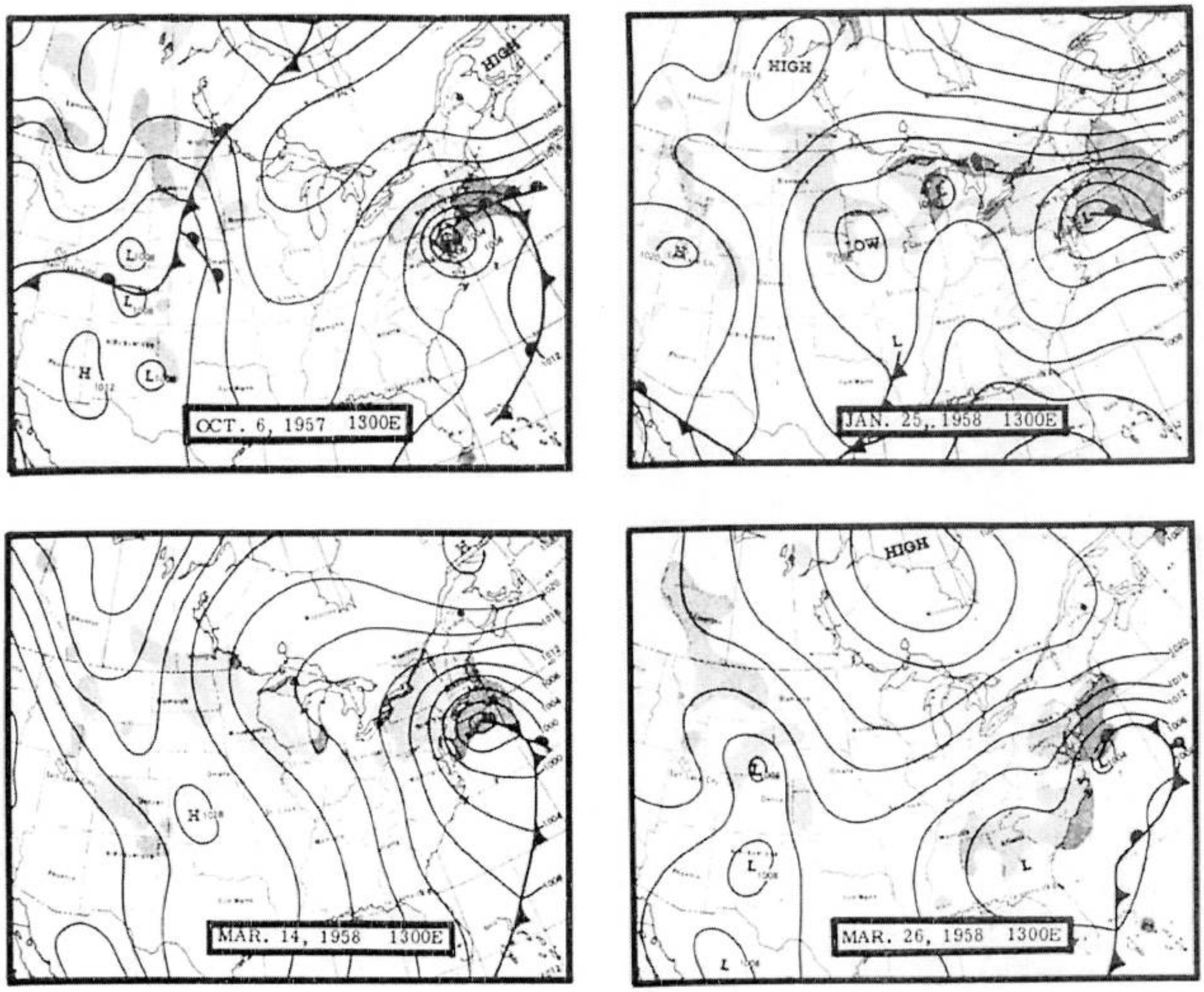

FIG. 2. Surface weather charts showing four typical East Coast storms included in this study.

tides than the main peak. This condition depends upon the phase of the astronomical tide.

