PREDICTION OF HURRICANE MOTION BY STATISTICAL METHODS

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ABSTRACT

Equations for the prediction of hurricane tracks have been developed by use of statistical methods. Data at sea level, 700 mb., and 500 mb. were selected as predictors. Forecasts are prepared in 12-hr. steps for periods up to 48 hr. The forecast equations have been tested on an operational basis during the 1964 and 1965 hurricane seasons. The accuracy of these forecasts compares favorably with that of other standard hurricane forecast techniques.

1. INTRODUCTION

During the past ten years a number of objective methods for forecasting hurricane movement has been developed [1, 2, 5, 7, 8, 9, 10]. Several of these methods have been evaluated at the National Hurricane Center [6]. The methods tested demonstrated varying degrees of forecast skill and some seemed to be worth further study. However, if forecasts were prepared by several different methods the forecaster was frequently confronted with a wide divergence in the forecast tracks, and this usually caused the forecaster to give little or no weight to any of the objective systems. To lessen this difficulty as much as possible the National Hurricane Research Laboratory has developed a set of prediction equations which seems to incorporate many of the best features of the earlier objective methods for hurricane forecasting.

Ideally the prediction of hurricane motion should be based on forecasts of the field of motion over a large area surrounding the vortex, as, for example, by numerical prediction on a hemispheric basis. However, the prediction of circulation patterns at low latitudes over oceanic regions, which is necessary for numerical prediction of hurricane movement, has thus far proved to be a difficult task. Recognizing these problems, many investigators have chosen to bypass the explicit prediction of circulation patterns. Instead they have chosen to develop forecast techniques which make use of the current circulation patterns, auto-correlation functions, and features of the immediate past, which are known to be related to the subsequent track of the tropical cyclone. This line of approach (essentially statistical and climatological) has the advantage of being able to produce results for immediate use, whereas the more desirable (from a physical standpoint) dynamical approach takes longer and may have to await vastly improved data networks in tropical regions. Also, at present the forecasts of hurricane motion based on statistical methods verify significantly better than those produced by such dynamical models as have been tested operationally, although it is to be expected that eventually the numerical forecasts will become superior, as prediction models and data networks improve.

The first of the objective systems for hurricane forecasting was developed by Riehl et al. [5]. They postulated that the hurricane would move with the speed of the vertically integrated flow surrounding the vortex, and used the 500-mb. chart to represent the vertical mean. The geostrophic wind components computed from the 500-mb. heights around the periphery of a small grid centered on the surface position of the cyclone were used as predictors. Miller and Moore [2] subsequently applied a Riehl-Haggard [5] type grid to the 700-mb. chart and derived a set of prediction equations which used the geostrophic wind components and the past movement of the cyclone center as predictors. An unpublished modification of the Miller-Moore method incorporated heights and height changes of the 700-mb. surface as predictors. Arakawa [1] has developed similar methods for use in the Pacific area.

In 1959 Veigas, Miller, and Howe [8] applied the screening-multiple linear regression statistical methods, developed by Miller [3, 4], to the problem of hurricane forecasting. These methods have become powerful tools in the development of statistical forecast systems, and they have since been refined and extended to numerous related problems. In the first hurricane forecast system developed by these methods [8], a small set of predictors was selected from an initial set which included 91 sea level pressures and the past motion of the cyclone. The sea level pressures were read from a grid formed by the intersection of latitude and longitude lines at 5° intervals. The grid was centered at the 5° intersection nearest the hurricane center. A revised method [9] was developed in 1960 in cooperation with the National Hurricane Research Laboratory. An equal-area grid, with grid

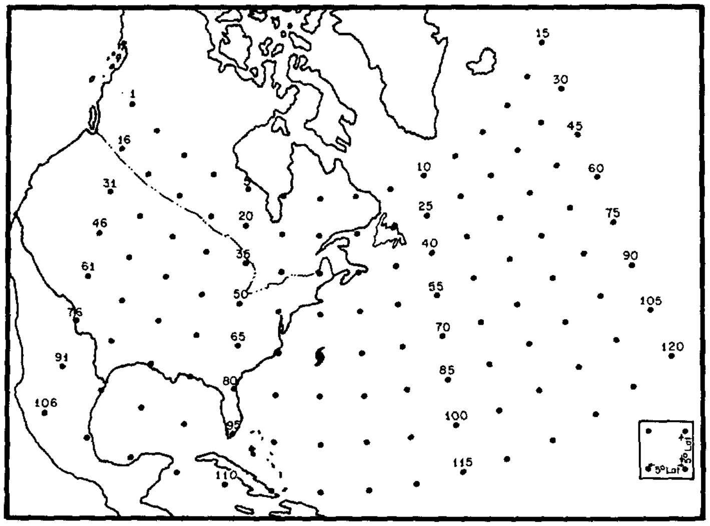

FIGURE 1.—The grid system.

