

U. S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service

NOAA Technical Memorandum NWS TM SR-63

A STATISTICAL METHOD OF COMBINING SYNOPTIC AND EMPIRICAL TROPICAL CYCLONE
PREDICTION SYSTEMS

Charles J. Neumann, John R. Hope, and Banner I. Miller

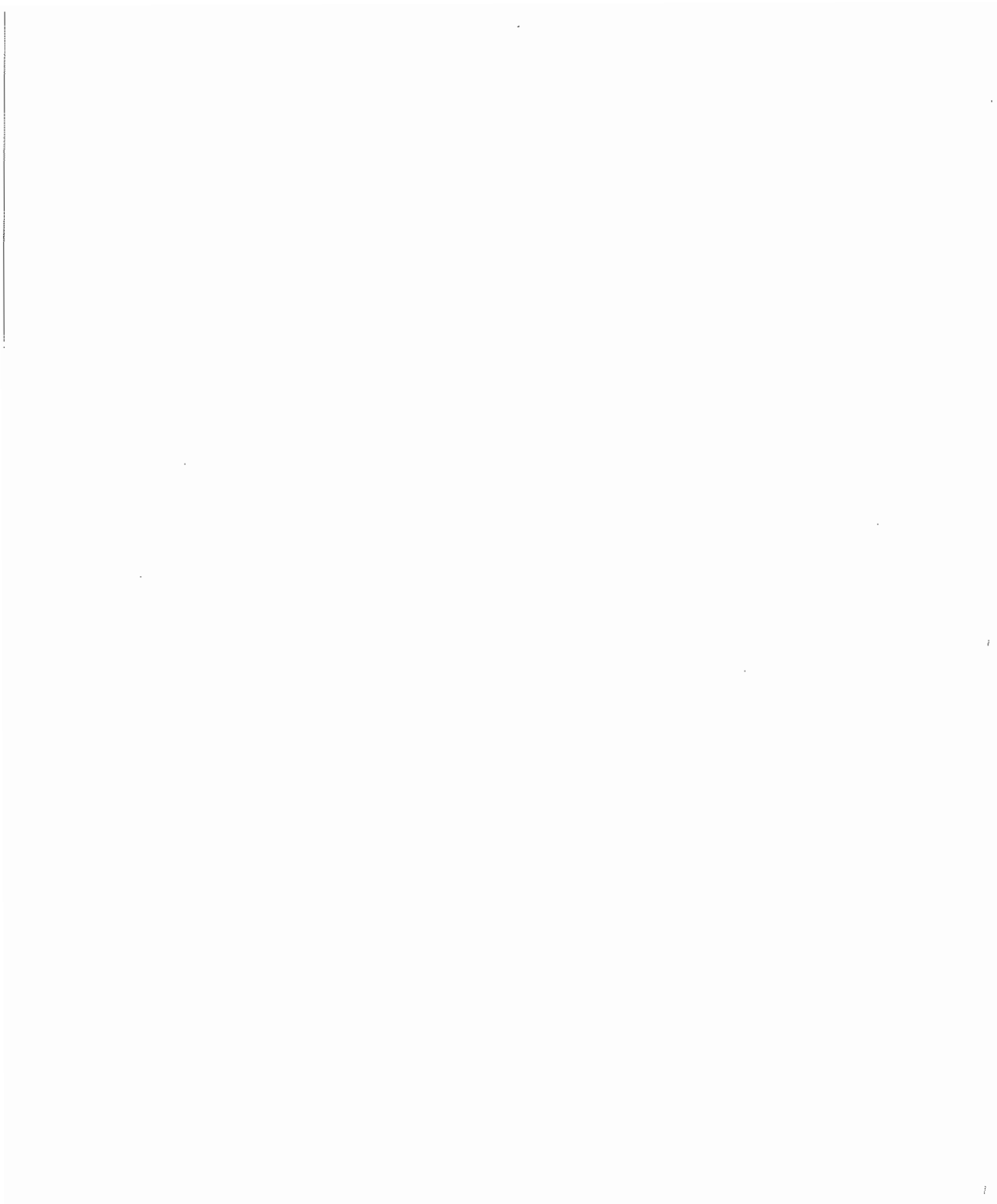
SOUTHERN REGION HEADQUARTERS
SCIENTIFIC SERVICES DIVISION
FORT WORTH, TEXAS
May 1972



A Statistical Method of Combining Synoptic and Empirical Tropical Cyclone
Prediction Systems

ABSTRACT

The National Hurricane Center uses four techniques as objective guidance preparatory to the issuance of tropical cyclone advisories. The NHC-67 and the CLIPER systems are based on a multivariate regression analysis. The former uses predictors derived primarily from observed geopotential height data. CLIPER excludes observed synoptic data but includes a more explicit use of climatology and persistence than does NHC-67. Another statistical technique, HURRAN, uses an analog approach. The fourth technique, SANBAR, uses a filtered barotropic model to predict tropical cyclone displacements. A new statistical system, NHC-72, combines the better features of NHC-67, CLIPER and HURRAN. This paper describes the derivation, application and expected errors of the NHC-72 equations.



A Statistical Method of Combining Synoptic and Empirical Tropical Cyclone
Prediction Systems

1. INTRODUCTION

A diversity of techniques for the objective forecasting of tropical cyclone motion is currently in use or under development at the National Hurricane Center (NHC). Three of these techniques, NHC-67 (Miller, et al, 1968), CLIPER (Neumann, 1972) and HURRAN (Hope and Neumann, 1970) are statistical. Another operational technique, SANBAR (Sanders and Burpee, 1968) is a filtered barotropic model while another, as yet experimental system (Miller, 1972), uses a seven-level baroclinic model to forecast changes in intensity as well as motion. While it is generally agreed that one of the latter numerical approaches will ultimately provide superior guidance, the more timely and economical statistical techniques continue to be the best immediate means of providing objective guidance preparatory to the issuance of tropical cyclone advisories. This paper describes a new statistical system, NHC-72, which combines the better features of the three statistical schemes currently in operational use at NHC.

Corzine (1964) describes a similar statistical technique which combined five of the tropical cyclone forecast systems in operational use at that time. Although based on a limited data sample and concerned only with the 24-hour forecast period, the results of Corzine's study were encouraging enough to suggest further evaluation of the principle when sufficient dependent data became available.

¹Portions of this paper presented at the Seventh Technical Conference on Hurricanes and Tropical Meteorology, Barbados, B.W.I., December 1971.

The NHC-67 system or its predecessor, NHC-64, (Miller and Chase, 1966), has been in use at NHC for a number of years. Zonal (E to W) and meridional (S to N) components of storm motion are computed from a series of multivariate regression equations derived through stepwise screening procedures using predictors from current geopotential height fields and height change fields at the 1000, 700 and 500-mb. surfaces. Although the system weights the past motion quite heavily for the initial 12-hour forecasts, this persistence is phased out gradually after 12 hours.

HURRAN is an analog system. All recorded tropical cyclone tracks subsequent to the year 1885 are computer scanned and those with time and space characteristics similar to a current storm are identified and translated to a common origin. The cluster of analog storm positions at the various time intervals are then fitted to a bivariate normal distribution, the centroids of which represent the forecast track.