The atmospheric forces include the onshore component of the wind stress which produces set-up and the alongshore component of the wind stress which generates alongshore currents which are in turn deflected to the right by the Coriolis force and cause a slope of the water surface upward toward the right. These two parameters represent the wind field near the shore. The third parameter is the atmospheric pressure and is a measure of the inverted barometer effect.

The geographic locations of the three stations and the resolution of the wind components are shown in Fig. 3. The coastline at Atlantic City is oriented roughly northeast-southwest. The onshore wind component (u) was defined to be positive from the southeast and the alongshore component (v) to be positive from the northeast. For the sake of consistency these definitions of onshore and alongshore components were also used for the Nantucket and Norfolk wind observations. Components of the wind speed squared, labeled u' and v' were also determined. These parameters are defined by the following expressions:

$$u = W \sin(\theta - 45°) \tag{1}$$

$$v = W \cos(\theta - 45°) \tag{2}$$

$$u' = W^2 \sin(\theta - 45°) \tag{3}$$

$$v' = W^2 \cos(\theta - 45°), \tag{4}$$

where W is the wind speed, and θ is the direction from which the wind blows.

These parameters, u, v, u', v', and the station pressure p, with various time lags constitute the predictors which were correlated to the Atlantic City storm surge.

4. Procedure

The empirical method derived in this study is actually an interpolation scheme in which the wind and pressure distribution over an oceanic area is evaluated over a time period prior to the storm surge observation. To determine practical prediction equations with small

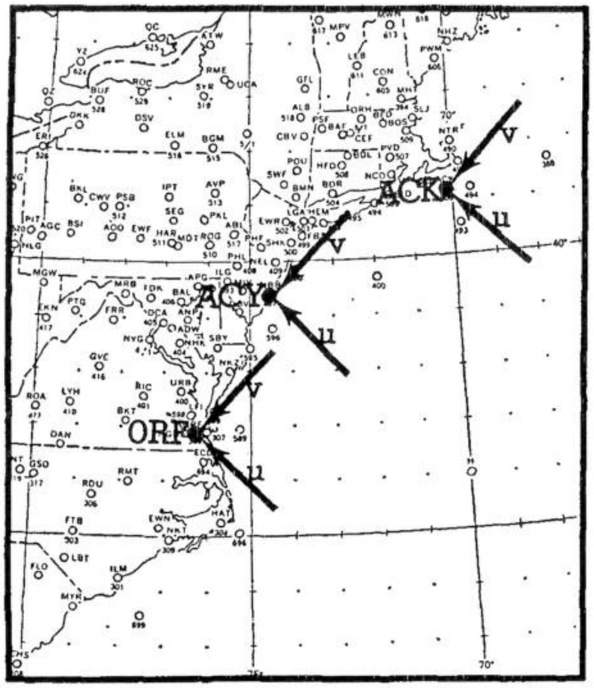

FIG. 3. Station locations and definitions of the onshore (u) and the alongshore (v) wind components. Station abbreviations are ACK for Nantucket, Mass.; ACY for Atlantic City, N. J.; and ORF for Norfolk, Va.

numbers of predictors the screening process was used. A detailed description of the selection of predictors by screening is given by Miller.[3] The screening procedure used to process a large number of predictors for a large number of observations requires the use of a high speed, large memory computer. The IBM 7090 and the IBM 7030 were used. The manner in which the predictors were screened is shown below:

1) $SS=A_1+B_1X_1$

2) $SS=A_2+B_2X_1+C_1X_2$

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

$\vdots$

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

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 first select the best single predictor (X_1) for regression equation 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 was carried out until all predictors were included.

[3] Miller, R. G., 1958: The screening procedure. Studies in Statistical Weather Prediction, Final Report, Contract No. AF19(604)–1590, Hartford, Conn., Travelers Weather Research Center, 86–95.

The screening process was not used in the usual manner in this study. Usually the significance of the improvement attained at each step of the screening is tested and the screening discontinued when the amount of improvement is found not to be significant. Near that point the addition of many more predictors usually lowers the predictive ability of the system on independent data. In an interpolation scheme the inclusion of more of the available data which helps to define the field in question should lead to a better result. This is borne out in this study by the comparison of predictions made on independent data by a short practical prediction equation which contains only a few predictors and the regression equation containing all of the predictors. This will be discussed in a later section. The selection of the practical prediction equations to be considered for operational use was made by subjective comparison of the prediction ability of the regression equations on the dependent data at several levels in the screening process.

