A REVISED TECHNIQUE FOR FORECASTING HURRICANE MOVEMENT BY STATISTICAL METHODS

BANNER I. MILLER*, ELBERT C. HILL**, and PETER P. CHASE*

*National Hurricane Research Laboratory and **National Hurricane Center, ESSA, Miami, Fla.

ABSTRACT

The NHC-64 statistical equations for predicting the movement of hurricanes have been in operational use for 4 yr. These equations have continued to perform well. Following the 1966 hurricane season, however, it was apparent that the equations could be improved. A new forecast technique, based on additional data and additional predictors, has been derived. Tests on independent data for 1966 and on an operational basis during 1967 indicate that the 1967 method is slightly superior to NHC-64.

1. INTRODUCTION

In a recent paper Miller and Chase [2] described a statistical method for predicting the movement of tropical cyclones. The method (referred to as the NHC-64 system) is capable of preparing forecasts for periods up to 72 hr. (the 48–72 hr. portion of the forecast having been added since the publication of the paper).

For the past 3 yr. the NHC-64 forecasts have been prepared routinely at the National Meteorological Center (NMC) from data obtained from NMC's objective analyses.

Comparison of various hurricane forecast methods by Tracy [3], Miller and Chase [2], and Dunn, Gentry, and Lewis [1] indicated that the NHC-64 technique was the best objective method in operational usage at the end of the 1966 season. The verification data also showed that the accuracy of the forecasts prepared by the NHC-64 equations was comparable to that obtained by the most experienced hurricane forecasters. Dunn, Gentry, and Lewis' data also showed a significant improvement in the accuracy of the official Weather Bureau hurricane forecasts over a 13-yr. period. Figure 1 shows the results of their study for one geographical area. While it is difficult to say with certainty just what caused the improvement in the hurricane forecasts, Dunn et al. attribute it to increased experience on the part of the forecasters, closer cooperation between forecast and research personnel, and to the development of improved objective forecast techniques. It is at least encouraging to note that one of the improvements indicated by the block diagram in figure 1 coincided with the development of improved objective forecast methods.

After 4 yr. of operational use (at the end of the 1967 season), the NHC-64 equations have continued to perform well. However, at the end of the 1966 season, it was apparent that the equations could be improved. After doing well in forecasting the movement of hurricane Faith (1966) and the first half of Inez (1966), the NHC-64 method did poorly in forecasting the erratic movement of Inez southwestward through the Gulf of Mexico. As a result of this unsatisfactory performance, the data have been reexamined, and a new set of prediction equations have been derived. The screening techniques used in deriving the NHC-67 equations were identical to those used in developing the NHC-64 set and will not be discussed here.

2. DEVELOPMENT DATA AND POSSIBLE PREDICTIONS

The basic data used in development of the prediction equations were the heights of the 1000-, 700-, and 500-mb. surfaces at 120 grid points, as shown in figure 2. The grid system moves with the center of the hurricane, and is the same used in the earlier study by Miller and Chase [2]. Data from hurricanes during the years 1962–1965 were added to the 1945–1961 period used in deriving the NHC-64 equations. Stratification of the data into South Zone and North Zone was continued, with 27.5°N. lat. separating the two zones. The additional dependent data permitted some further stratification of the cases, and this will be discussed in a later section. A total of 460 cases, 224 in the South Zone and 236 in the North Zone, were used in developing the 48-hr. forecast equations.

Several additional predictors were screened in developing the NHC-67 equations. Many of the added predictors were selected. The list of predictors included the following, where the i-index refers to the location of the grid point (fig. 2):

P_i, H_i, and Z_i	1000-, 700-, and 500-mb. heights in meters,
DP_i, DH_i, and DZ_i	1000-, 700-, and 500-mb. 24-hr. height changes in meters,
TZH_i, THP_i	700–500- and 1000–700-mb. thickness in meters.

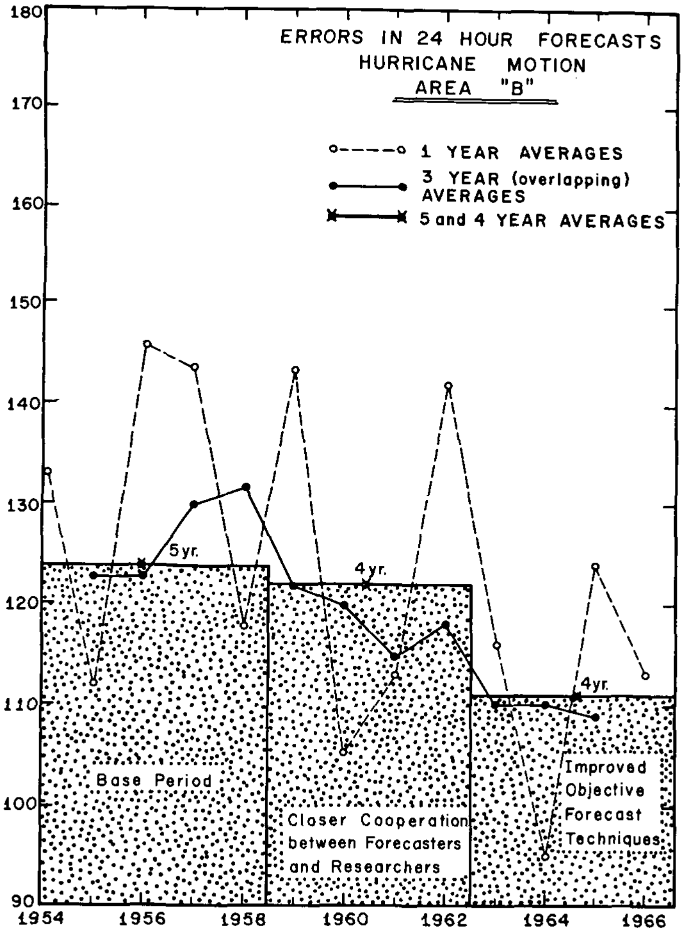

FIGURE 1.—Average forecast errors for area "B" for a 13-yr. period. Dashed line is yearly average. Solid line is 3-yr. overlapping average. Blocks indicate 5- and 4-yr. averages.

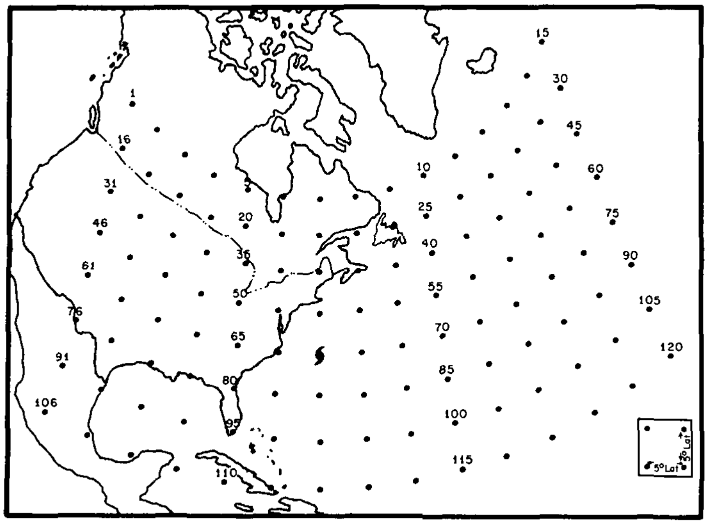

FIGURE 2.—The grid system.