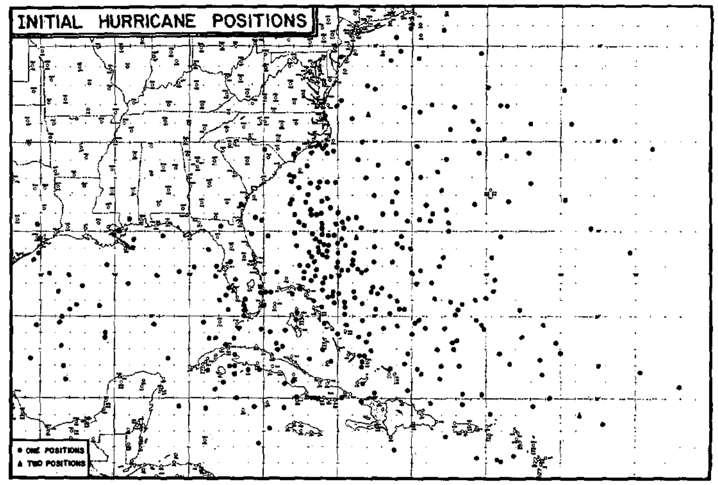

FIGURE 2.—Location of tropical cyclones used in developmental sample.

length 300 n. mi., centered on the surface position of the cyclone was adopted (fig. 1). The grid moves with the cyclone.

In tests conducted at the National Hurricane Center, Tracy [6] showed that four objective systems (Riehl-Haggard-Sanborn, Miller-Moore, Travelers-1959, and Travelers-1960) possessed some degree of forecast skill. Efforts were made to combine these four techniques into one. These efforts resulted in the development of the set of equations which will be described in this paper. These equations were first tested on an operational basis in 1964 and will be referred to as the NHC–64 system.

2. DEVELOPMENT DATA

The dependent data sample from which the prediction equations were derived was obtained from 56 selected tropical cyclones located west of 50° W. longitude in the Atlantic, Caribbean, and Gulf of Mexico. A total of 504 cases was available from the years 1945–1961. The grid shown in figure 1 was centered on the surface position of the cyclone. Sea level pressures, 700-mb. heights, and 500-mb. heights were tabulated. Because of missing data within large areas of the grid, however, a number of cases had to be discarded. A few were rejected because the hurricane moved inland and dissipated or became extra-tropical in less than 48 hr. Tropical cyclones of less than storm intensity were also omitted from the development sample. This left a total of 368 cases out of the original 504. These were divided into two classes, with the initial latitude of the center position being used to separate the cases. Those located south of 27.5° N. latitude were placed in the south zone (183 cases) and the remainder formed the north zone sample (185 cases). This geographical division served two purposes. First, it made some use of climatology, since the average latitude of recurvature [1] is near the point chosen for the stratification into zones. Second, there were many missing data points for cyclones located at the lower latitudes and failure to stratify the data would have required that these same data points be omitted from the screening process for all cases, which would have resulted in the loss of data with possible predictive value. The initial locations of the cases used are shown in figure 2.

3. THE PREDICTION EQUATIONS

The prediction equations were developed by use of a screening-multiple linear regression technique [4]. The screening procedure examines a large number of possible predictors, from which a small sub-set is selected. The screening process was terminated when a maximum of 15 predictors had been selected, or when the F-ratio was less than 1.0. This criterion is probably too liberal, but not all the predictors selected were retained. In general those predictors which contributed less than 1 percent to the reduction in the variance were arbitrarily rejected. This test was violated in the 12-hr. longitude equations in order to include the 1000–700-mb. thickness at grid point number 50 (south zone) and the 500-mb. height change at grid point 53 (north zone), because these were considered to be physically significant. The last two predictors in the south zone equation probably should have been rejected.

The initial set of predictors include the following, where $_i$ indicates the number of the grid point (fig. 1) where the value is obtained:

P_i Sea level pressures (mb.)
H_i 700-mb. heights (meters)
Z_i 500-mb. heights (m.)
DH_i 1000–700-mb. thicknesses (m.)
TH_i 700–500-mb. thicknesses (m.)

DZ_i 500-mb. height changes (m.)

S_5, T_3, S_7, U_7 Geostrophic wind components at three levels

P_x, P_y The past 12-hr. movement of the cyclone center (n. mi.) (westward and northward positive)

Equations were derived for forecast periods up to 48 hr. Forty-eight-hour forecasts could be prepared in three ways: (1) in one time step, i.e., a 0–48 hr. forecast; (2) in two steps, i.e., a 0–24 hr. displacement plus a 24–48-hr. displacement; (3) in four steps by 12-hr. increments. Equations were derived for all three ways, and tests on independent data showed no large differences in the accuracy of the 48-hr. forecast positions. Those prepared by 12-hr. increments were slightly better, but this may have been accidental. However, the forecasts prepared in 12-hr. time steps have the advantage of showing the intermediate positions along the track, which may be of critical interest whenever changes in direction occur. Consequently the latter were adopted for operational use and the others will not be discussed here.

The forecast equations are listed below. All forecasts are in nautical miles, with north and west considered positive. The predictands are identified as follows:

Y_{12} 00–12-hr. latitude forecast
X_{12} 00–12-hr. longitude forecast
Y_{24} 12–24-hr. latitude forecast
X_{24} 12–24-hr. longitude forecast
Y_{36} 24–36-hr. latitude forecast
X_{36} 24–36-hr. longitude forecast
Y_{48} 36–48-hr. latitude forecast
X_{48} 36–48-hr. longitude forecast

Forecasts for periods greater than 12 hr. were prepared by adding forecast displacments for successive periods.