CLIPER is a technique used for the first time during the 1971 hurricane season. The system makes explicit use of climatology and persistence through a series of non-linear multiple regression equations fitted essentially to the same predictors employed in the analog sense by HURRAN. Although HURRAN and CLIPER usually give similar forecast tracks, the latter has the distinct advantage of always providing a forecast whereas HURRAN fails to find sufficient analogs for a forecast in about one out of three tries.

In addition to these three statistical schemes, a filtered barotropic model, known as SANBAR, is also in operational use. The system uses input derived from observed 1000- to 100-mb. pressure weighted winds. Although some "bogus" data are required to augment the wind field in sparse data regions, the system, as originally conceived, does not use any persistence. However, Pike (1972) shows that forcing initial storm motion into the wind field substantially improved the verification statistics of SANBAR for the 1971 hurricane season.

These four operational systems represent entirely different approaches to the problem of tropical cyclone forecasting. Each is capable of producing acceptable or unacceptable forecasts and it is not at all unusual for one or more of the systems to predict widely variant tracks. Under such conditions, it is difficult for the hurricane forecaster to make a decision as to which track is likely to have minimum error. Although objective guidelines are currently being used in decision making (Simpson, 1971), the problem of which objective forecast track to follow, if any, remains as one of the critical operational decisions which confront the hurricane forecaster.

2. PROCEDURE

The NHC-72 system is based on principles discussed in Neumann and Hope, 1972, where it was demonstrated that an optimum statistical forecasting scheme must derive its variance reducing potential from both empirical and synoptic² sources. Storms with a westerly component

²In the sense used here, synoptic predictors refer to those derived from observed geopotential height data, whereas empirical predictors refer to climatology, persistence, analogs, etc.

of motion were shown to have only about 50 percent of their motion variance explained by current synoptic data. Such a situation is quite discouraging when one considers that the bulk of storms which strike land areas in the United States, Central America and the Caribbean (Hope and Neumann, 1971) are in this category. Neumann and Hope (1972a) show that the HURRAN system performs quite well on storms with a westerly component of motion. Similarly, Neumann (1971) points out that the CLIPER system, designed as an alternate to HURRAN also performs well on storms with a westerly component of motion.

The NHC-72 system computes two independent sets of forecasts, each set consisting of five pairs of zonal and meridional displacements for the periods 0 to 12 hours, 0 to 24 hours, 0 to 36 hours, 0 to 48 hours, and 0 to 72 hours. One set, hereinafter referred to as the SYNOPTIC set, is based entirely on predictors derived from observed geopotential height data; the other set, CLIPER, is based entirely on predictors derived from empirical sources. The two sets of forecasts are statistically combined into a final NHC-72 set using additional regression coefficients as weighting factors. The procedure is schematically illustrated in figure 1.

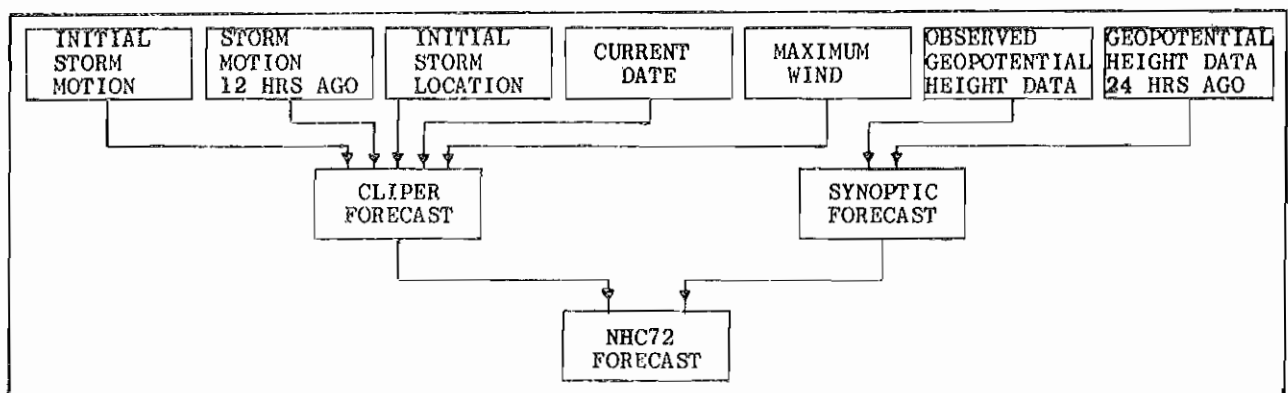


Figure 1. Schematic illustration of the NHC-72 system.

Keeping the CLIPER and SYNOPTIC forecasts as separate entities insures that all significant predictors are retained in the system. This insures that a bad persistence input will at least be partially offset by the observed surrounding synoptic data. If the CLIPER displacements or the independent variables used to compute the 12 and 24 displacements were allowable predictors in the SYNOPTIC scheme, few, if any grid-height values would be selected because of inter-correlations in the data.

3. THE CLIPER FORECASTS

The CLIPER system derives its variance reducing potential from the eight basic empirical predictors listed in Table 1. An additional 156 secondary predictors are generated by considering all of the possible second and third-order products and cross-products of the original eight predictors. The secondary predictors are of the form $P_i P_j$, $P_i P_j P_k$, $P_i P_j^2$, or P_i^3 . A stepwise screening procedure of the type described by Efroymsen (1964) was used to select that most significant of the 164 basic and higher order predictors.

Table 1. The Eight Basic Predictors of the CLIPER System

<u>P(I)</u>	<u>PREDICTOR</u>
P(1)	Initial longitude
P(2)	Initial latitude
P(3)	Initial zonal motion
P(4)	Initial meridional motion
P(5)	Zonal motion 12 hours ago
P(6)	Meridional motion 12 hours ago
P(7)	Maximum wind
P(8)	Day number

The final prediction equation, for 72 hour zonal motion (DX_{72}), for example, is given by,

$$DX_{72} = -60.3 + 46.26(P_3) - 8.81(P_5) + 29.12(P_2 - 24) + 32.91(P_4) - 0.022(P_4)^2(P_5) - 0.086(P_2 - 24)(P_4)(P_5) + 3.29(P_1 - 68) \quad (1)$$

where the predictors correspond to those given in Table 1. The complete set of prediction equations and further details on their derivation can be found in Neumann, (1972).

In spite of the lack of current synoptic data input, the CLIPER system (and HURRAN) give results quite comparable to the other statistical schemes in which climatology and persistence are used implicitly or not at all. Since most tropical cyclones behave quite normally, the explicit use of empirical predictors in CLIPER explains a considerable portion of the variance of tropical cyclone motion. Another, and perhaps equally important reason for the relative success of the CLIPER and HURRAN systems is the inability of synoptic data, as currently used, to explain instantaneous tropical cyclone motion. Neumann and Hope (1972b), for example, point out that if one knows the current synoptic geopotential height field and the 24-hour height changes (these values as reported on operational constant pressure charts), only about 50% of the 12-hour motion variance is explainable by this knowledge. On the other hand, if one knows the exact location and motion of a storm, over 90% of the 12-hour motion variance can be explained.