TABLE 1.—*Locations of grid points used in computing (a) average height changes, and (b) the u-, and (c) the v-wind components*

(a)

AVERAGE CHANGES	FOR GRID POINTS
$\overline{DZ}_0$	35, 50, 65, 80
$\overline{DZ}_1$	36, 51, 66, 81
$\overline{DZ}_3$	39, 54, 69, 84
$\overline{DZ}_4$	50, 51, 52, 53, 54
$\overline{DZ}_5$	35, 36, 37, 38, 39
$\overline{DZ}_6$	5, 20, 35, 50
$\overline{DZ}_7$	34, 35, 36, 37, 38
$\overline{DZ}_8$	6, 21, 36, 51, 66
$C\overline{DH}$	$(\overline{DH}_3-\overline{DH}_0)$

(b)

u-WIND COMPONENTS (kt.)	CALCULATED FROM AVERAGE HEIGHTS AT GRID POINTS
u_1	(35, 36, 37, 38, 39) – (50, 51, 52, 53, 54)
u_2	(80, 81, 82, 83, 84) – (95, 96, 97, 98, 99)
u_3	(35, 36, 37, 38, 39) – (95, 96, 97, 98, 99)
u_4	(35, 36, 37, 38, 39) – (80, 81, 82, 83, 84)
u_6	(20, 21, 22, 23, 24) – (50, 51, 52, 53, 54)
$\bar{u}$	$(u_1+u_2)/2$

(c)

v-WIND COMPONENTS (kt.)	CALCULATED FROM AVERAGE HEIGHTS AT GRID POINTS
v_1	(39, 54, 69, 84, 99) – (35, 50, 65, 80, 95)
v_2	(38, 53, 68, 83, 98) – (36, 51, 66, 81, 96)
v_5	(9, 24, 39, 54, 69) – (5, 20, 35, 50, 65)
v_6	(21, 36, 51, 66, 81) – (18, 33, 48, 63, 78)
v_7	(26, 41, 56, 71, 86) – (23, 38, 53, 68, 83)
v_8	(39, 54, 69, 84) – (35, 50, 65, 80)
v_9	(6, 21, 36, 51) – (3, 18, 33, 48)

The height changes at the three levels were relative to the center of the hurricane, i.e., the grid moved with the storm.

Geostrophic wind components were computed from the heights at the three levels. These were defined as follows, the j-index referring to the array of points used in making the computations. These arrays are listed in table 1.

Pu_j, Pv_j	u- and v-components at the 1000-mb. level,
Hu_j, Hv_j	u- and v-components at the 700-mb. level,
Zu_j, Zv_j	u- and v-components at the 500-mb. level,
$TZHu_j$, $TZHv_u$	thermal winds computed from 700–500-mb. thickness,
$THPu_j$, $THPv_j$	thermal winds computed from the 1000–700-mb. thickness,
$\overline{DP_k}$, $\overline{DH_k}$, and $\overline{DZ_k}$	are average height changes at a number of grid points at the 1000-, 700-, and 500-mb. surfaces. The locations of the points are listed in table 1.

L is an operator defined as $s^2\nabla^2$, ∇^2 being the horizontal Laplacian operator, and s the distance between grid points. L was applied to heights, height changes, thicknesses, and to $\overline{Z}_i$, the arithmetical average of the 1000-, 700-, and 500-mb. heights. The i-index refers to the central point used in making the calculation. For example

$$LDP_{22}=(DP_7+DP_{23}+DP_{37}+DP_{21}-4DP_{22}).$$

These predictors were included because of their obvious relationship to the geostrophic vorticity and to the vorticity advection. Some of them were selected during the screening process. P_x and P_y are the past 12-hr. movement of the center in nautical miles, with westward and northward being positive.

3. THE REVISED FORECAST EQUATIONS

Equations were derived to forecast the northward and the westward movement of the hurricane center for periods up to 48 hr. in 12-hr. steps as was done in the earlier work. The NHC has an operational requirement to issue 72-hr. forecasts, and equations were derived to make the 48–72 hr. forecast, but the authors feel that these equations are of questionable value, and they will not be discussed here.

The initial stratification of the data continued to be according to latitude, with 27.5°N. (which is in the South Zone) being the dividing line. This stratification is done primarily to make some use of the different climatology of the two zones. It is also dictated by the fact that many of the data for the southern portion of the grid are missing in the South Zone, and stratification permits the use of many more data points in the North Zone than would be possible if all latitudes were screened at once.

The North Zone equations were derived in the following way: An initial screening was done using all available data (236 cases). A preliminary 24-hr. forecast was then prepared, using the dependent data sample. For cases where the initial forecast speed was 7.0 kt. or more (165 cases), the data were screened again to develop a set of fast equations. From those cases where the preliminary forecast was less than 13.0 kt. (165 cases), a set of slow equations was derived. In operational usage, the preliminary equations were applied if the initial forecast was equal to or greater than 7.0 kt., but less than 13.0 kt. The slow equations were used if the initial forecast was less than 7.0 kt., and the fast equations were used if the preliminary equations forecast 13.0 kt. or more. This procedure was adopted on the theory that certain predictors would be selected in different order, or given different weights when used to forecast slow moving and fast moving storms. It was also reasoned that such a stratification would be helpful in forecasting the extreme cases, which statistical methods frequently fail to do. It was also felt that this procedure would result in a crude classification according to synoptic types in a manner similar to the more elaborate scheme proposed by Tse [4] for typhoon forecasting in the Pacific area.

The screening process was terminated when a maximum number of 15 predictors had been selected, or when the F-ratio became less than 1.0. The screening program used, however, writes the regression equations following the selection of each predictor. As a general rule the equation selected for operational testing was the last one which resulted in a reduction of the unexplained variance by 1.0 percent or more, although a few predictors were retained which resulted in a reduction of variance of less than 1.0 percent. The list of predictors (in the order selected), the forecast equations, the reductions in variance contributed by each predictor, and the residual errors for the three sets of equations are listed in table 2. It will be noted that there are several significant differences in selection of predictors and the contribution each makes to the reduction in variance. For example in the 00–12-hr. west equations, the past motion, P_x, contributes 75.5 percent to the reduction in the fast equations, but only 42.0 percent in the slow set. In the 12–24-hr. north equations $\overline{DZ}_0$ was selected first in the preliminary and in the fast equations, but in the slow equations PV_6 was the first to be selected. In the 12–24-hr. west equations, HU_3 contributed 63.6 percent to the reduction in variance in the fast set, but only 43.6 percent in the slow set. A careful examination of table 2 will reveal numerous other differences of this nature.