The south zone equations apply when the original position of the hurricane center is south of 27.5° N. They are:

$$Y_{12}=-286.5+0.66941\,P_y-0.29613\,H_{66}+1.64873\,P_1+0.19547\,H_{55}-4.70968\,P_{52}+3.66274\,P_{69}$$

$$X_{12}=-1766.7+0.60582\,P_x+0.65069\,Z_{38}-3.70010\,P_{75}+0.41391\,DH_{50}+1.04993\,P_7-0.22969\,TH_{39}$$

$$Y_{24}=1036.1+0.39484\,P_y-0.48572\,Z_{66}+2.95035\,P_2+0.66416\,TH_{83}-0.56308\,DZ_{50}+0.18039\,H_6+0.50282\,H_{85}-5.04286\,P_{80}$$

$$X_{24}=-2947.9+0.75767\,Z_{37}+0.32222\,P_x+0.18878\,DZ_{23}+0.13761\,Z_{12}-0.25162\,P_y-1.22724\,DH_{53}+0.94423\,DH_{54}-4.21241\,P_{73}+2.83216\,P_{39}$$

$$Y_{36}=-7609.3-0.83436\,Z_{52}+0.04664\,Z_{23}+0.51920\,Z_{70}-0.71777\,DZ_{50}+2.35781\,P_2+0.36816\,P_y+0.27499\,Z_7+0.57775\,Z_{47}-0.86002\,H_{68}+4.49646\,P_{75}$$

$$X_{36}=-1064.1+0.91156\,Z_{37}+0.28164\,H_{13}+0.20401\,DZ_7+0.40150\,H_{40}-5.94821\,P_{73}-0.27231\,P_y-0.13140\,TH_{21}$$

$$Y_{48}=-4646.5+2.93003\,P_2-8.50895\,P_{52}+11.12384\,P_{70}+0.80225\,TH_{70}-0.52414\,Z_{68}+1.00678\,Z_{47}-0.75137\,H_{64}+0.17289\,Z_7-0.77409\,Z_{52}$$

$$X_{48}=3061.7+1.18778\,H_{37}+0.33403\,H_{13}+0.39161\,DZ_{21}-6.49004\,P_{74}-0.40141\,P_y-0.46128\,TH_{19}$$

The north zone equations are to be used at and north of 27.5° N. These are:

$$Y_{12}=2402.1+0.37333\,P_y+0.07530\,S_5+0.07786\,S_7-4.37184\,P_{94}+6.01754\,P_{103}+0.23446\,H_{21}-0.27886\,DZ_{48}$$

$$X_{12}=548.7+0.59869\,P_x+0.09337\,U_7-0.17597\,H_5+0.12244\,DZ_{12}-0.33705\,DZ_{53}$$

$$Y_{24}=-1293.6-0.51706\,DZ_{50}+0.83227\,Z_{62}-0.84591\,Z_{80}+0.05841\,S_5-0.52227\,Z_{51}+0.21873\,DZ_2+4.43696\,P_{71}$$

$$X_{24}=-1288.6+0.21176\,U_7-0.30490\,H_{46}+0.23418\,DZ_{12}-0.21411\,H_6+0.68175\,TH_{37}+1.25490\,H_{112}-0.49010\,Z_{83}$$

$$Y_{36}=1236.4+0.13101\,S_7+0.08936\,S_5+2.65820\,P_7-0.58650\,DZ_{65}+0.71993\,H_{61}-0.86362\,Z_{98}-0.38668\,TH_{41}$$

$$X_{36}=2584.1+0.17241\,U_7-5.59111\,P_5+0.40508\,DZ_{12}-0.40708\,Z_{70}+7.98410\,P_{49}-0.81026\,H_{63}+0.0637\,T_3$$

$$Y_{48}=-8333.7+0.23875\,S_7+0.81928\,H_{38}-0.60680\,TH_{37}+2.70569\,P_7+4.67972\,P_{32}-0.48206\,DZ_{32}-0.31332\,P_y$$

$$X_{48}=-4556.3+0.24931\,U_7+0.43053\,DZ_{12}-1.33096\,H_{54}+5.10815\,P_{40}+22.72443\,P_{98}-16.25212\,P_{69}-2.86867\,P_3$$

The measures of the geostrophic wind were defined on the basis of experience gained from the Riehl-Haggard and the Miller-Moore forecast systems. They were designed to approximate the "steering current" at each level. In addition, some were defined after a careful examination of the correlation coefficients between the predictands and the height fields at each level. Those selected by the screening process are defined below and the locations of the grid points used in determining them are shown in figure 3.

$$S_5=[(Z_{39}+Z_{54}+Z_{69}+Z_{84}+Z_{99})-(Z_{35}+Z_{50}+Z_{65}+Z_{80}+Z_{95})]/\sin\phi_0$$

$$T_3=[(Z_{33}+Z_{34}+Z_{35}+Z_{36}+Z_{37}+Z_{38}+Z_{39}+Z_{40}+Z_{41}+Z_{42})-(Z_{48}+Z_{49}+Z_{50}+Z_{51}+Z_{52}+Z_{53}+Z_{54}+Z_{55}+Z_{56}+Z_{57})]/\sin(\phi_0+7.5)$$

$$S_7=[(H_{33}+H_{48}+H_{63}+H_{78})-(H_{21}+H_{36}+H_{51}+H_{66})]/\sin\phi_0$$

$$U_7=[(H_{35}+H_{36}+H_{37}+H_{38}+H_{39})-(H_{95}+H_{96}+H_{97}+H_{98}+H_{99})]/\sin\phi_0$$

where ϕ_0 is the latitude of the center at forecast time.