4. THE SYNOPTIC FORECASTS

Dependent data and grid system-The National Hurricane Research Laboratory of ERL, NOAA, maintains and continuously updates a master hurricane data tape.

Residing on this tape are the 1000, 700 and 500-mb geopotential height fields for approximately 1000 tropical cyclone forecast situations dating back through the year 1945. The height fields are defined by an approximate storm-centered 8 x 15 grid system as illustrated in figure 2. The grid system and the grid-data are identical to that used in the NHC-67 screening runs except that the data were updated through the 1969 hurricane season. Also on the tape, are the best-track³ storm positions, the pre-computed CLIPER and HURRAN forecasts and other pertinent storm reference data.

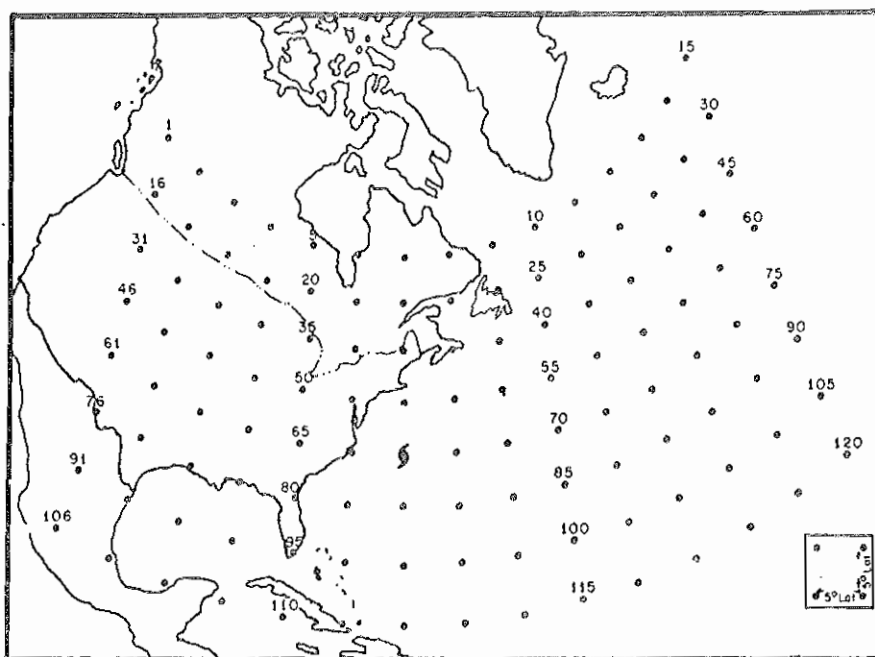


Figure 2. The location of the 120 grid points with a storm centered at 35N., 70W. Grid spacing is 300 n.mi.

Stratification of the dependent data set-All previous objective systems have found that results can be improved with some stratification of the data.

³The best-track positions are the accepted storm positions after a post-storm analysis.

Work with the HURRAN and CLIPER systems suggests that stratification according to the initial motion provides a logical breakdown and one which improves the final product. Figure 3 illustrates the stratification scheme used in NHC-72. The origin is at the center of the X, Y axes. The radials are direction of initial storm motion and the concentric circles are initial storm speeds at 3 knot intervals. The entire sample of initial storm motions was fitted to a bivariate normal distribution. A new coordinate axes system through the centroid of the distribution, located near 340 degrees at 6 knots, was then rotated counterclockwise through 12 degrees. At this new orientation, components of storm motion along these axes are uncorrelated. The elliptical area includes 99 percent of the initial motion vectors of the sample. Details concerning this fitting process are discussed in Hope and Neumann (1970). The new A, B coordinate system conveniently divides the data into four sub-sets with the storms in each sub-set having similar motion characteristics.

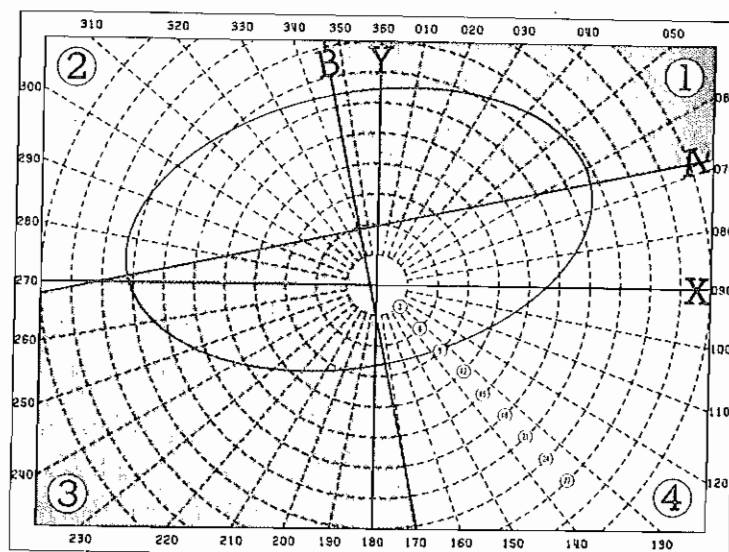


Figure 3. The Stratification Scheme

Predictor screening runs-A total of 720 predictors was available for each screening run. These consisted of 120 grid-point values defining the height field and the 24-hour changes in the height field of the 1000, 700 and 500-mb. surfaces. A stepwise screening procedure was used to test the variance reducing potential of each of these predictors. Separate screening runs were made for each of the two orthogonal components of storm motion for the periods 0 to 12 hours, 0 to 24 hours, 0 to 36 hours, 0 to 48 hours, and 0 to 72 hours. Because of practical limitations in the screening regression computer program, each of the 40 synoptic prediction equations required seven screening runs. The first six runs selected the 20 best predictors from each of the six height fields while the seventh run considered the final combined set. This final run was programmed to terminate when the addition of another predictor failed to reduce the variance an additional one percent or when 12 predictors had been selected, whichever came first. In general, the former restriction halted the regression in the case of zonal motion while the 12-predictor limit applied in the case of meridional motion. Limiting the number of predictors insured that F-test statistical significance criteria were satisfied at the one percent level, (Burington and May, 1958).

Supplemental screening runs were also made using other derived predictors and predictor functions. These included the 1000 to 700-mb, the 1000 to 500-mb. and the 700 to 500-mb. thicknesses and various geostrophic steering functions. Although these derived predictors were sometimes selected, their inclusion did not reduce the variance any more than did the primary set. The additional loss of degrees of freedom did not warrant their inclusion in the final prediction equations.

Correlation fields—Each of the screening runs generated a correlation coefficient field between predictor and predictand. Figure 4 shows a typical correlation field between 36-hour zonal motion in quadrant 4 and 700-mb. heights. In this example, the difference in heights between grid point 37, 600 n.mi. north of the storm and grid point 99, 850 n.mi. southeast of the storm were selected as a prime predictor pair.