For the South Zone a preliminary set of equations was obtained by screening the 224 available cases. A second screening was also done in an effort to improve the forecasting of the slow, or erratically moving hurricanes, such as Flora (1963), Ginny (1963), Betsy (1965), and Inez (1966). Bases for selection of these cases were: Past motion or preliminary forecast equal to or less than 6.0 kt., DZ_{37} was +10 m. or more, and HV_7 was 0.0 kt. or less. A total of 135 cases fell within this group. The second set has been termed the slow equations, although some hurricanes with predominantly fast westward motion may also be included, as for example when Z_{37} is above normal and rising. The pertinent data for these two sets of equations are listed in table 3. As in the North Zone, there are numerous differences between the two sets of equations. In the 12–24-hr. west preliminary equations Z_{37} was selected first and contributed 64.3 percent to the reduction in variance, while in the slow equation P_x was selected first, contributing 62.7 percent to the reduction in variance. In the 24–36-hr. north equations, DZ_{50} was selected first in the preliminary set, while PV_8 was picked first in the slow set. In the 24–36-hr. west equations, Z_{37} was picked first in the preliminary set, while ZU_4 was first in the slow set, in which Z_{37} was selected eighth. A comparison between the accuracy of the forecasts prepared by the preliminary equations and those prepared by the several optional sets will be presented in a later section.

The earlier paper by Miller and Chase [2] discussed possible physical relationships between the predictors selected by the screening process and predicted tracks. The current study has more or less confirmed the conclusions based on the earlier one, without indicating much additional information concerning the physical interpretation of the results of the screening. For this reason only a brief summary will be repeated here.

Figure 3 shows the location of the 24-hr. height changes selected as predictors. They are listed without regard to level, since changes at the three levels are highly correlated with each other. In the interest of simplicity

TABLE 2.—*The North Zone prediction equations, reductions in variance, and residual errors for (a) 00–12 hr., (b) 12–24 hr., (c) 24–36 hr., and (d) 36–48 hr.*

(a)

NORTH ZONE

PRELIMINARY			FAST			SLOW		
Constants	Predictor	PR	Constants	Predictor	PR	Constants	Predictor	PR
			00–12 H R. North					
+47.493		63.2	+752.8			−546.44		
+0.50152	P_{-}	63.2	+0.48027	P_{-}	56.7	+0.42563	P_{-}	52.7
+0.26199	$C\overline{DH}$	5.4	−0.51874	DP_{66}	6.5	+1.3698	PV_2	5.9
−0.42031	P_{51}	3.0	+0.95792	DP_{97}	3.2	−0.61958	DZ_{65}	3.6
+0.29121	P_{49}	1.9	+0.12487	$C\overline{DH}$	2.8	+0.59878	DP_{85}	3.4
+0.17566	DZ_{22}	1.6	+0.32960	Z_{62}	2.1	+0.10192	Z_1	1.9
+0.77655	DP_{97}	1.7	−0.31121	Z_{66}	3.3	+0.52686	DP_{97}	1.8
−0.31470	DZ_{65}	1.0	+0.63488	DP_{85}	1.7	−0.37467	DZ_{66}	1.6
+2.9216	PV_2	1.2	+1.9198	$Z\overline{\mathrm{C}}$	1.1	+0.14583	DZ_{22}	1.6
+0.58470	DP_{85}	1.1	−0.41479	$\overline{DZ}_0$	1.5	+0.096292	LDP_{22}	1.5
−0.43820	$\overline{DZ}_1$	1.0	−0.25778	H_{51}	.7	+1.5978	ZV_2	.9
Total P R		81.1	Total P R		79.6	Total P R		74.9
Residual Error		32.5	Residual Error		31.8	Residual Error		29.8
			00–12 H R. West					
−44.713			−11.619			−648.74		
+0.57627	P°	73.0	+0.59729	P°	75.6	+0.63028	P°	42.0
+0.19092	DZ_{37}	7.2	+0.15077	DZ_{37}	6.0	+0.20609	DZ_{37}	28.0
+3.2734	HC_5	1.8.	−0.29446	$L\overline{Z}_{59}$	2.0	+4.8303	HC_5	2.6
−1.0562	DP_{97}	1.3	−0.98755	DP_{97}	1.7	−2.1141	$Z\overline{\mathrm{C}}$	1.3
+0.38602	DZ_{53}	1.4	+3.9767	HC_3	1.1	+1.353	ZV_6	1.2
+0.33094	P_{53}	.8	+0.5331	DZ_{52}	1.0	+0.35494	DP_{63}	1.6
			−0.33286	DZ_{66}	.7	−0.57743	DP_{97}	1.5
						+0.22279	TZH_{21}	1.2
						+0.28113	P_{53}	.8
Total P R		85.5	Total P R		88.0	Total P R		80.2
Residual Error		38.0	Residual Error		37.0	Residual Error		30.0

(b)

NORTH ZONE

PRELIMINARY			FAST			SLOW		
Constants	Predictor	PR	Constants	Predictor	PR	Constants	Predictor	PR
			12–24 HR. North					
−815.81			−901.76			−59.174		
−0.92343	$\overline{DZ}_0$	37.8	−0.98261	$\overline{DZ}_0$	34.7	+5.2997	PV_2	20.9
+0.82225	Z_{62}	9.8	+0.28125	Z_{61}	12.1	−0.45131	DZ_{65}	12.5
−0.83429	Z_{51}	9.3	−0.97737	Z_{51}	10.2	+0.2816	P_y	6.6
+4.1589	HV_1	6.5	+3.635	ZU_3	5.4	+2.574	PV_7	4.5
−0.10116	DZ_{12}	2.6	+0.38312	Z_{85}	4.2	+0.46533	H_{63}	3.4
+0.39802	H_{72}	1.8	+0.12775	Z_1	2.5	+0.33777	DZ_{22}	3.2
+0.32614	TZH_{21}	1.1	+0.9072	DP_{97}	1.7	−0.17088	H_7	4.1
−0.11885	LTH_{37}	1.3	+0.35485	Z_{62}	1.0	+0.12937	Z_1	2.6
+0.10818	DZ_2	.9	−0.10522	DZ_{11}	1.1	+0.74399	DP_{97}	2.3
+0.56045	DP_{97}	.9	+0.21671	DZ_{23}	1.0	−0.68974	$\overline{DH}_0$	2.5
			+2.5399	PV_7	1.1	−0.59106	TZH_{50}	2.2
			−0.3918	DZ_{53}	1.4	−0.34443	DZ_{66}	1.4
Total PR.......		72.0	Total PR.......		76.4	Total PR.......		66.2
Residual Error.		47.7	Residual Error..		43.5	Residual Error..		36.3
			12–24 HR. West					
+1554.5			+3761.8			−292.74		
+5.2225	HU_3	60.3	+11.239	HU_3	63.6	+5.197	HU_3	43.6
−0.30313	Z_{61}	5.7	−0.96613	DP_{100}	5.1	+0.23119	DZ_{37}	6.9
−0.94227	DP_{100}	4.2	−0.47711	Z_{61}	5.5	−0.40007	P_x	3.9
+0.33933	DZ_{52}	2.1	+0.72725	P_{53}	1.1	−2.7034	ZV_1	2.8
−0.094448	$L\overline{Z}_{34}$	1.6	+0.13263	H_{27}	1.1	−0.19597	Z_{32}	3.3
+0.53241	TZH_{21}	1.3	−1.0868	DZ_{65}	1.1	+0.53763	TZH_{21}	2.2
+0.40085	P_{49}	1.0	+0.92752	$\overline{DH}_1$	1.3	+0.33108	DP_{49}	3.2
−0.30444	$L\overline{Z}_{22}$	.9	−0.45474	H_{85}	.9	−0.44652	DP_{100}	1.7
+0.27210	P_x	1.2	−0.29999	P_{61}	.8	+0.30405	P_{49}	1.5
+0.53753	DH_{54}	.9				+0.17481	DH_{27}	1.3
−0.39494	H_{69}	1.0				−0.30975	P_{61}	1.3
						+0.41775	DP_{53}	1.3
Total PR.......		80.2	Total PR.......		80.5	Total PR.......		73.0
Residual Error.		49.1	Residual Error..		50.9	Residual Error..		38.2