The prediction equations contain the predictors in the order in which they were selected by the screening process. The contribution of each variable to the reduction in variance is summarized in tables 1a–h.

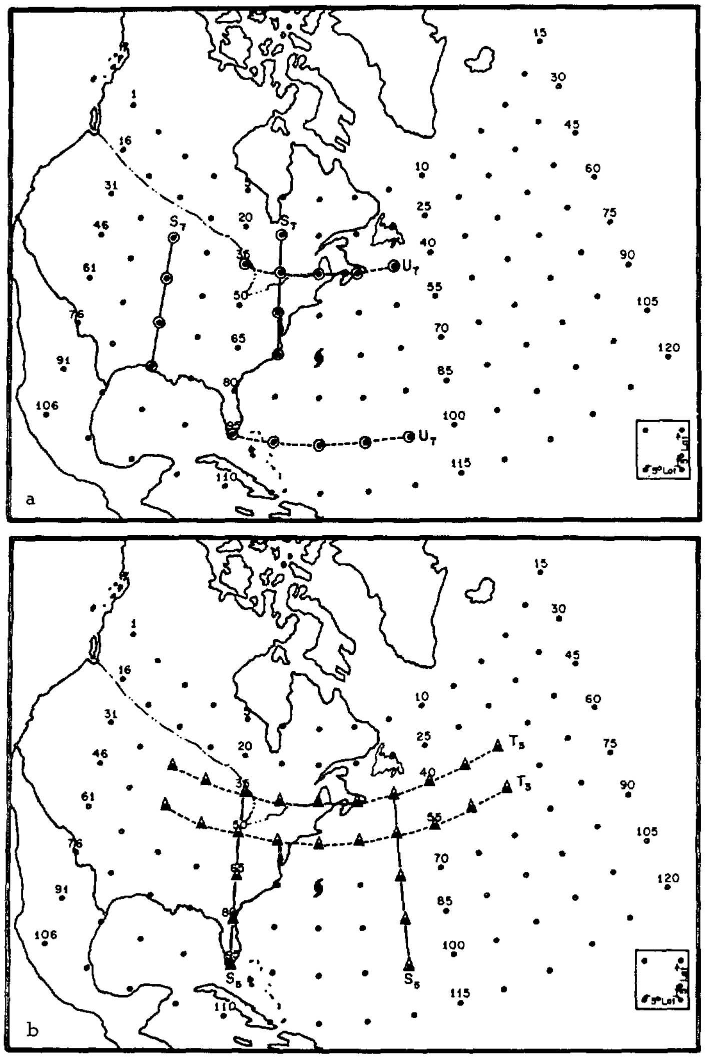

FIGURE 3.—Location of grid-point data needed to define steering parameters: (a) S_7 and U_7; (b) S_5 and T_3.

TABLE 1.—*Contribution of each predictor to the reduction in variance*

Order selected	Latitude		Longitude	
	Predictor	Percent reduction	Predictor	Percent reduction
(a) 12-hr. Forecast (South Zone)				
1	P_y	44.7	P_x	80.8
2	H_{66}	4.4	Z_{38}	5.0
3	P_1	3.5	P_{10}	1.2
4	H_{55}	2.3	DH_{50}	0.9
5	P_5	2.2	P_3	0.5
6	P_6	1.7	TH_{39}	0.4
Total PR		58.8		88.8
Residual error		32.0 n. mi.		31.1 n. mi.
(b) 12–24-hr. Forecast (South Zone)				
1	P_y	15.3	Z_{37}	67.3
2	Z_{66}	9.4	P_x	5.9
3	P_2	7.2	DZ_{23}	3.4
4	TH_{83}	3.5	Z_{12}	2.4
5	DZ_{50}	2.7	P_y	1.3
6	H_6	3.3	DH_{53}	1.2
7	H_{85}	2.6	DH_{54}	1.1
8	P_{80}	2.6	P_{73}	0.8
9			P_{39}	1.0
Total PR		46.6		84.4
Residual error		41.3 n. mi.		38.6 n. mi.
(c) 24–36-hr. Forecast (South Zone)				
1	Z_{52}	13.0	Z_{37}	54.3
2	Z_{23}	9.0	H_{13}	7.6
3	Z_{70}	8.6	DZ_7	4.2
4	DZ_{50}	5.5	H_{40}	2.4
5	P_2	5.0	P_{73}	2.5
6	P_y	3.2	P_y	1.7
7	Z_7	3.0	TH_{21}	1.2
8	Z_{47}	3.9		
9	H_{68}	3.1		
10	P_{75}	2.7		
Total PR		57.0		73.9
Residual error		45.1 n. mi.		50.6 n. mi.
(d) 36–48-hr. Forecast (South Zone)				
1	P_2	10.0	H_{37}	39.3
2	P_{52}	10.4	H_{13}	10.9
3	P_{70}	10 2	DZ_{21}	5.1
4	TH_{70}	4.0	P_{74}	2.7
5	Z_{68}	4.8	P_y	2.3
6	Z_{47}	5.1	TH_{19}	1.8
7	H_{64}	3.3		
8	Z_7	2.4		
9	Z_{52}	3.3		
Total PR		53.5		62.1
Residual error		56.4 n. mi.		67.0 n. mi.