Another reason the objective standard significance tests were not used is, as pointed out by Panofsky and Brier (1958), that they may be misleading on application to meteorological data as the underlying assumptions may be violated. The predictors used here are certainly interdependent in time and space. Often the most practical and convincing test of significance can be an application of the statistical result to an independent set of data. The emphasis is placed in this study on this type of significance test.

Two types of multiple regression screening analyses were made on the Atlantic City storm surge data. The first considered only predictors at Atlantic City, whereas the second considered predictors at all three stations, Atlantic City, Nantucket, and Norfolk.

5. One-station model

Several multiple correlation-screening runs were made using the Atlantic City weather parameters as predictors. These are summarized in Table 1 where the order of selection of the first few predictors is shown along with the correlation coefficients. Also the correlation attained by using all of the predictors that were considered is shown in the row labeled, "Final Eq." The correlation attained by using only a few predictors is nearly as great as that by using the final regression equation.

The first run considered the following 70 predictors:

Pressure (p) with time lags of 0, 1, 2, 3, 6, 12, 18, and 24 hours,

Onshore wind component (u) with time lags of 0 to 30 hours at 1-hour intervals,

Alongshore wind component (v) with time lags of 0 to 30 hours at 1-hour intervals.

Run 2 considered predictors with the same time lags but used components of wind speed squared (u' and v')

TABLE 1. Selection of predictors by screening process for the one-station model. Lag is expressed in hours. Components of wind speed are u and v. Components of wind speed squared are u' and v'.

Predictors	Run 1 p, u, v (minimum lag: 0 hr)			Run 2 p, u', v' (minimum lag: 0 hr)			Run 3 p, u, v (minimum lag: 6 hr)			Run 4 p, u', v' (minimum lag: 6 hr)		
	Var.	Lag	r	Var.	Lag	r	Var.	Lag	r	Var.	Lag	r
Eq 1	p	0	0.57	p	0	0.57	v	7	0.54	v'	6	0.54
Eq 2	v	5	0.71	v'	2	0.71	p	6	0.67	p	6	0.64
Eq 3	v	30	0.75	v'	10	0.74	v	6	0.68	v'	14	0.65
Eq 4	v	1	0.77	v'	30	0.75	v	30	0.70	u'	6	0.66
Final Eq	70 terms $r=0.80$			70 terms $r=0.79$			54 terms $r=0.73$			54 terms $r=0.68$		

TABLE 2. Selection of predictors by screening process for the three-station model. Lag is expressed in hours. Components of wind speed are u and v. Components of wind speed squared are u' and v'.

Predictors	Run 5 p, u, v (minimum lag: 0 hr)				Run 6 p, u', v' (minimum lag: 0 hr)				Run 7 p, u, v (minimum lag: 6 hr)				Run 8 p, u', v' (minimum lag: 6 hr)			
	Var.	Lag	Stat.	r	Var.	Lag	Stat.	r	Var.	Lag	Stat.	r	Var.	Lag	Stat.	r
Eq 1	p	3	ORF	0.71	p	3	ORF	0.71	p	6	ORF	0.70	p	6	ORF	0.70
Eq 2	v	6	ACK	0.85	v'	4	ACK	0.81	v	6	ACK	0.83	v'	6	ACK	0.78
Eq 3	v	20	ACK	0.87	v'	20	ACK	0.83	p	6	ACK	0.85	p	6	ACK	0.83
Eq 4	p	6	ACK	0.89	p	6	ACK	0.88	v	18	ACK	0.89	v'	20	ACK	0.87
Final Eq	90 terms $r=0.93$				90 terms $r=0.93$				66 terms $r=0.91$				66 terms $r=0.91$			

instead of components of wind speed. There is practically no difference in the correlation coefficients of Run 1 and Run 2 which indicates there is little difference in the results obtained by using the linear and quadratic stress laws.