(c)

NORTH ZONE

PRELIMINARY			FAST			SLOW		
Constants	Predictor	PR	Constants	Predictor	PR	Constants	Predictor	PR
			24–36 HR. North					
−2075.2			+224.01			−2030.7		
−8.5094	HV_6	33.8	−3.0472	HV_6	38.7	+0.6634	H_{61}	15.4
−1.1624	$\overline{DZ}_0$	13.7	−1.8392	$\overline{HZ}_0$	9.2	−0.50297	$\overline{DZ}_0$	15.0
+0.3691	H_{61}	6.8	+1.0738	H_{61}	8.5	+0.5006	P_{56}	8.2
+0.41826	P_{56}	2.2	−0.41565	Z_{51}	3.3	−4.9870	PV_6	7.2
−0.73599	Z_{51}	2.5	+0.24147	P_{43}	2.2	+0.84256	THP_{61}	2.9
+0.89164	Z_{62}	2.9	+0.13821	Z_1	1.6	−0.96615	TZH_{50}	2.8
+5.3173	ZV_6	2.3	+0.65939	DH_{48}	1.3	−1.1273	$\overline{DP}_0$	2.0
−0.092888	DZ_{11}	1.2	−0.14381	DZ_{11}	1.3	+0.37032	DP_{37}	2.3
+0.13974	DZ_{22}	.7	+0.76924	TZP_{61}	1.3	+0.16761	Z_1	1.6
			+0.77871	• P_{103}	1.2	−0.16867	Z_{32}	1.8
			−0.8931	H_{97}	1.5	−0.10078	DZ_{12}	1.6
			−0.22045	Z_{32}	1.0	−2.9093	HU_3	1.6
Total PR.......		66.1	Total PR.......		71.1	Total PR.......		62.4
Residual Error.		62.6	Residual Error..		59.0	Residual Error..		47.0
			24–36 HR. West					
+1055.6			+2079.0			+84.937		
+10.974	HU_3	44.6	+14.23	HU_3	44.8	+2.5492	HU_3	27.6
−0.85890	H_{61}	6.8	−1.1053	H_{69}	6.3	+0.086081	$\overline{DZ}_5$	10.2
−0.31978	P_y	5.3	−0.61087	DP_{100}	2.9	−0.12757	Z_1	6.0
+0.25335	H_{27}	2.8	+0.83199	$\overline{DP}_4$	3.3	+0.79196	TZH_{21}	4.0
−1.5016	DP_{85}	2.4	−1.4886	DP_{85}	2.0	+0.13829	DZ_{12}	4.1
+1.1483	$\overline{DP}_1$	3.3	−0.92543	H_{61}	2.0	+0.85164	$\overline{DP}_5$	4.0
−0.41766	$L\overline{Z}_{22}$	1.3	+0.27427	H_{27}	2.1	−0.7660	H_{85}	2.5
			+1.1053	H_{96}	2.2	−0.27176	Z_{32}	2.2
−5.9910	$P\overline{U}$	1.7	−0.20585	$L\overline{Z}_{34}$	1.2	−0.65989	DP_{100}	1.3
			+1.0003	DP_{66}	1.3	+0.26415	P_{49}	1.8
+0.84567	P_{49}	1.4	−0.82909	DH_{65}	1.1	+0.41592	P_{56}	1.4
+0.28050	TZH_5	1.4	+0.74772	DH_{99}	.9	+0.76822	H_{36}	2.0
Total PR.......		71.0	Total PR.......		70.1	Total PR.......		67.1
Residual Error.		67.8	Residual Error..		70.1	Residual Error..		55.0

(d)

NORTH ZONE

PRELIMINARY			FAST			SLOW		
Constants	Predictor	PR	Constants	Predictor	PR	Constants	Predictor	PR
			36–48 HR. North					
−3441.7			−3940.8			−1494.2		
−1.2968	HV_6	34.0	−2.2079	HV_6	37.1	−6.5677	PV_6	23.0
+0.75930	H_{61}	6.0	+0.42869	H_{61}	6.2	+0.27363	THP_{61}	12.7
−1.1059	$\overline{DZ}_0$	5.7	−0.57348	DH_{35}	4.6	+0.41244	P_{56}	6.7
−0.21306	Z_{32}	2.7	−7.3692	PV_6	1.9	−0.8197	$\overline{DZ}_0$	3.8
+0.14115	Z_1	2.0	+0.13857	LDZ_{37}	1.6	+0.66174	H_{63}	2.6
+0.72878	H_{63}	1.2	+0.29366	P_{43}	2.1	−0.33875	THP_6	2.6
−4.9977	PV_6	1.2	+0.75892	H_{85}	1.1	+3.0312	PV_5	1.9
+3.2903	PV_7	1.5	−0.77482	P_{83}	1.2	−1.2411	TZH_{50}	1.3
+0.14843	LDZ_{37}	1.2	−0.6216	TZH_{50}	.8	+0.21064	Z_1	2.2
+0.22816	DZ_{22}	.8	+0.63618	H_{63}	1.4	−9.6185	$TZHV_1$	1.9
−0.24354	THP_6	.9				+0.48465	Z_{61}	1.6
						−0.19113	Z_{32}	1.3
Total PR.......		57.2	Total PR.......		58.0	Total PR.......		61.6
Residual Error.		77.3	Residual Error..		81.2	Residual Error..		57.5
			36–48 HR. West					
+4580.9			+7941.5			+2259.1		
+12.492	HU_3	22.1	+10.915	HU_3	16.9	+0.50384	$\overline{DH}_5$	20.0
−8.4143	ZV_1	9.0	−1.6831	H_{69}	7.4	−0.9729	H_{85}	11.4
−1.0376	H_{63}	4.2	+0.18143	DH_{35}	4.5	+1.9483	PV_6	7.6
+0.38883	P_{43}	4.4	−1.9957	DP_{100}	3.6	−0.35037	DZ_2	3.1
+0.40390	P_{49}	3.7	+0.31735	LDZ_{37}	3.8	+0.95705	H_{36}	3.3
+0.19519	DZ_{12}	3.1	+0.78005	$\overline{DP}_4$	3.9	−0.36339	Z_{32}	2.9
+0.55637	$L\overline{Z}_{37}$	2.6	+1.4455	DH_{99}	2.8	+0.67434	DH_{19}	4.3
−0.50728	H_{32}	1.7	−0.35117	DP_{19}	1.7	+0.27522	P_{43}	3.1
−1.4669	DP_{85}	1.5	+1.1745	H_{97}	2.1	−1.0226	DP_{100}	2.6
+1.4251	$\overline{DP}_4$	2.8	−0.60277	Z_{61}	1.9	−0.24927	LDP_{22}	1.7
−0.21634	DZ_2	1.6	+0.24899	H_{27}	1.8	+0.54821	TZH_{21}	1.8
+0.48948	H_{33}	.9	−5.1532	$THPV_2$	1.8	−0.60181	TZH_{61}	1.7
Total PR.......		57.6	Total PR.......		52.2	Total PR.......		63.5
Residual Error.		88.2	Residual Error..		94.0	Residual Error..		70.3