4. DISCUSSION

The physical interpretation of the results of the screening process is not always clear cut, although if a selected predictor continues to contribute significantly to forecast accuracy there must obviously be some physical explanation for that fact, however obscure it may be. Meteorological variables are highly correlated both in space and time, and these correlations make it difficult to determine whether a selected predictor is physically significant for its own sake or because both the predictor and the predictand are correlated with some unidentified factor. However, a brief discussion of the forecast equations may be of some benefit to the forecaster who must make the decision as to the accuracy of a particular forecast which he may encounter operationally.

Figures 4–8 show the locations of the sea level pressures, 700-mb. heights, 500-mb. heights, 24-hr. height changes at the 500-mb. surface, and the thickness values which were selected as predictors. These locations are in addition to the ones used to define the steering components at the 700- and 500-mb. levels, since the interpretation of the forecast value of these components (S_5, T_3, S_7, and U_7) is relatively simple.

The letters N and W, together with a sign and a number have been entered on figures 4–8. The letter indicates the forecast equation in which each predictor appears, i.e., N means that the predictor appears in an equation used to forecast north-south movement and W, an equation to forecast east-west movement. The sign designates the sign of the coefficient of each predictor. The number denotes the equation in which the predictor appears. A "2" indicates that the predictor appears in the 0–12-hr. prediction equation, a "4", in the 12–24-hr. equation, a

TABLE 1.—*Contribution of each predictor to the reduction in variance*—Continued

Order selected	Latitude		Longitude	
	Predictor	Percent reduction	Predictor	Percent reduction
(e) 12-hr. Forecast (North Zone)				
1	P_y	55.9	P_x	75.6
2	S_6	7.4	U_7	5.9
3	S_7	5.4	H_5	2.2
4	P_{94}	2.1	DZ_{12}	1.7
5	P_{103}	2.4	DZ_{53}	0.9
6	H_{21}	1.4		
7	DZ_{48}	2.2		
Total PR		76.8		86.3
Residual error		38.2 n. mi.		39.3 n. mi.
(f) 12–24-hr. Forecast (North Zone)				
1	DZ_{50}	40.0	U_7	58.5
2	Z_{62}	10.0	H_{46}	5.2
3	Z_{80}	10.7	DZ_{12}	4.2
4	S_5	3.7	H_6	2.6
5	Z_{51}	2.8	TH_{37}	2.3
6	DZ_2	3.0	H_{112}	1.6
7	P_{71}	2.2	Z_{83}	1.2
Total PR		72.4		75.6
Residual error		54.4 n. mi.		59.8 n. mi.
(g) 24–36-hr. Forecast (North Zone)				
1	S_7	44.1	U_7	37.9
2	S_5	9.6	P_6	8.5
3	P_7	4.6	DZ_{12}	8.4
4	DZ_{65}	2.2	Z_{70}	2.8
5	H_{61}	2.5	P_{49}	2.5
6	Z_{98}	2.5	H_{63}	3.2
7	TH_{41}	1.9	T_3	2.4
Total PR		67.4		65.7
Residual error		67.4 n. mi.		79.6 n. mi.
(h) 36–48-hr. Forecast (North Zone)				
1	S_7	37.2	U_7	15.8
2	H_{38}	7.5	DZ_{12}	9.7
3	TH_{37}	2.5	H_{54}	6.6
4	P_7	2.3	P_{40}	4.9
5	P_{32}	1.9	P_{98}	4.1
6	DZ_{32}	2.5	P_{69}	3.6
7	P_y	2.2	P_3	2.4
Total PR		56.1		47.1
Residual error		80.1 n. mi.		105.7 n. mi.

"6", in the 24–36-hr. equation, and an "8", in the 36–48-hr. equation. Predictors which appear in the north zone equations are underlined.

Looking at figure 3 one sees that in general above normal pressures to the east and below normal pressures to the north of the center are associated with northward motion of the hurricane. Similarly above normal pressures to the north are associated with westward motion. There is also a tendency for gradients to be defined in a crude way even though the screening program used did not specifically select predictors in pairs. For example, in the north-south equations for a 12-hr. forecast (south zone) P_{69} (to the east of the center) appears with a plus sign, while P_{52} to the north of the center appears with a minus sign. Less obvious is the tendency for northward motion to be

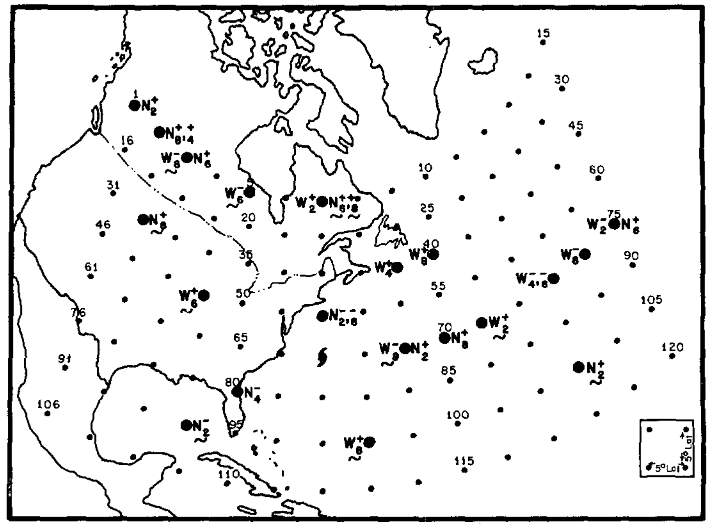

FIGURE 4.—Sea level pressures used as predictors.