It seems desirable to have a regression scheme which is dependent on weather conditions which have occurred several hours earlier. For that reason, two runs, 3 and 4, were made in which the predictors had minimum lags of 6 hours. The predictors of Runs 1 and 2 with lags of six hours or more were used as predictors in Runs 3 and 4. There were 54 predictors for each of these runs. Only slight reductions occurred in the correlations by changing the minimum lag from 0 to 6 hours. This type of regression equation gives a prediction for 6 hours if current observations are used as predictors and for more than 6 hours if wind and pressure forecasts are used as predictors.

Subjective comparison of the predictions made by the equations of the two runs using minimum lags of 6 hours suggests the following regression equation from Run 3 as a practical prediction equation:

$$SS=13.66+0.10v_{-7}-0.26(p_{-6}-1000)+0.30v_{-6}+0.13v_{-30}, \quad (5)$$

where SS is storm surge in tenths of feet, v is the alongshore component of wind in knots, p is the station pressure in millibars, and the time lag in hours is represented by the subscripts of the variables.

Here the terms of v_{-6} and v_{-7} show the importance o the alongshore currents generated by the alongshore wind components in the recent past. The v_{-30} term indicates that a long duration of alongshore winds is favorable to storm surge generation. The predominance of the v-terms and the lack of u-terms is indicative of the importance of the alongshore components as compared to the onshore components.

Two additional runs were made to determine the relationship of the v-components to the storm surge as compared to the u-components without the interdependence between the pressure and the u- and v-components masking these relationships. The first related storm surge to the u-component with lags of 0 to 30 hours at 1-hr intervals and the second related the v-component with the same time lags to the surge. The maximum correlation of the v-components to the storm surge is 0.74, whereas the maximum correlation of the u-components to the surge is only 0.36. These runs do not imply that onshore winds, if they occur, cannot produce significant storm surges, but rather that the surges of the extratropical coastal storms are dependent mainly on the alongshore wind components.

This method is an interpolation procedure in which the continuous weather conditions of a storm surge-generating area are represented by hourly observations at one point in space. This supports the preference of using the linear wind stress law instead of the quadratic law because if the observation is not wholly representa-