TABLE 3.—*The South Zone prediction equations, reductions in variance, and residual errors for (a) 00–12 hr., (b) 12–24 hr., (c) 24–36 hr., and (d) 36–48 hr.*

(a)

SOUTH ZONE

PRELIMINARY			SLOW		
Constants	Predictors	PR	Constants	Predictors	PR
		00–12 HR. North			
+1550.2			+2390.0		
+0.55007	P_y	49.9	+0.59127	P_y	47.7
+0.45467	$\overline{CDH}$	6.3	+0.40824	$\overline{CDH}$	8.9
+3.7022	ZV_8	2.5	−0.28954	H_{66}	3.1
−0.27583	Z_{52}	2.2	+5.4717	PV_8	2.9
+0.24827	THP_{21}	1.7	+0.19110	P_{32}	1.4
−0.076947	DZ_9	1.4	−0.10786	DZ_3	1.6
−0.43533	DP_{52}	1.0	−0.19843	H_{55}	0.9
−0.21738	THP_{39}	1.1	−0.3195	TZH_{65}	.9
+0.34774	DP_{69}	1.0	−0.10435	DP_3	1.1
			−0.12293	LDP_{37}	.9
Total PR		67.1	Total PR		69.4
Residual Error		29.5	Residual Error		26.2
		00–12 HR. West			
−721.73			−2709.5		
+0.71343	P_x	80.1	+0.8155	P_x	79.8
+0.32232	Z_{37}	4.3	+0.5766	Z_{37}	3.9
+2.0646	ZU_4	.7	−0.24394	P_y	1.1
−0.38533	THP_{53}	.5	−0.10821	Z_3	.8
			−0.33593	P_{51}	1.1
Total PR		85.6	Total PR		86.7
Residual Error		32.3	Residual Error		30.0

(b)

SOUTH ZONE

PRELIMINARY			SLOW		
Constants	Predictors	PR	Constants	Predictors	PR
		12–24 HR. North			
−525.64			+147.45		
+0.37325	P_y	21.7	+0.35775	P_y	22.7
+0.27305	$\overline{CDH}$	10.2	+0.37934	$\overline{CDH}$	10.7
−0.92868	P_{51}	5.5	−0.59733	Z_{66}	7.5
+0.58039	P_{85}	4.6	+0.54208	H_{85}	4.7
+0.16179	DP_{31}	1.9	−0.36792	P_{34}	4.5
−0.51655	DZ_{50}	1.7	−0.2455	$\overline{DZ_6}$	2.8
+0.18336	H_7	2.0	+0.24343	Z_{33}	2.5
+0.15437	P_1	1.3	+0.56513	DP_{83}	1.6
−0.21593	DP_3	1.4	+0.19302	PU_6	1.1
−0.18710	LDP_{37}	1.1	+0.361	TZH_{39}	1.1
+0.57359	DP_{83}	1.3	−3.1362	ZU_4	1.6
+0.16376	P_3	1.2	+1.7392	ZU_6	3.1
Total PR		53.9	Total PR		63.9
Residual Error		38.9	Residual Error		31.5
		12–24 HR. West			
−3005.9			+1439.3		
+0.66113	Z_{37}	64.3	+0.60239	P_x	62.7
+0.48872	P_x	6.8	+0.71495	DZ_{37}	9.7
−0.23875	Z_{68}	2.9	+5.8076	HU_4	3.6
+0.36629	$\overline{DZ_7}$	1.7	−0.31677	P_y	1.8
−0.23531	P_y	.8	−0.53323	TZH_{65}	1.1
+0.43295	DP_{39}	1.3	−1.6157	HU_6	.8
+0.094287	Z_{11}	1.0			
Total PR		78.8	Total PR		79.7
Residual Error		41.2	Residual Error		39.7

(c)

SOUTH ZONE

PRELIMINARY			SLOW		
Constants	Predictors	PR	Constants	Predictors	PR
		24–36 HR. North			
−766.4			+2418.2		
−1.0599	DZ_{50}	14.0	+7.6275	PV_8	14.2
+0.6745	DP_{69}	10.1	−0.85282	Z_{52}	15.2
+0.38623	P_3	5.9	+0.5441	$\overline{CDH}$	5.9
−0.85932	P_{51}	6.0	+0.40702	DP_{33}	3.2
+0.42869	P_{85}	4.0	−0.27937	DZ_3	5.2
+2.2312	ZV_9	3.0	+0.62506	Z_{48}	3.0
−0.19262	DP_{12}	2.4	−0.6847	TZH_{19}	2.0
+0.23933	P_y	1.3	+0.1528	Z_7	2.8
+0.59736	Z_{48}	1.4	−0.47545	P_{39}	3.1
−0.71545	H_{65}	2.4	+2.7858	ZV_8	1.7
+0.15588	DP_7	1.3	+2.444	DZ_{12}	1.2
−0.15622	TZH_{11}	1.0	−0.22996	DH_{12}	1.8
Total PR		52.8	Total PR		59.3
Residual Error		46.6	Residual Error		41.8
		24–36 HR. West			
−1620.6			−932.73		
+1.1942	Z_{37}	47.3	+3.3029	ZU_4	46.7
+0.35215	DH_{21}	5.8	+0.35589	P_x	9.3
+0.29778	P_x	3.9	−0.28462	P_y	5.0
−0.30335	P_y	2.6	+0.73942	DH_{37}	4.2
+0.77356	DP_{39}	2.8	−0.66513	Z_{23}	1.8
+0.18323	Z_{11}	2.2	+0.46809	LDP_{50}	1.4
−1.2549	THP_{65}	1.5	−0.39446	H_3	2.0
+0.56887	THP_{50}	1.9	+0.63606	Z_{37}	1.3
−0.20348	DP_3	1.1	+0.21029	Z_{11}	1.1
−0.72896	DP_{83}	1.0	−0.2111	DP_{12}	1.5
−0.28327	Z_{23}	1.1	+0.19355	Z_7	1.0
−0.45057	Z_{52}	.9	+0.28545	DH_3	1.4
Total PR		72.1	Total PR		76.7
Residual Error		47.7	Residual Error		41.3