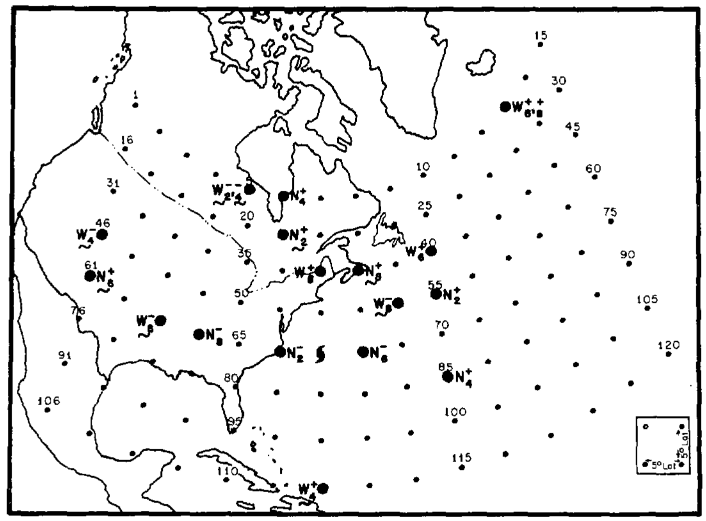

FIGURE 5.—700-mb. heights selected as predictors.

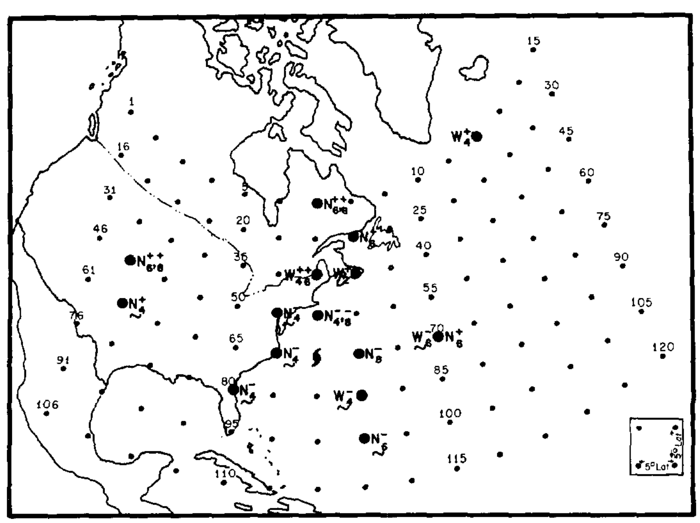

FIGURE 6.—500-mb. heights selected as predictors.

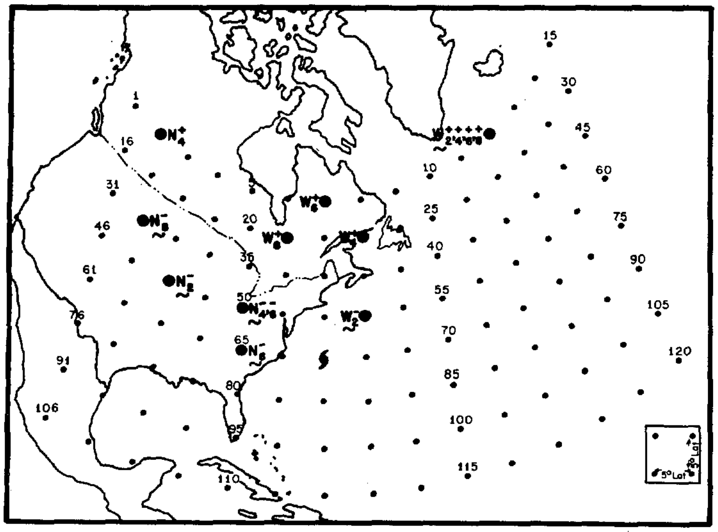

FIGURE 7.—500-mb. height changes selected as predictors.

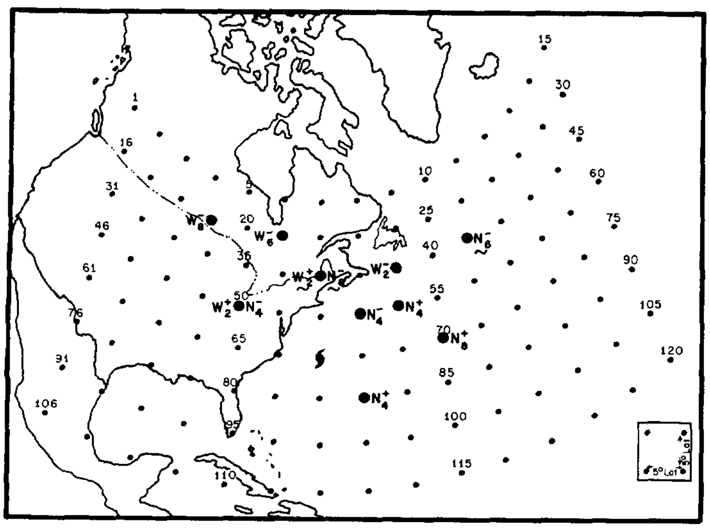

FIGURE 8.—Thicknesses used as predictors.