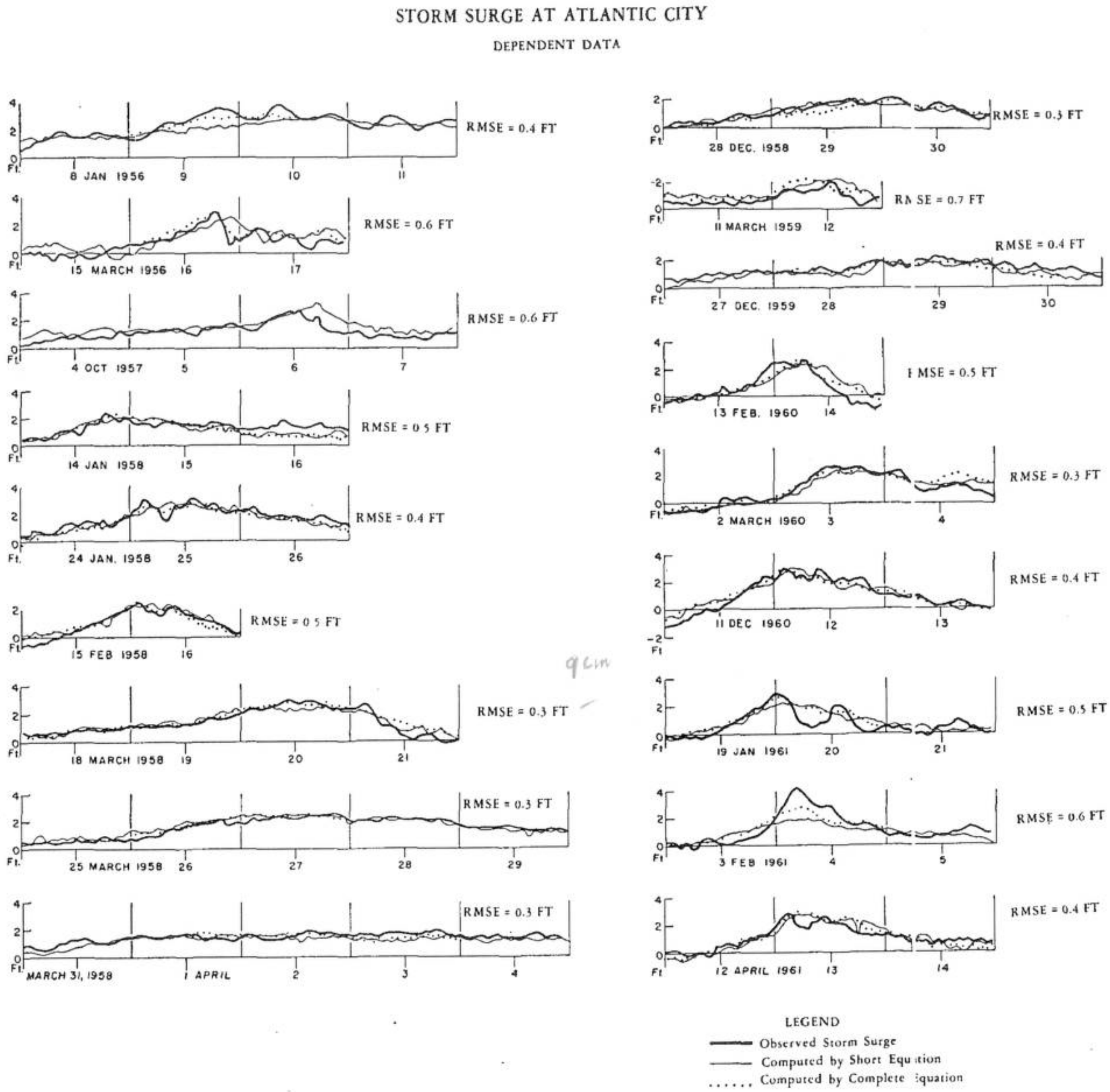

FIG. 4. Storm surges and calculations of the dependent cases. The date for each day is placed at the noon position. The light solid lines show the calculations by Eq 6, the five predictor equation from the three-station model. The dotted lines show the calculations by the 90 term prediction equation. The root mean square error shown for each storm is for the five predictor equation. The over-all rms error of the dependent cases is 0.5 ft.

tive of the surge-generating area, the error will be less amplified in the components of wind speed than in the components of wind speed squared.

Calculations by Eq (5) for the independent storms in the period 1956–1961 are fairly good and have approximately the same degree of accuracy as those for the dependent storms. None of the calculations for either the dependent or independent storms by the one-station model are shown in this paper. Three other independent storms, November 1950, November 1953, and March 1962, were used to test the method on record-breaking storms, although storms of such intensity were not included in the derivation of the prediction equation. The surge computations were less satisfactory for these storms because the size and intensity which determine the fetch length and duration time cannot be represented by observations at one station.

The system was then expanded to include predictors from three stations in an effort to improve the accuracy of the predictions for both the typical storms and the record-breaking storms.