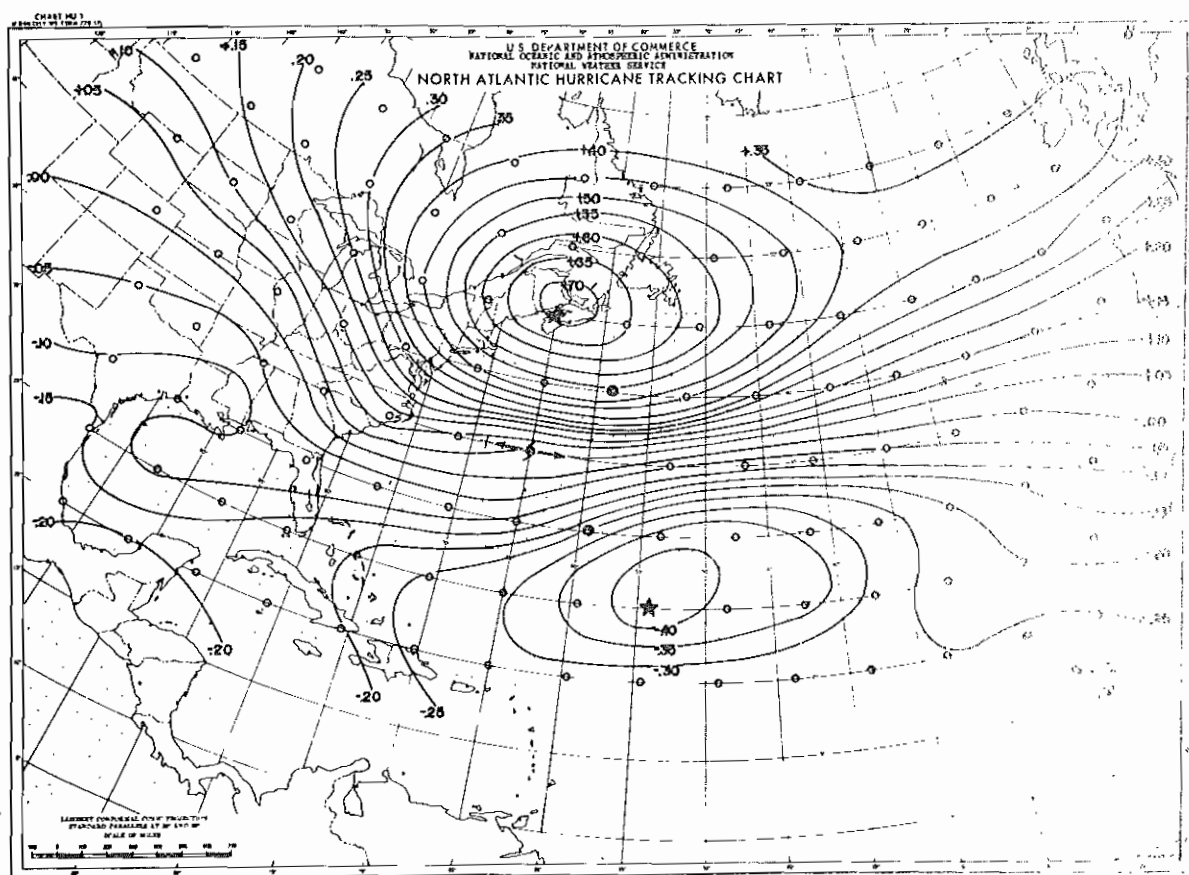


Figure 4. Linear correlation coefficient field between 36-hour zonal motion in quadrant 4 and 700-mb. height. Grid points marked as shown were selected as the initial two predictors while those marked with darkened circles were selected as predictors 6 and 7. (See Table 10) Other grid-points are shown as open circles. Heavy line shows location of zero correlation.

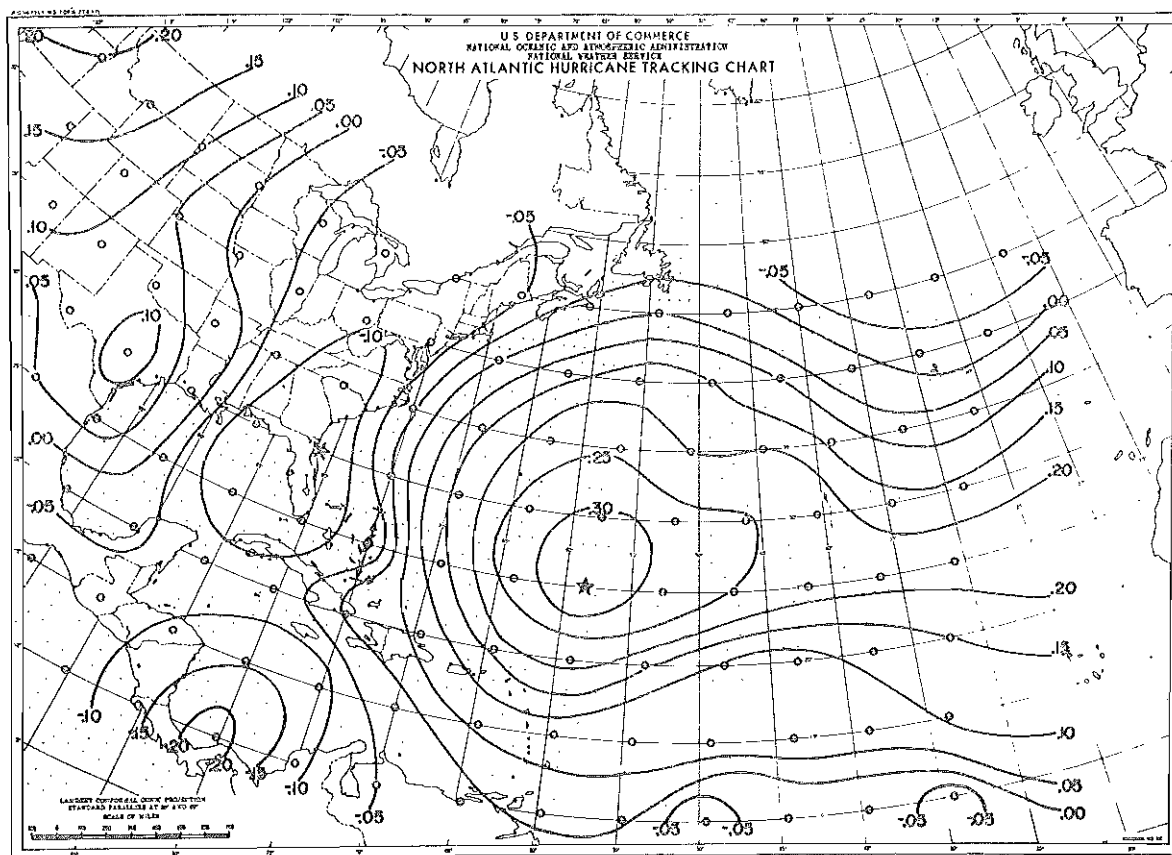


Figure 5. Linear correlation coefficient field between 24-hour meridional motion in quadrant 2 and 1000mb. height. Grid-points marked as stars were selected as predictors 1 and 2. (See Table 4) Other grid-points are shown as open circles. Heavy line shows location of zero correlation.