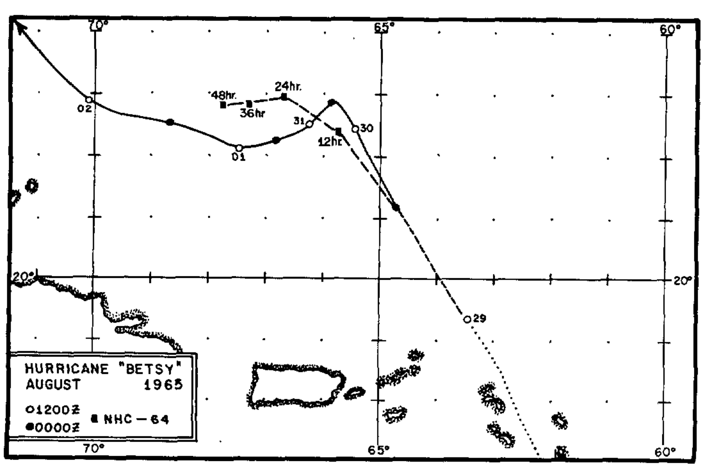

FIGURE 9.—A forecast prepared by NHC-64 for hurricane Betsy 1965.

associated with above normal pressures over the extreme northwestern part of the grid. This may imply (in a statistical-climatological sense) that if an anticyclone at sea level is situated over that portion of the grid, a trough is probably located near the longitude of the hurricane which is about 1500–1800 n. mi. to the east.

A similarpattern seems to exist at both 700 and 500 mb. (figs. 5 and 6). The heights 10° north of the center at both 700 and 500 mb. are particularly important in forecasting east-west motion. For example, in the 12–24-hr. longitude forecast (south zone) Z_{37} was the first predictor selected, and contributed 67.3 percent to the reduction in the variance. In the 36–48-hr. forecast of east-west movement (north zone) H_{37} was the first predictor selected and made a 39.3 percent contribution to the reduction in variance.

The selection of 500-mb. height changes (fig. 7) reflects well known empirical rules for forecasting acceleration of hurricanes. Falls to the west of the center are associated with northward acceleration, while rises to the west are associated with deceleration. Rises to the north or northeast are associated with slowing down or turning westward, while falls to the north may result in acceleration or recurvature. Below normal thickness values (fig. 8) to the north are related to eastward movement, while above normal values are related to westward motion. Above normal values to the south or east are associated with northward displacement.

The past 12-hr. movement of the hurricane center was among the original set of possible predictors screened. For a 12-hr. forecast the past motion was the first predictor selected in both zones. In the south zone the past motion (P_y) was also selected as the first predictor in making a 12–24-hr. forecast of meridional motion, but in the zonal forecast equation the past motion (P_x) was selected second. For periods beyond 24 hr. in the south zone the past motion makes no substantial contribution to the forecast. In the north zone the past motion is unimportant after the first 12 hr. Thus the NHC–64 equations are not heavily dependent upon persistence for their forecast skill. That deceleration and changes in direction (even though climatologically improbable) may be forecast by these equations is indicated by a forecast made for hurricane Betsy (1965) as shown in figure 9.

5. RESULTS

The NHC–64 equations were derived from a dependent data sample extending over the period 1945–61. Tests on independent data for 1962 and 1963 showed that the results for 76 forecasts compared favorably with those obtained from other standard forecast techniques. The equations were used to prepare forecasts on an operational basis at the National Hurricane Center during the 1964 hurricane season. These forecasts were based on hand analyses prepared at the Center. In all 68 forecasts were prepared. Following the 1964 season the data required to prepare the same forecasts were obtained from the

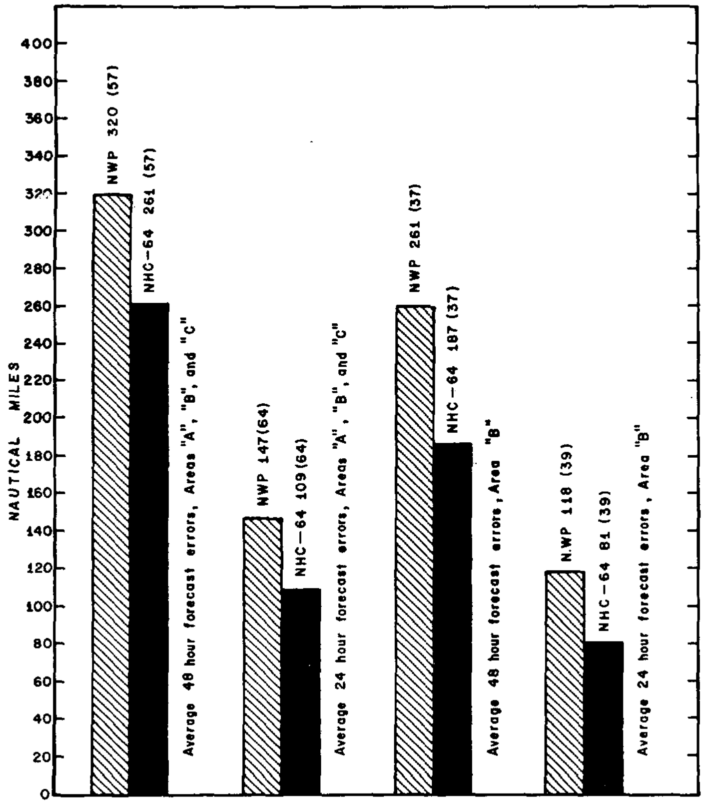

FIGURE 10.—Average 24- and 48-hr. forecast errors for NWP and NHC-64 operational forecasts, 1964 and 1965 seasons. Numbers in parentheses indicate the sample size.