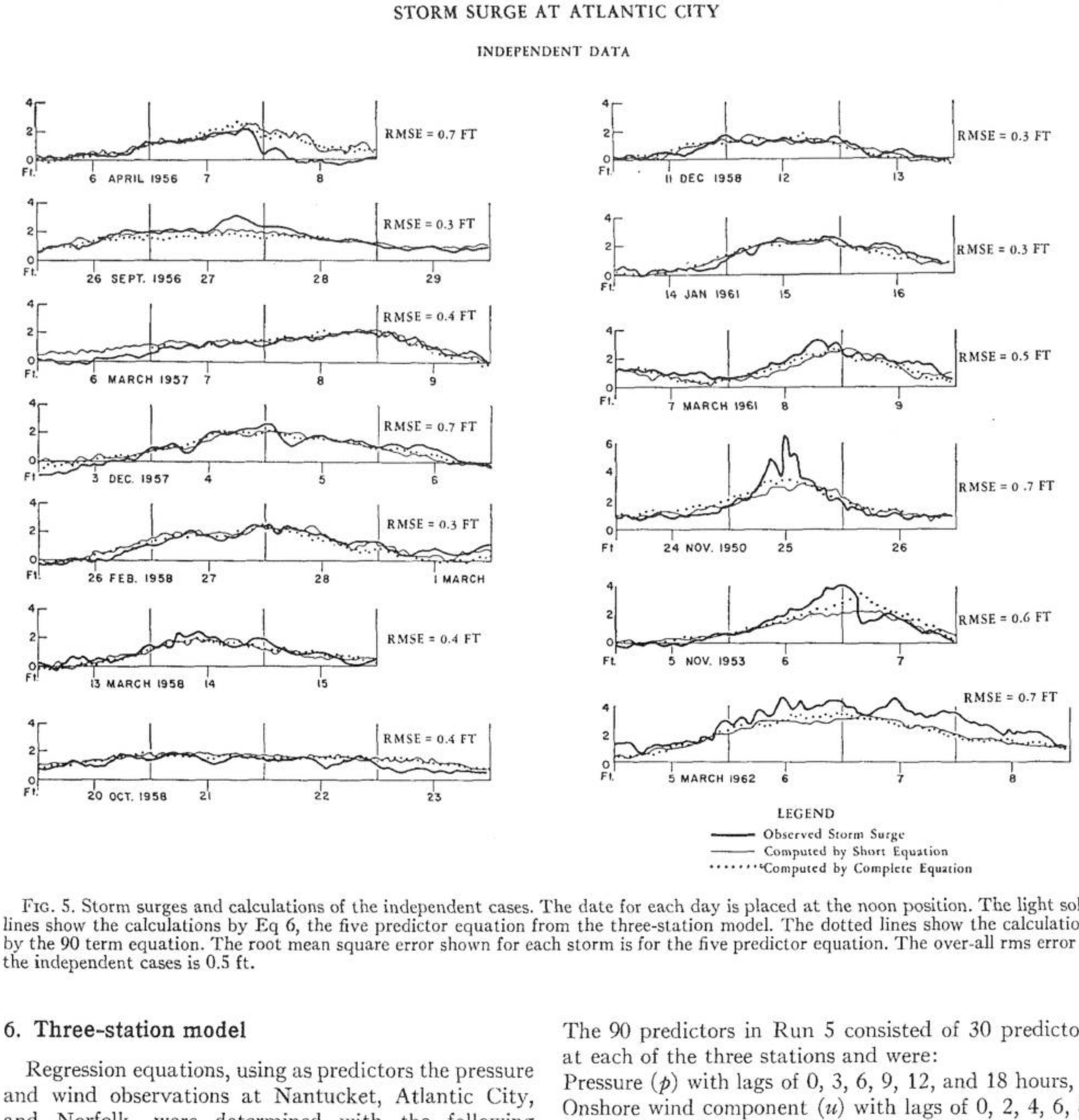

FIG. 5. Storm surges and calculations of the independent cases. The date for each day is placed at the noon position. The light solid lines show the calculations by Eq 6, the five predictor equation from the three-station model. The dotted lines show the calculations by the 90 term equation. The root mean square error shown for each storm is for the five predictor equation. The over-all rms error of the independent cases is 0.5 ft.

6. Three-station model

Regression equations, using as predictors the pressure and wind observations at Nantucket, Atlantic City, and Norfolk, were determined with the following expectations:

1) The Norfolk pressure and wind observations should serve as an early warning system for the surges at Atlantic City for storms approaching from the southeastern part of the country or off the Carolina coasts;

2) The combination of observations from these three stations should give an indication of fetch length and duration time of the wind over the important surge-generating area of the continental shelf.

The runs are summarized in Table 2 in the same manner as were the runs of the one-station model except that here the station is also indicated for each predictor. The 90 predictors in Run 5 consisted of 30 predictors at each of the three stations and were:

Pressure (p) with lags of 0, 3, 6, 9, 12, and 18 hours,

Onshore wind component (u) with lags of 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20 and 22 hours,

Alongshore wind component (v) with lags of 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20 and 22 hours.

Run 6 was similar to Run 5 except that the onshore and alongshore wind components were those of wind speed squared. As with the one-station model, there is little difference between the results obtained with the linear and quadratic wind stress laws.

Runs 7 and 8 considered the 22 predictors at each station with lags of 6 hours or more for a total of 66 predictors and supported the conclusion from the one-station model that little accuracy was lost by using a minimum lag of 6 hours.