The differences in heights between grid-points 53, 425 n.mi. northeast of the storm and 93, 425 n.mi. southeast of the storm were selected as secondary predictors. Another example, this time between the 24-hour meridional motion in quadrant 2 and the 1000-mb. heights is given in figure 5. Here, the pair of grid-points located 425 n.mi. northwest of the storm and one located 900 n.mi. east of the storm, provide the prime reduction of variance. In both of these figures, the storms were positioned in areas with motion characteristics typical of the appropriate quadrant.

The final synoptic prediction equations-The final predictors selected for meridional motion are listed in Tables 3 through 6. Symbolic references to each predictor are defined in Table 2.

Table 2. Predictors included in the synoptic regression analysis. The subscript (I) refers to grid-point addresses given in Figure 2.

1000-mb. height	(H10(I), I = 1,120)
700-mb. height	(H7 (I), I = 1,120)
500-mb. height	(H5 (I), I = 1,120)
1000-mb. 24-hr. height change	(DH10(I), I = 1,120)
700-mb. 24-hr. height change	(DH7 (I), I = 1,120)
500-mb. 24-hr. height change	(DH5 (I), I = 1,120)

Tables 3 through 6 also specify the incremental reduction of variance provided by each predictor where reduction of variance (RV) is defined,

$$RV = R_m^2 = 1 - (SE)^2 / (SD)^2 \quad (2)$$

where R_m is the multiple correlation coefficient, SE is the standard deviation of the error of estimate (standard error) and SD is the standard deviation of the original data. The last row in each table gives the total reduction of variance provided by the complete set of predictors. The predictors for zonal motion in each quadrant are listed in Tables 7 through 10.

The regression coefficients corresponding to the meridional motion predictors in Tables 3 through 6 are given in the Appendix as Tables 11 through 14 while those for zonal motion are also listed in the appendix as Tables 15 through 18. The actual prediction equation for meridional motion (DY) in a particular quadrant at time 12k is given by,

Table 3 Variance analysis on quadrant 1 meridional motion

Predictor Selection	12 HOUR FCST		24 HOUR FCST		36 HOUR FCST		48 HOUR FCST		72 HOUR FCST	
Order	Predictor	RV	Predictor	RV	Predictor	RV	Predictor	RV	Predictor	RV
j=1	H5(51)	.186	DH5(51)	.224	DH5(51)	.227	DH5(51)	.197	H7(62)	.181
2	H5(54)	.147	DH10(71)	.065	H5(62)	.088	H5(62)	.119	H7(36)	.087
3	H5(76)	.058	DH7(92)	.058	H7(51)	.081	H7(50)	.060	H10(3)	.047
4	DH10(102)	.027	DH5(65)	.037	H10(72)	.065	H10(72)	.059	H5(102)	.050
5	H10(9)	.019	H10(9)	.031	H5(23)	.042	H7(49)	.026	H7(66)	.021
6	DH7(10)	.030	H5(85)	.035	H5(85)	.027	DH7(35)	.026	H7(39)	.025
7	DH7(7)	.037	H7(51)	.055	H7(120)	.014	H5(70)	.022	H10(58)	.018
8	DH5(65)	.019	H7(69)	.023	DH7(92)	.015	H10(9)	.022	DH7(63)	.016
9	H7(69)	.015	H5(62)	.017	DH10(102)	.012	H10(3)	.016	DH7(35)	.019
10	H7(120)	.021	DH7(10)	.015	DH10(9)	.010	H7(92)	.014	H5(62)	.016
11	H10(105)	.015	DH7(7)	.013	DH5(65)	.010	H10(80)	.012	DH7(83)	.014
12	H7(92)	.012	H7(120)	.012			DH10(100)	.014	H5(36)	.016
Total Reduction	(k=1)	.586	(k=2)	.587	(k=3)	.592	(k=4)	.585	(k=6)	.511

Table 4 Variance analysis on quadrant 2 meridional motion

Predictor Selection	12 HOUR FCST		24 HOUR FCST		36 HOUR FCST		48 HOUR FCST		72 HOUR FCST	
Order	Predictor	RV	Predictor	RV	Predictor	RV	Predictor	RV	Predictor	RV
j=1	H7(69)	.110	H10(70)	.106	H10(70)	.114	H5(70)	.120	H10(70)	.139
2	H5(65)	.081	H10(51)	.080	H10(51)	.082	H5(50)	.079	H10(98)	.064
3	DH5(6)	.037	DH7(6)	.060	DH7(20)	.062	H7(62)	.056	H5(32)	.057
4	DH10(73)	.025	DH10(110)	.026	H5(70)	.030	DH7(20)	.051	H7(14)	.062
5	H5(70)	.024	DH10(53)	.025	H10(39)	.029	H7(24)	.027	DH10(54)	.024
6	DH7(15)	.019	H7(76)	.023	H5(65)	.022	H10(1)	.020	DH5(66)	.020
7	H10(51)	.015	DH7(15)	.020	H7(48)	.027	H10(51)	.018	DH7(20)	.020
8	DH5(4)	.021	DH5(65)	.016	DH5(70)	.019	DH7(114)	.017	H5(70)	.016
9	DH10(54)	.017	H5(70)	.017	DH7(54)	.018	DH7(99)	.018	H10(1)	.013
10	H7(76)	.018	DH5(70)	.025	DH10(110)	.017	H7(14)	.016	H5(50)	.016
11	H10(111)	.017	DH7(54)	.017	DH5(8)	.014	DH10(54)	.012	DH7(63)	.013
12	DH5(70)	.012	DH5(71)	.015	DH5(73)	.013	DH5(70)	.013	H7(114)	.011
Total Reduction	(k=1)	.396	(k=2)	.431	(k=3)	.446	(k=4)	.447	(k=6)	.453

Table 5 Variance analysis on quadrant 3 meridional motion

Predictor Selection	12 HOUR FCST		24 HOUR FCST		36 HOUR FCST		48 HOUR FCST		72 HOUR FCST	
Order	Predictor	RV	Predictor	RV	Predictor	RV	Predictor	RV	Predictor	RV
j=1	H5(40)	.160	H5(73)	.145	H7(55)	.128	H7(55)	.122	H7(55)	.119
2	DH7(20)	.153	DH5(35)	.114	DH7(20)	.107	DH7(20)	.091	H5(61)	.063
3	DH5(47)	.039	H10(50)	.067	H10(51)	.084	H10(51)	.079	H7(14)	.068
4	H10(51)	.027	H7(85)	.041	H10(85)	.041	H10(85)	.057	H10(50)	.045
5	H5(70)	.033	DH5(3)	.030	H7(22)	.031	H7(22)	.026	H10(85)	.039
6	DH5(7)	.022	H5(24)	.023	DH7(8)	.024	H7(14)	.022	H10(97)	.030
7	DH7(34)	.024	H5(66)	.020	DH7(34)	.018	DH10(62)	.018	H10(16)	.022
8	H7(22)	.018	DH7(34)	.015	DH10(62)	.017	H10(16)	.017	H7(15)	.014
9	H5(66)	.015	DH5(7)	.018	H10(16)	.019	H10(97)	.011	H10(51)	.010
10	H5(96)	.013	DH5(71)	.015	DH5(70)	.012	H5(96)	.013	DH7(19)	.014
11	H5(94)	.017					H7(98)	.012	DH7(115)	.015
12	H5(73)	.010					DH7(8)	.010		
Total Reduction	(k=1)	.532	(k=2)	.490	(k=3)	.482	(k=4)	.478	(k=6)	.440