(d)

SOUTH ZONE

PRELIMINARY			SLOW		
Constants	Predictors	PR	Constants	Predictors	PR
		36–48 HR. North			
−472.61			+599.53		
−0.9788	DZ_{50}	11.3	+10.203	PV_8	11.6
+1.1486	DP_{69}	9.4	−0.63278	Z_{52}	13.5
+0.39703	P_3	5.7	−0.40356	TZH_3	5.0
−0.21431	P_{34}	4.6	+0.25333	Z_7	4.4
+0.18737	DP_7	3.4	−0.25188	P_{11}	3.4
−0.43214	DZ_{66}	1.6	+1.0105	Z_{48}	3.3
−0.78758	THP_{70}	1.8	−1.3737	TZH_{35}	3.6
−1.154	P_{51}	2.3	−0.56358	P_{53}	3.2
+0.60606	P_{85}	3.5	+0.42006	DP_7	2.2
+0.17605	H_7	1.8	−0.57729	DH_{21}	4.0
−0.21879	P_{11}	1.8	+0.71462	TZH_{37}	2.1
+0.42226	Z_{48}	2.3	−0.40231	H_{66}	1.4
Total PR		49.5	Total PR		57.7
Residual Error		57.2	Residual Error		51.9
		36–48 HR West			
−843.17			−1834.6		
+3.422	ZU_4	31.9	+4.8154	ZU_4	36.2
+0.99921	$\overline{DZ_8}$	6.8	−0.26804	THP_8	6.6
+0.74922	P_{49}	4.5	+0.19759	P_x	5.9
−1.4169	DP_{69}	3.7	+0.032765	P_y	3.5
+0.62923	DH_3	2.3	+0.5783	$\overline{DZ_7}$	2.0
−0.44829	P_3	4.3	−1.5834	DP_{69}	2.6
+0.76767	DP_{39}	2.6	+0.6561	DH_3	1.3
+0.27694	H_{11}	2.3	−0.40252	P_3	2.8
−0.29709	LZ_{37}	1.6	+0.45654	Z_{48}	1.6
−0.27220	P_5	1.4	+0.17732	DZ_7	1.8
			+0.72586	$\overline{DP_7}$	1.2
			−0.14129	DZ_9	1.3
Total PR		61.4	Total PR		66.8
Residual Error		61.1	Residual Error		51.5

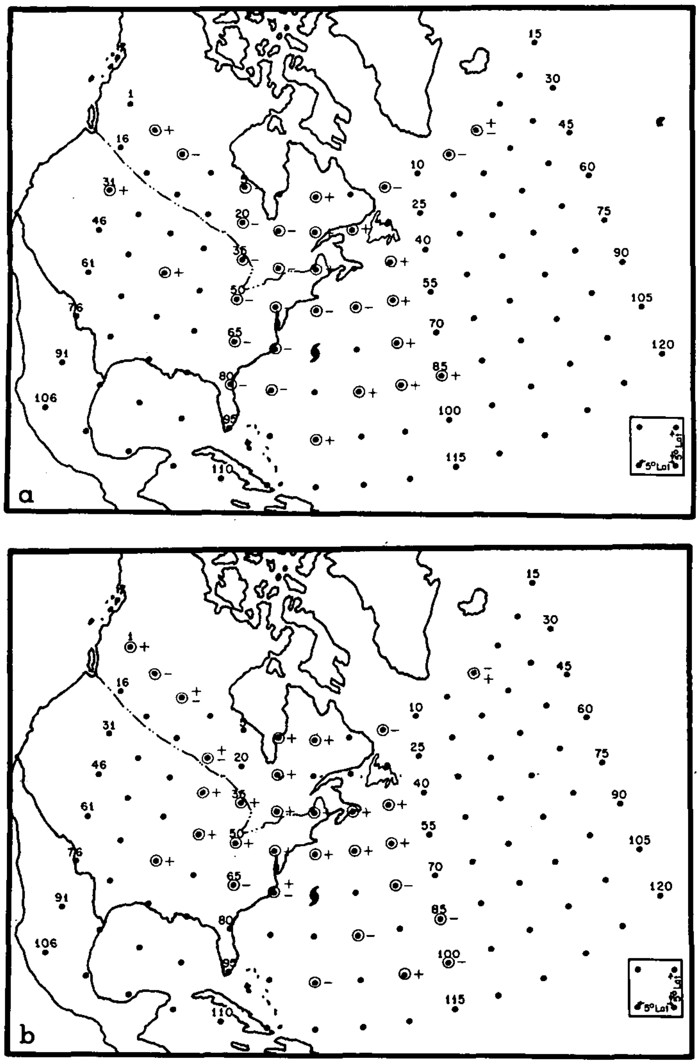

FIGURE 3.—Height changes selected to forecast a) northward movement and b) westward movement.

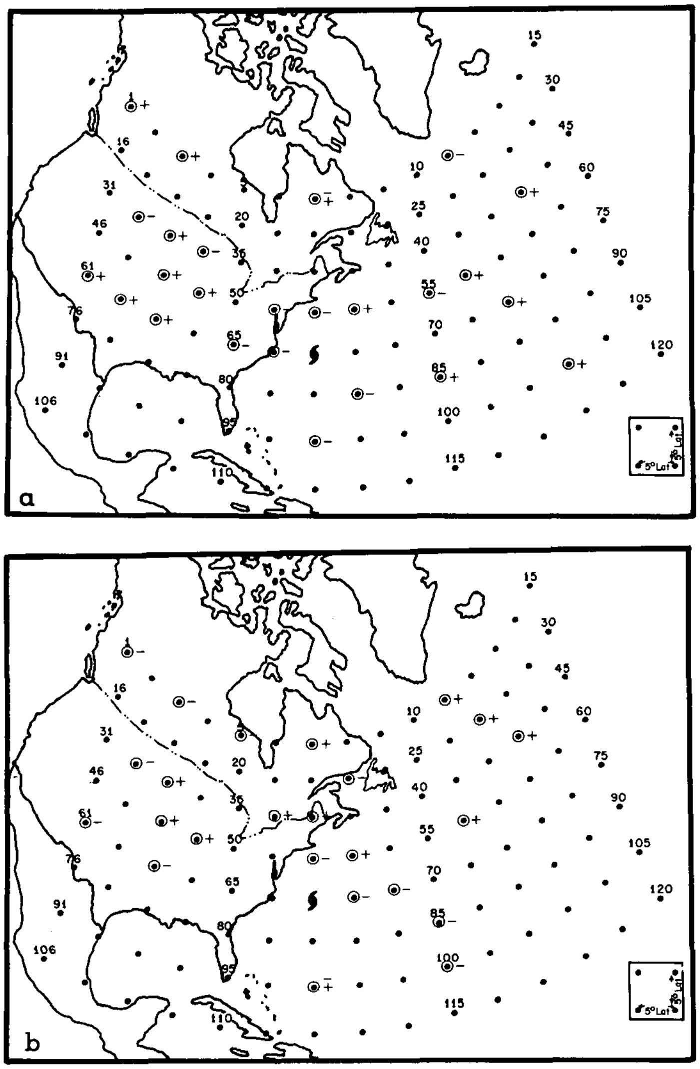

FIGURE 4.—Heights selected to forecast a) northward movement and b) westward movement.

no differentiation is made regarding forecast period to which each applies. Many of the changes were selected more than once, but this is not indicated for cases where the coefficients of the predictor had the same sign every time it was selected. The sign, + or — by the grid point indicates the sign of the coefficient of that predictor in the forecast equations.