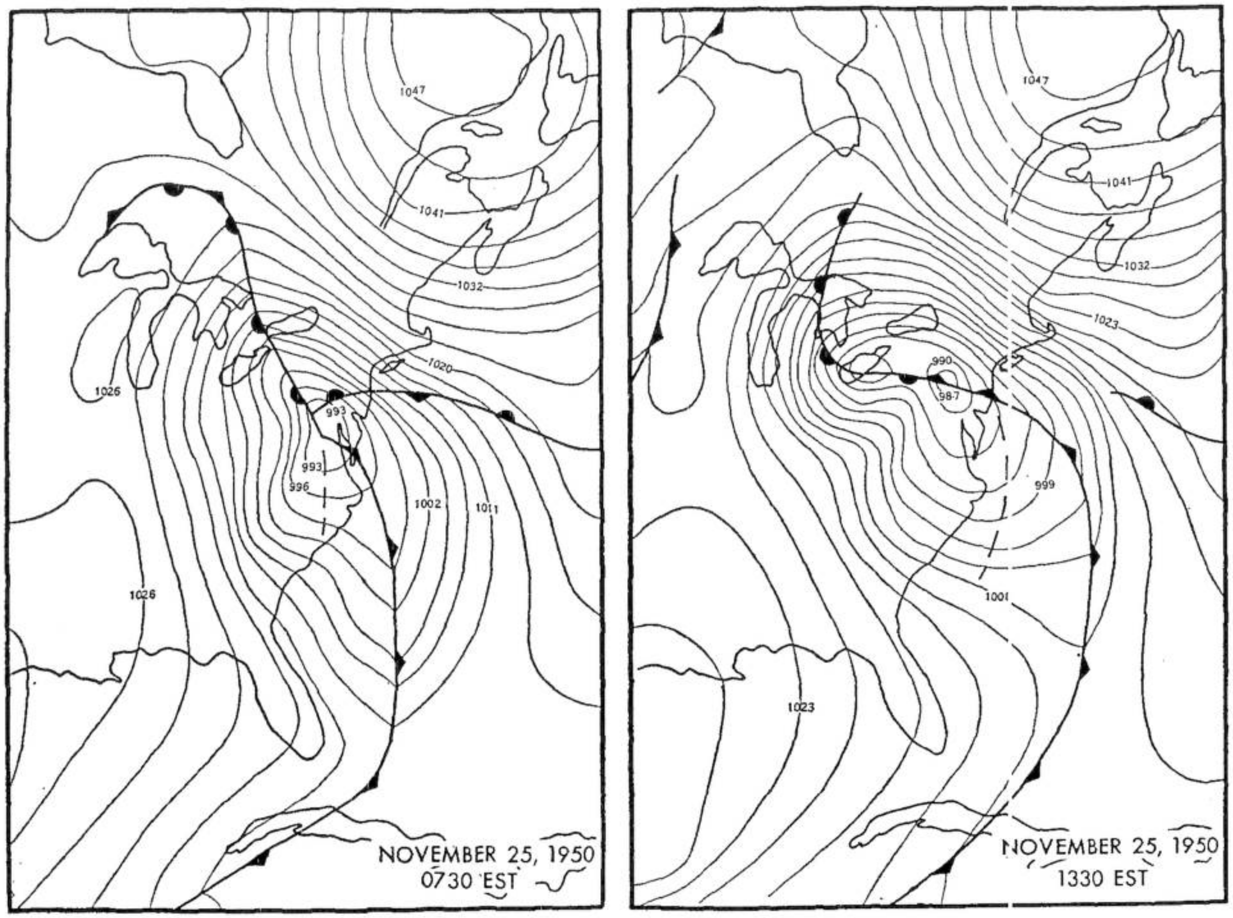

FIG. 6. Synoptic surface charts showing pressure patterns and front locations for the November 1950 storm. Analyses from WBAN Analysis Center charts.

The five predictor equation from Run 7 is presented below:

$$SS=10.60+0.36(p_{-6}-1000)_{\mathrm{ACK}}-0.69(p_{-6}-1000)_{\mathrm{ORF}} +0.24(v_{-6}+v_{-18})_{\mathrm{ACK}}-0.14(u_{-10})_{\mathrm{ORF}}, \quad (6)$$

where SS is storm surge in tenths of feet, p is station pressure in millibars, v is alongshore component of wind in knots, u is onshore component of wind in knots, and the time lag in hours and the station identification are indicated by subscripts.