Table 6 Variance analysis on quadrant 4 meridional motion

Predictor Selection	12 HOUR FCST		24 HOUR FCST		36 HOUR FCST		48 HOUR FCST		72 HOUR FCST	
Order	Predictor	RV	Predictor	RV	Predictor	RV	Predictor	RV	Predictor	RV
j=1	H5(72)	.137	H5(72)	.147	DH5(51)	.168	H5(47)	.170	H5(47)	.188
2	DH5(51)	.089	DH5(51)	.138	H5(72)	.140	DH5(51)	.124	H7(14)	.079
3	DH10(85)	.077	DH10(85)	.055	H10(51)	.042	DH10(85)	.055	H10(51)	.060
4	H10(79)	.048	H5(7)	.045	DH10(100)	.036	H5(72)	.030	H7(103)	.037
5	DH10(114)	.041	H5(65)	.032	H5(48)	.032	H5(50)	.031	H5(48)	.030
6	DH10(89)	.026	H5(48)	.045	H5(50)	.052	H5(48)	.040	H5(50)	.026
7	DH10(31)	.023	H5(50)	.025	DH7(35)	.026	H5(2)	.031	H5(2)	.027
8	H7(48)	.020	H5(69)	.023	H7(54)	.016	DH7(35)	.023	DH5(15)	.017
9	H5(65)	.036	DH7(35)	.022	H5(51)	.019	H7(14)	.014	DH10(88)	.012
10	DH7(35)	.025	H5(51)	.011	H10(1)	.014	H10(24)	.014	H10(92)	.014
11	H7(69)	.021	H5(2)	.019	DH7(80)	.014	H7(15)	.011	H5(120)	.016
12	H5(7)	.012	DH10(1)	.011	H10(92)	.010	H5(85)	.011	H10(24)	.015
Total Reduction	(k=1)	.553	(k=2)	.573	(k=3)	.569	(k=4)	.553	(k=6)	.521

Table 7 Variance analysis on quadrant 1 zonal motion						
Predictor Selection Order	12 HOUR FCST		24 HOUR FCST		36 HOUR FCST	
	Predictor	RV	Predictor	RV	Predictor	RV
j=1	H5(37)	.564	H5(37)	.537	H5(37)	.460
2	DH10(97)	.055	H7(84)	.068	H7(84)	.111
3	DH5(56)	.023	DH5(56)	.025	H10(38)	.025
4	H7(91)	.012	DH10(97)	.022	DH5(56)	.020
5	H10(38)	.010	H10(38)	.019	DH10(97)	.013
6	H10(8)	.016	H10(106)	.012	H10(106)	.012
7	H10(83)	.013	H5(66)	.012	H5(36)	.010
8			H10(8)	.010	H5(66)	.012
9						
10						
11						
Total Reduction	(k=1)	.693	(k=2)	.705	(k=3)	.664
					(k=4)	.639
					(k=6)	.613

Table 8 Variance analysis on quadrant 2 zonal motion						
Predictor Selection Order	12 HOUR FCST		24 HOUR FCST		36 HOUR FCST	
	Predictor	RV	Predictor	RV	Predictor	RV
j=1	H5(37)	.329	H5(22)	.370	H5(22)	.373
2	H10(75)	.077	H5(12)	.060	H5(12)	.092
3	DH10(97)	.033	H5(37)	.035	H10(75)	.039
4	H7(15)	.028	H10(75)	.039	H7(36)	.032
5	H7(38)	.013	DH10(97)	.030	DH10(97)	.027
6	H10(89)	.010	DH7(15)	.018	DH7(15)	.016
7	H5(12)	.012	H10(89)	.014	H10(89)	.012
8			H10(37)	.012	H5(38)	.010
9					H5(82)	.011
10						
Total Reduction	(k=1)	.502	(k=2)	.577	(k=3)	.612
					(k=4)	.621
					(k=6)	.600

Table 9 Variance analysis on quadrant 3 zonal motion						
Predictor Selection Order	12 HOUR FCST		24 HOUR FCST		36 HOUR FCST	
	Predictor	RV	Predictor	RV	Predictor	RV
j=1	H5(37)	.304	H5(37)	.322	H5(36)	.300
2	H10(75)	.056	H10(75)	.063	H10(75)	.079
3	H10(118)	.033	H10(118)	.039	H7(12)	.031
4	H5(65)	.014	DH5(6)	.028	H7(61)	.040
5	H5(81)	.028	H5(84)	.016	H5(37)	.025
6	H7(84)	.016	H5(65)	.020	H10(118)	.019
7	DH7(65)	.011	H5(81)	.018	DH5(21)	.017
8	DH7(51)	.017	H10(89)	.011	DH5(81)	.012
9			H5(13)	.015	DH5(52)	.010
Total Reduction	(k=1)	.479	(k=2)	.533	(k=3)	.534
					(k=4)	.565
					(k=6)	.613

Table 10 Variance analysis on quadrant 4 zonal motion						
Predictor Selection Order	12 HOUR FCST		24 HOUR FCST		36 HOUR FCST	
	Predictor	RV	Predictor	RV	Predictor	RV
j=1	H5(37)	.532	H5(37)	.525	H7(37)	.492
2	H7(83)	.067	H7(99)	.085	H7(99)	.111
3	H7(53)	.048	DH7(55)	.036	DH5(51)	.027
4	DH7(55)	.021	H7(75)	.023	DH7(55)	.024
5	H7(51)	.017	H5(50)	.015	H5(36)	.023
6	DH7(62)	.012	H5(66)	.014	H7(83)	.014
7	DH10(98)	.011	H5(52)	.019	H7(53)	.019
8			H10(53)	.014	DH7(100)	.011
9			H7(83)	.014		
10						
11						
12						
Total Reduction	(k=1)	.709	(k=2)	.745	(k=3)	.721
					(k=4)	.747
					(k=6)	.713

$$DY(12k) = C(0,k) + \sum_{\substack{j=1,N \\ k=1,6}} C(j,k)P(j,k) \quad (k \neq 5) \quad (3)$$

where $P(j,k)$ refers to 1 of N predictors referenced in the appropriate table 3, 4, 5, or 6, and $C(j,k)$ is the corresponding regression coefficient referenced in table 11, 12, 13, or 14. Similarly, zonal motion (DX), at time $12k$ is given by,

$$DX(12k) = C(0,k) + \sum_{\substack{j=1,N \\ k=1,6}} C(j,k)P(j,k) \quad k \neq 5 \quad (4)$$

where the appropriate value of $P(j,k)$ and $C(j,k)$ can be found in one of tables 7 through 10 and one of tables 15, through 18. For example, 36 hour zonal motion (n.mi.) in quadrant 4 is given by

$$\begin{aligned} DX(36) = & -2833.0 + .6135H7(37) - 1.3803H7(39) + 1.3461D5(51) \\ & + 1.0294DH7(55) + 1.1769H5(36) - 2.2887H7(83) \\ & + 1.7655H7(53) - 1.3402DH7(100). \end{aligned} \quad (5)$$

These equations provide an estimate of tropical cyclone displacement based entirely on predictors derived from observed synoptic height data.