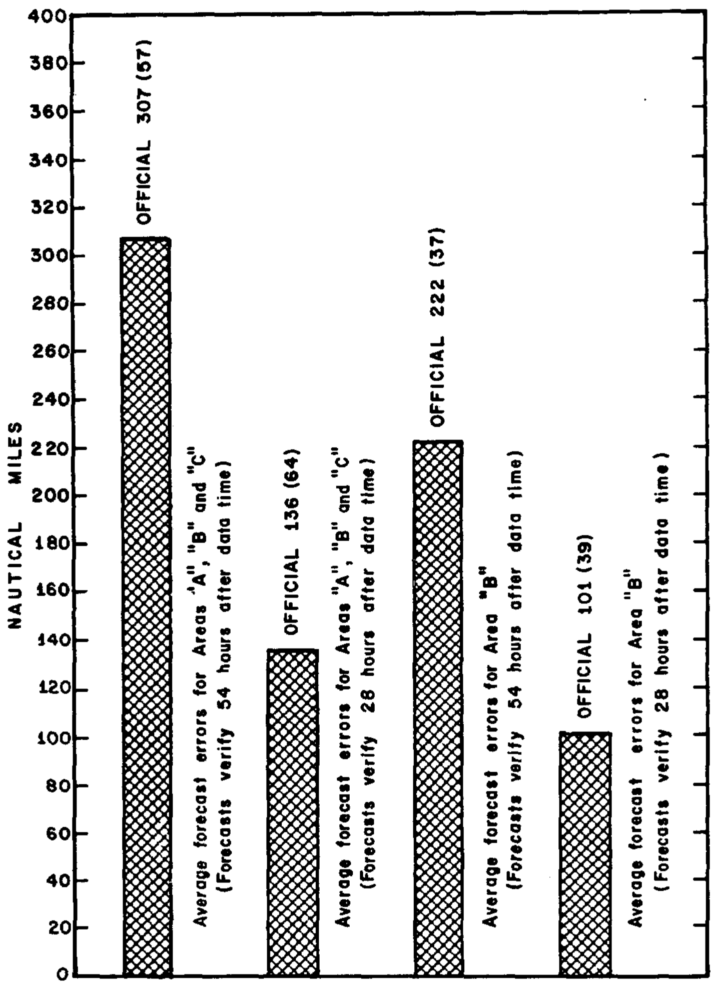

FIGURE 11.—Average errors for official forecasts prepared from same initial data as those shown in figure 10, but verifying four hours later. Numbers in parentheses indicate the sample size.

National Meteorological Center's (NMC) objective analysis tapes. The forecasts were recomputed and the results compared with those obtained from the hand analyses. No significant differences could be detected between the accuracy of the two sets of forecasts.

As a result of these tests the forecasts were prepared at NMC during the 1965 season. Forecasts were made from the preliminary analyses in order that they might be available to the hurricane forecaster before he issued his own forecast, which is issued at 0400 GMT and 1600 GMT but is actually prepared about 1½ hr. earlier. In most cases the NHC-64 forecasts were available prior to the time the official forecasts were prepared. The forecasts were also prepared from the final NMC analyses. Those made from the preliminary analyses were almost as good as those made from the final analyses.

A complete evaluation of several forecast techniques (including the NHC-64) has been performed by Tracy [6] and will not be repeated here. However, a brief summary of some of Tracy's results is shown in figures 10 and 11. Figure 10 shows the average errors for 24- and 48-hr. forecasts prepared by the numerical weather prediction model [7] and the NHC-64 statistical equations. The official forecasts, issued at 0400 and 1600 GMT, were prepared from the same initial data as the NWP and NHC-64

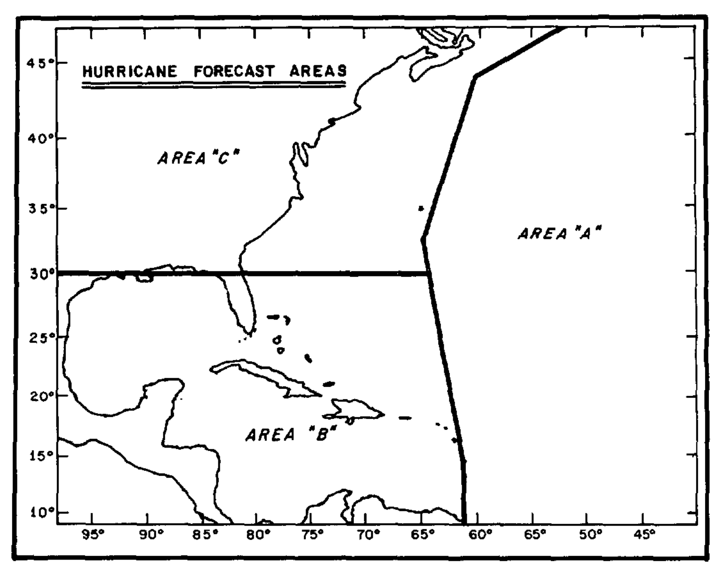

FIGURE 12.—Locations of geographical areas A, B, C.

forecasts, but verify four hours later. These are shown in figure 11. All are operational forecasts prepared during the 1964 and 1965 seasons. The samples compared are homogeneous. The forecasts errors are shown by geographical areas as defined by figure 12. These results show that the NHC–64 forecasts are significantly better than the NWP forecasts and that they are comparable to those issued by the hurricane forecast centers.

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