Figure 3a indicates that in general rises to the south or east and falls to the north and west are associated with northward movement. One exception (also noted in the NHC-64 equations) is a tendency for northward motion to be associated with rises over the extreme northwest portion of the grid and falls along the northeast portion. Both probably indicate the progression of short waves in the westerlies across the northern portion of the grid, and that the passage of the wave normally has the effect of accelerating the center northward. The tendency for northward motion to be associated with rises over the north central part of the grid is somewhat anomalous, and is perhaps a reflection of the height change pattern associated with storms moving on a northwestward track.

Figure 3b shows the changes selected for forecasting westward motion. There is nothing unexpected in this figure, since there is a tendency for westward motion to be associated with rises to the north of the center and falls to the south, while falls to the north and rises to the south are related to eastward motion.

The heights (in addition to those used in making geostrophic computations) selected as predictors in the equations for forecasting northward motion are listed in figure 4a, and those for forecasting westward motion in figure 4b. These confirm the earlier conclusion that northward motion is associated with above normal heights to the east, or well to the west of the center, and with below normal heights just north and west of the center. Southward or below normal northward progression would be associated with above normal heights to the north and west of the center, or with below normal heights several

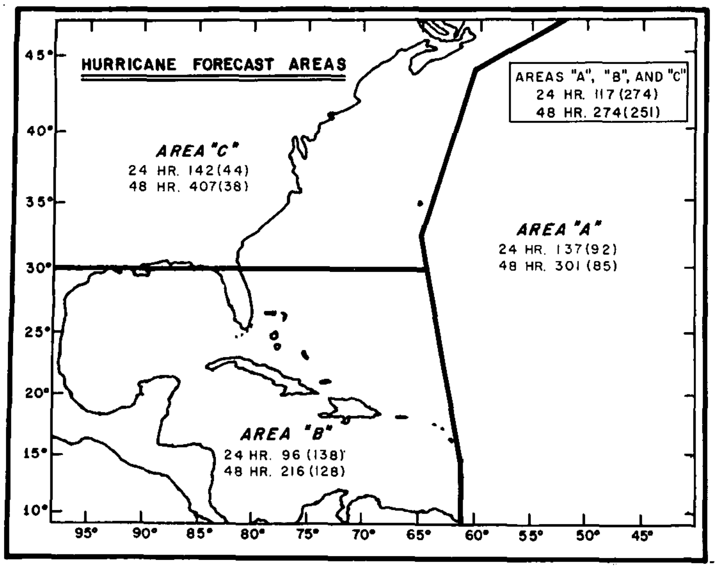

FIGURE 5.—A 4-yr. average of NHC-64 forecast errors (n.mi.). Numbers in parentheses indicate sample size.

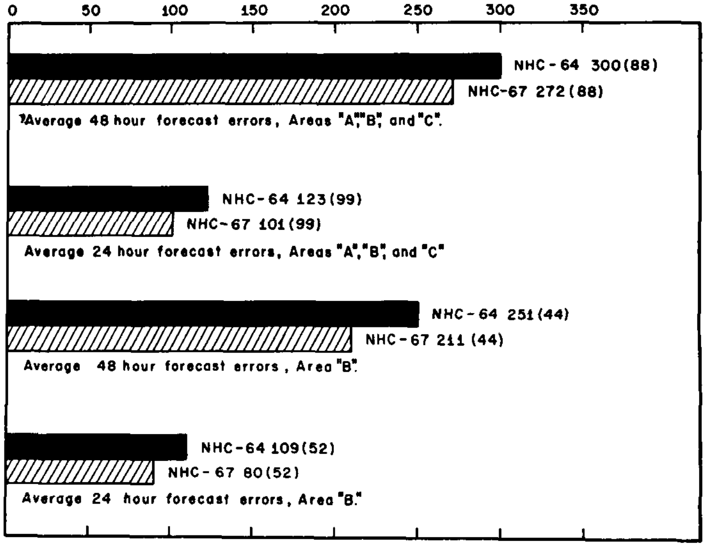

FIGURE 6.—A 2-yr. comparison between NHC-64 and NHC-67 forecast errors (n.mi.) by areas. Numbers in parentheses indicate sample size.

hundred miles to the west. Figure 4b shows that westward motion is associated with above normal heights to the north and west, while eastward movement should be expected if heights are below normal to the north or west of the center.

4. VERIFICATION OF SOME HURRICANE FORECASTS

The NHC-64 forecast equations have now been in operational use for 4 yr. Figure 5 shows a summary of the average forecast errors[1] by geographical areas. The equations have continued to produce forecasts of about the same order of accuracy indicated in the earlier report by Miller and Chase [2]. For example the overall average errors are 117 n.mi. for a 24-hr. forecast and 274 n.mi. for a 48-hr. forecast, compared with the 2-yr. averages of 109 n.mi. and 261 n.mi. In area "B" the averages for 4 yr. of operations are 96 and 216 n.mi., compared to the 2-yr. averages of 81 and 187 n.mi. reported in the previous paper. These numbers indicate that the equations are relatively stable. Much of the increase in the forecast errors is due to a few erratically moving hurricanes, e.g. Inez (1966) and Doria (1967).

Figure 6 shows a comparison between the errors in the forecasts prepared by the NHC-64 and the NHC-67 sets of equations. This is a homogenous comparison based on 1966 and 1967 data. The 1967 forecasts were operational forecasts, and the 1966 forecasts were prepared from independent data used to prepare the operational NHC-64 forecasts. The improvement appears to be significant. For example the 48-hr. errors in area "B" were reduced from 251 to 211 n.mi., while the 24-hr. forecasts were reduced from 109 to 80 n.mi. For all areas the 24-hr. errors were reduced from 123 n.mi. to 101 n.mi. (for a total of 99 forecasts).

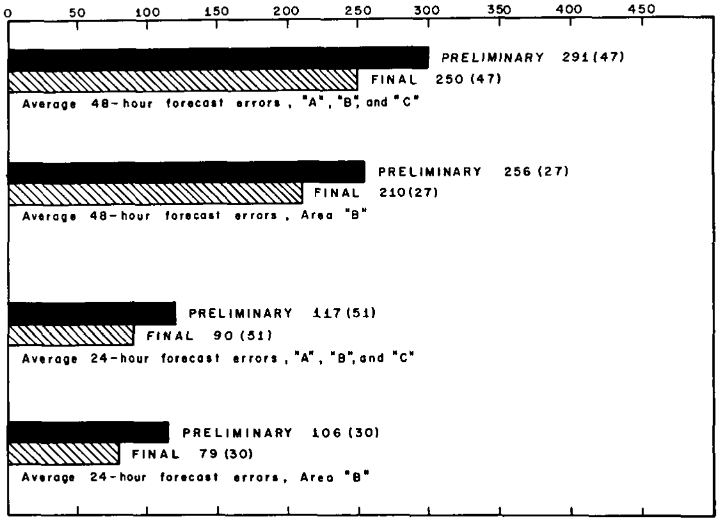

FIGURE 7.—A 2-yr. comparison between NHC-67 forecast errors (n.mi.) made by preliminary and final regression equations. Number in parentheses indicate sample size.