5. THE NHC72 FORECASTS

Following the schematic in figure 1, the final NHC72 forecasts (NF) are obtained by combining the CLIPER forecasts (CF) described in section 3, with the SYNOPTIC forecasts (SF) described in section 4 such that,

$$NF = f(SF, CF). \quad (6)$$

As demonstrated by Neumann and Hope (1972b), any weighting factor used in this combination must be both time and space dependent. Accordingly, a separate set of weighting factors were derived by regression techniques for each time period and for each quadrant. In general, it was found that greater weights are given to the CLIPER forecasts with decreasing latitude and at the shorter forecast periods. In order to account for any

nonlinearity in the data, function (6) was represented by a second order polynomial,

$$NF(CF, SF) = C_1 + C_2(SF) + C_3(SF)^2 + C_4(CF) + C_5(CF)^2 + C_6(SF)(CF) \quad (7)$$

where the constants C_1 through C_6 were determined by regression techniques. The computed constants for the 40 equations (5 pairs of equations in each of the four quadrants) are given in the appendix as Table 19. The final equation for 36-hour zonal motion (DX_{36}) in quadrant 2 for example, is given by,

$$DX_{36} = -1.2 + .5325(SF) - .0005(SF)^2 + .5742(CF) - .0004(CF)^2 + .0008(SF)(CF) \quad (8)$$

and for 36-hour meridional motion (DY_{36}) in quadrant 2 is given by,

$$DY_{36} = 13.7 - .0206(SF) + .0005(SF)^2 + .6190(CF) - .0007(CF)^2 + .0014(SF)(CF). \quad (9)$$

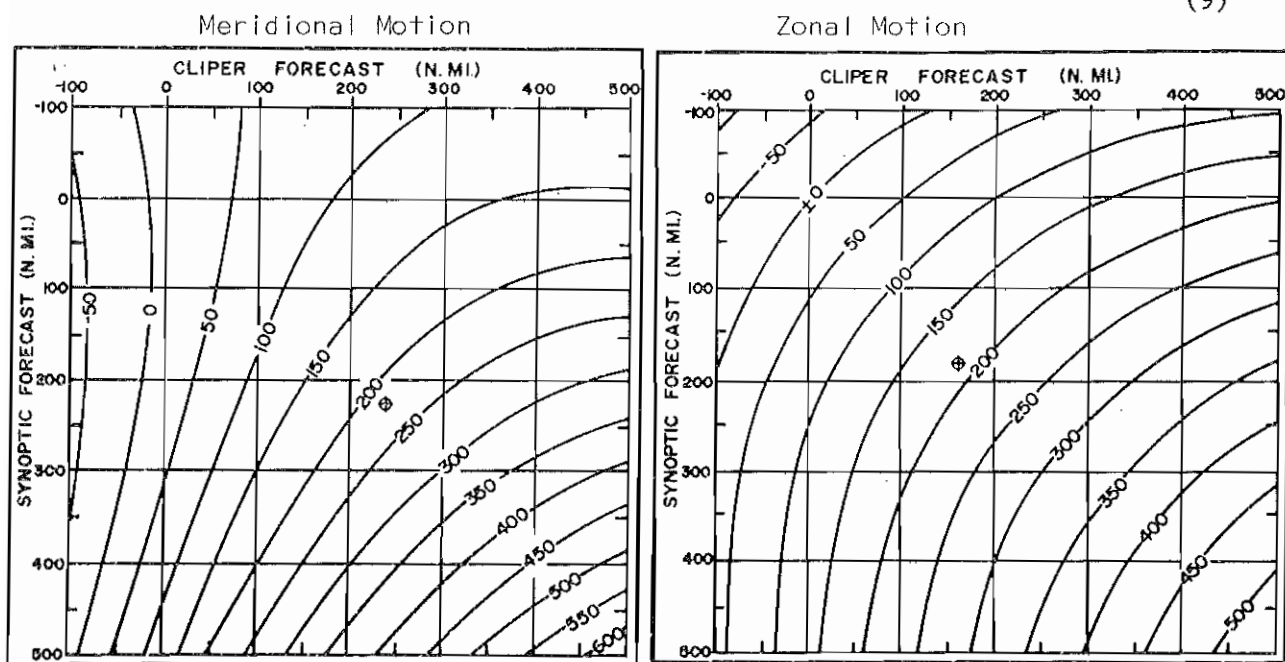


Figure 6. (left), and Figure 7 (right), showing the graphical solution to equations (8) and (9). The curved lines give the final NHC-72 36 hour forecast displacement in quadrant 2 as a function of the CLIPER and SYNOPTIC displacements. The symbol ($\oplus$) locates the mean of the marginal distributions.

Graphical solutions to (8) and (9) are given in figures 6 and 7. The figures illustrate the advantage of using a higher order function to

compute the final forecast displacement. It can be noted, for example, that a meridional CLIPER forecast of, say, 400 n.mi. and a SYNOPTIC forecast of 400 n.mi. will yield a final NHC-72 forecast displacement of 458 n.mi., greater than either the CLIPER or SYNOPTIC contribution. Similarly, it can be noted on figure 6, that a CLIPER and SYNOPTIC forecast, each of 100 n.mi., yields a final displacement forecast of 86 n.mi., less than either of the individual contributions. Thus, the second order equation (7) provides a better means of resolving the tails of the data distribution than would a simpler linear function.

7. OPERATIONAL IMPLEMENTATION OF THE SYSTEM

Data retrieval- The NHC-72 equations were programmed in the Fortran IV computer language and cataloged in the NOAA CDC 6600 computer system at Suitland, Md. Access to the computer system is through the user-200 terminal located in the Miami NOAA complex at the University of Miami. The synoptic data required to run the program are retrieved from current files, routinely stored in the computer by the National Meteorological Center. The NHC-72 forecasts for the 1600GMT and the 0400GMT advisories use the initial 1200GMT and 000GMT analyses available approximately 1 1/2 hours after observation time. The 2200GMT and the 1000GMT NHC-72 runs are based on a six hour forecast for the "observed" data while the 24 hour height change data are computed from a mean of the previous analyses made 12 and 24 hours earlier.