It is interesting to note that none of the predictors from Atlantic City appear in this equation, as no Atlantic City predictor was selected by the screening procedure until the eighth predictor. The pressure terms are an indication of pressure gradient between Nantucket and Norfolk and therefore are indicative of the onshore flow. The term involving alongshore components shows the importance of the alongshore currents over the wide continental shelf between Nantucket and Atlantic City, both for the recent past and for the relatively distant past of 18 hours. The Norfolk u-term is indicative of the position of the storm and indicates a favorable surge-producing position when the wind has shifted to northwest or west at Norfolk several hours earlier.

Calculations using the above regression equation are shown in Fig. 4 for the dependent data and in Fig. 5 for the independent data. The root mean square error of both sets of calculations is 0.5 feet. There is some improvement in the calculations over those of the one-station model for most of the regular storms, some improvement for the record-breaking storms of 1950 and 1953, and much improvement in the calculations for the March 1962 storm.

The independent forecast showing the least accurate fit to the observed storm surge is that for the 24–26 November 1950 storm. This storm was a very intense atypical storm. There was a southeast fetch of long duration time affecting the Atlantic City tide which could not be well represented by the interpolation scheme of Eq (6). The surge was further complicated by the frontal passage and the shift to offshore winds. A series of synoptic charts for this storm is given in Fig. 6.

Calculations by the final equation which contains the

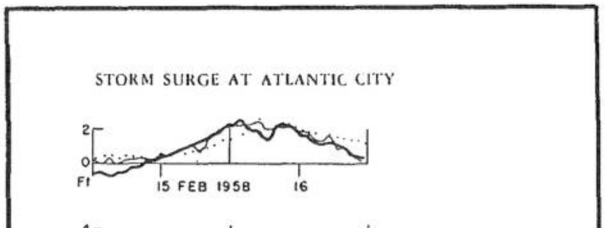

FIG. 7. Comparison of storm surges with two sets of calculations. One set used predictors with a minimum lag of 6 hours. The other used predictors with a minimum lag of 12 hours.

90 terms of Run 5 are also shown in Figs. 4 and 5 for most of the storms. The calculations by the final equation are generally better for the peaks of the surge curves, even though the over-all correlation coefficient is only 0.04 higher than that of the short equation. These results are contrary to those usually obtained with the screening procedure in which a large number of predictors show less skill on independent data than a small number of significant predictors. A reasonable explanation for the slightly better agreement of the final equation containing many predictors is that it gives a more detailed interpolation of the wind field.

It is desirable to take advantage of the greatest minimum time lags that are practical without sacrificing needed accuracy. For that reason regression equations using minimum time lags of 12 and 18 hours were determined and the calculations of these equations were compared to those made by the 6-hr minimum lag model. Fig. 7 shows the predictions using minimum lags of 6 hours and 12 hours for several of the storms and indicates that 6 hours is about as far into the future as storm surge forecasts can be made using current meteorological observations.

7. Conclusions

The implications of the analysis of the data are:

1) Practical predictions of the extratropical storm surges associated with the winter storms that move through the southeastern United States or approach the Middle Atlantic coastal area from offshore of the southeast coast can be made with a regression equation containing only a few terms. Slightly better predictions for the peak storm surges of most storms can be made using the complete prediction equation containing many more predictors probably because the large number of predictors give a slightly better interpolation of the wind field.

2) The extratropical storm surge at Atlantic City is much more dependent on the alongshore component of wind than on the onshore component.

3) There is little difference in prediction ability between the system which uses the linear wind stress law and that which uses the quadratic law.

4) There is a time lag of several hours between the wind and the resulting storm surge.

5) The storm surge generating factors over the ocean may be represented by weather observations at one station for the usual type of winter extratropical storms affecting Atlantic City; however, additional accuracy is obtained by representing the surge-generating area by three stations. Occasionally these methods will not produce satisfactory predictions when meteorological conditions generate fetch lengths and duration times that cannot be indicated by the terms in the regression equations.

Acknowledgments. Appreciation is expressed to the Coast and Geodetic Survey for the tide data, to Mr. D. L. Harris and Mr. G. W. Brier for suggestions, and to Mr. J. E. Fimiani for the drafting of the figures.

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