The question as to whether or not the stratification and rescreening described in section 3 actually improved the final forecasts may logically arise. To answer this question the forecasts for the 2 independent yr. (1966–67) were prepared in both ways. The forecasts were prepared by use of the preliminary equations only, and these have been compared with the forecasts made by the various sets of optional equations listed in tables 2 and 3. The comparisons are shown in figure 7. Only those cases when one of the alternate choices was made are considered, i.e. the forecasts compared are homogenous.

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[1] Hurricane Heidi occurred after figures 5–8 were prepared, and errors for this storm are not included in this paper.

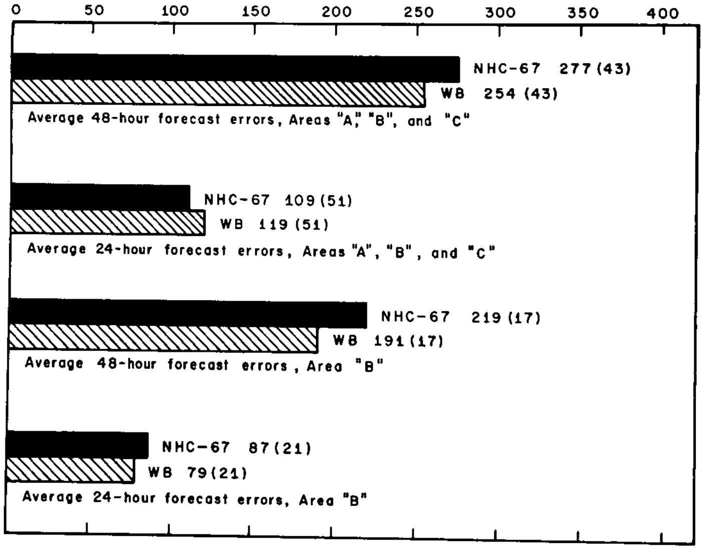

FIGURE 8.—A 1-yr. comparison between operational NHC-67 and official Weather Bureau forecast errors (n.mi.). Numbers in parentheses indicate sample size.

In all areas the average error in the final forecasts are smaller than the preliminary errors. The averaged 24-hr. errors for 51 cases for all areas was 121 n.mi. for the preliminary and 90 n.mi. for the final forecasts. In area "B" the averages were 106 n.mi. and 79 n.mi., respectively, for 30 cases. For 48-hr. forecasts the average errors (47 cases) for all areas were 299 n.mi. for the preliminary and 250 n.mi. for the final forecasts. In area "B", the averages were 256 n.mi. and 210 n.mi. for 27 cases. These numbers seem to substantiate the validity of the method used in the stratification of the developmental data.

Prior to the 1967 hurricane season, the official Weather Bureau forecasts were prepared to verify at advisory times, i.e. at 0400 GMT and at 6-hr. intervals thereafter. This made it difficult to compare the official forecasts with the objective forecasts, since the latter have always been prepared to verify at synoptic times, usually 0000 GMT and 1200 GMT only. In 1967 the Weather Bureau began to issue forecasts with the verifying time coinciding with the synoptic times. This has permitted a direct comparison of the official forecasts with the objective forecasts. One such comparison between the official forecast and the NHC-67 forecasts is presented in figure 8. This is a homogenous comparison based on all available NHC-67 forecasts prepared operationally during the 1967 season.

For a 24-hr. forecast (51 cases) for all areas, the NHC-67 average error was 109 n.mi., where the official error was 119 n.mi. For area "B", however, the official average was smaller (21 cases) being 79 n.mi. against 87 n.mi. for the NHC-67. For 48-hr. forecasts the average errors for the official forecasts were smaller in area "B" considered alone and when all areas were combined. However, in many cases the forecasters prepared the official forecast after seeing that made by the NHC-67 system.

5. SOME REMAINING PROBLEMS

While the NHC-64 equations continue to perform well after 4 yr. of operational use, and while the NHC-67 version seems to be a slight improvement over the earlier set, experience gained from the use of these methods has indicated some remaining problems. Unfortunately, however, this experience does not point to an obvious solution of the problems, and it is in fact problematical if the data situation and the nature of the statistical process will permit any great additional increase in the accuracy of such forecast techniques as the NHC-64 and NHC-67 equations. However, NHRL and NHC will continue efforts to improve these methods (while at the same time attempting to develop more satisfying dynamical hurricane prediction models), and perhaps a statement of some of the problems is in order here.

In a statistical climatological sense, to make a 48-hr. forecast it is necessary to consider data more than 2,000 mi. away from the center of the hurricane. This is indicated by figures 3 and 4. It occasionally happens that the circulation so far away has no effect on the motion of the hurricane during the 48-hr. forecast period. This happens when a series of short waves with small amplitude are moving rapidly in a predominantly strong zonal flow separated from the hurricane by a narrow ridge. In such cases too much northward motion, or a too rapid recurvature of the center may be forecast.

Another situation in which the statistical forecast systems do not do well occurs when the circulation patterns over the grid do not evolve in a normal manner (in a statistical sense), as for example, when a quasi-stationary blocking ridge is present to the north or northeast of the hurricane. This prevents the normal progression of troughs and ridges (which the statistical forecast system must consider), and an inferior forecast can result. In such cases, unfortunately, it is difficult to anticipate in what sense the forecast may be in error.

Another difficulty occurs when a small hurricane is located near or south of 15.0°N. lat. In some (but not all) of these cases, the statistical techniques tend to forecast too much northward motion as the small cyclone may not be able to break through a narrow ridge to the north. Some suggested means for correcting this deficiency are to stratify the dependent data on the basis of storm size, or derive a set of equations for storms south of 20.0°N., but it is doubtful if there are enough cases to permit any meaningful sample size. An objection to these suggestions is the fact that frequently the impulse which eventually leads to the hurricane breaking through a subtropical ridge originates in the middle latitude westerlies and not at low latitudes. Finally, problems have arisen due to the use of actual values of the heights of the constant pressure surfaces as predictors. During the latter part of the hurricane season, the heights may depart significantly from the seasonal normal, particularly over the northern portions of the grid. Perhaps more effective use could be made of departures from normal. It may also be desirable to develop a forecast system based on prognostic data as suggested by Veigas [5]. This possibility is being investigated.

While there are no immediate and obvious solutions to these problems, the authors believe that an awareness of the possible deficiencies in the NHC-64 and NHC-67 systems will enable the hurricane forecaster to derive maximum usefulness from the objective aids.

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