Sample program output- Figure 8 shows a typical output from the program. The CLIPER and SYNOPTIC forecast displacements are presented for information only and provide the forecaster with some insight into the magnitude of the components of the final NHC72 forecast. Figure 9 shows a portion of additional program output. These are supplemental

data and can be used to trace any possible irregularities in the program. Excessive departures from normal in column 9, for example, might indicate that the height data given in column 6 are invalid. The abbreviation (CLM), appended to column 5 in the case of 12 hour zonal motion.

```

NHC-72 FORECAST PACKAGE ON STORM GINGER          9/27/71 0000GMT.
INPUT DATA---INITIAL MOVEMENT 230/02, MOVEMENT T-12 HRS 000/00
MAX WIND 80KTS, QUADRANT 3 EQUATIONS USED.
FCST PERIOD  VALID TIME      CLIPER      SYNOPTIC      NHC-72
T+ 0 HRS      9/27/71 00Z    27.8N 70.2W  27.8N 70.2W  27.8N 70.2W
T+12 HRS      9/27/71 12Z    27.6N 70.6W  27.2N 71.1W  27.5N 70.7W
T+24 HRS      9/28/71 00Z    27.8N 70.9W  27.0N 72.5W  27.2N 71.5W
T+36 HRS      9/28/71 12Z    28.2N 71.3W  27.9N 71.7W  27.6N 71.6W
T+48 HRS      9/29/71 00Z    28.8N 71.5W  28.0N 71.9W  27.5N 71.8W
T+72 HRS      9/30/71 00Z    30.8N 71.3W  31.4N 75.1W  30.5N 73.9W

```

Figure 8. Sample program output

```

9/27/71 0000GMT GINGER INITIAL POSITION, 27.8N 70.2W
CONTRIBUTION (N.MI.) OF EACH SYNOPTIC PREDICTOR TO 72HR MERIDIONAL MOTION.
*****
PREDICTOR * REGRESSION * GRID * GRID-POINT * PREDICTOR * MEAN PREDICTOR * DEPARTURE FROM
NUMBER * COEFFICIENT * ADDRESS * LOCATION * PREDICTOR * VALUE (METERS) * CONTRIBUTION * VALUE (METERS) * NORMAL CONTRIBUTION
*****
0 INTERCEPT -13480.46
1 1.3604400 (5,10) 32.8N 52.4W 700MB HT 3198.0 4350.69(NWD) 3184.8 18.0(NWD)
2 1.8071030 (4,1) 27.8N 104.1W 500MB HT 5894.0 10651.07(NWD) 5859.9 81.6(NWD)
3 -1.3362830 (8,14) 47.8N 18.1W 700MB HT 3136.0 -4190.58(SWD) 3124.0 -16.0(SWD)
4 .1486974 (5,5) 32.8N 82.1W 1000MB HT 165.0 24.54(NWD) 138.7 3.9(NWD)
5 2.4279950 (3,10) 22.8N 53.9W 1000MB HT 138.0 335.06(NWD) 129.0 21.2(NWD)
6 -2.6765240 (2,7) 17.8N 70.2W 1000MB HT 99.0 -264.98(SWD) 104.9 15.8(NWD)
7 .7620446 (7,1) 42.8N 111.1W 1000MB HT 60.0 45.72(NWD) 121.3 -46.7(SWD)
8 1.0356660 (8,15) 47.8N 10.7W 700MB HT 3089.0 3199.17(NWD) 3130.6 -43.1(SWD)
9 -2.4506220 (5,6) 32.8N 76.1W 1000MB HT 158.0 -387.20(SWD) 138.9 -46.8(SWD)
10 -1.0369390 (7,4) 42.8N 90.6W 700MB CHG 34.0 -35.26(SWD) -4.6 -40.0(SWD)
11 -3.3531660 (1,10) 12.8N 54.8W 700MB CHG 9.0 -30.18(SWD) 4.4 -15.4(SWD)
NORMAL DISPLACEMENT FORECAST IS 304.4 N.MI. ACTUAL FORECAST = 217.6 N.MI. TOTAL DEPARTURE IS -86.8 N.MI.

CONTRIBUTION (N.MI.) OF EACH SYNOPTIC PREDICTOR TO 12HR ZONAL MOTION.
*****
PREDICTOR * REGRESSION * GRID * GRID-POINT * PREDICTOR * MEAN PREDICTOR * DEPARTURE FROM
NUMBER * COEFFICIENT * ADDRESS * LOCATION * PREDICTOR * VALUE (METERS) * CONTRIBUTION * VALUE (METERS) * NORMAL CONTRIBUTION
*****
0 INTERCEPT -4496.25
1 .7227983 (6,7) 37.8N 70.2W 500MB HT 5817.0 4204.52(WWD) 5882.7 -47.5(EWD)
2 -.3194008 (4,15) 27.8N 25.0W 1000MB HT 145.0 -46.31(EWD) 143.2 0.0(NIL)
3 .6068524 (1,13) 12.8N 39.4W 1000MB HT (CLM) 127.0 77.07(WWD) 127.0 0.0(NIL)
4 .6016613 (4,5) 27.8N 81.5W 500MB HT 5907.0 3554.01(WWD) 5881.3 15.5(WWD)
5 -.3973381 (3,6) 22.8N 75.6W 500MB HT 2861.0 -2328.80(EWD) 5864.4 1.4(WWD)
6 -.2905358 (3,9) 22.8N 59.4W 700MB HT 3175.0 -922.45(EWD) 3166.2 -2.6(EWD)
7 -.6329339 (4,5) 27.8N 81.5W 700MB CHG -21.0 13.29(WWD) -1.5 12.3(WWD)
8 .4443388 (5,6) 32.8N 76.1W 700MB CHG -14.0 -6.22(EWD) -2.7 -5.0(EWD)
NORMAL DISPLACEMENT FORECAST IS 74.9 N.MI. ACTUAL FORECAST = 48.9 N.MI. TOTAL DEPARTURE IS -26.0 N.MI.

```

①
②
③
④
⑤
⑥
⑦
⑧
⑨

Figure 9. Supplemental program output

(Contribution of Predictor 3) indicates that climatic data were substituted at grid point (1,13)*, located in this example at 12.8N, 39.4W. This location is south of the NMC octogonal grid, and therefore actual height values were unavailable.

8. ERROR ANALYSIS

Dependent data- Table 20 gives the mean vector error (MVE) of the final NHC-72 equations applied to the dependent data set. For any given forecast interval, the large inter-quadrant variations of MVE reflect not so much a different degree of skill in forecasting for the various quadrants but rather the different standard deviations of displacements within these quadrants.

Table 20. Mean Vector Error (n.mi.) of NHC-72 forecasts based on the dependent data set.

	FORECAST INTERVAL (HRS)					Number of Cases
	12	24	36	48	72	
Quadrant 1	26	81	142	210	362	172
Quadrant 2	22	61	106	163	294	213
Quadrant 3	19	57	100	144	252	198
Quadrant 4	24	73	137	189	333	188
All quadrants	23	68	120	175	308	771

The "all quadrant" data listed in Table 20 are plotted alongside the MVE of the HURRAN and CLIPER dependent data sets in figure 10. The decrease in MVE of NHC-72 over these two systems averages about 20 percent over the five forecast periods.

* In this printout, grid addresses are in the form (I,J).where I is the row number and J is the cloumn number starting in the southwest corner of the grid.

Table 22, included in the Appendix, presents a much more detailed error analysis than that contained in Table 20. The number of cases listed in Table 22 are greater than in Table 20 since the former includes some cases from adjacent quadrants. This overlap effects a smoother transition between displacement forecasts when passing from one quadrant to an adjacent quadrant. Some of the data from Table 22 have been plotted in either Figure 11 or Figure 12. Figure 11 includes data from quadrants

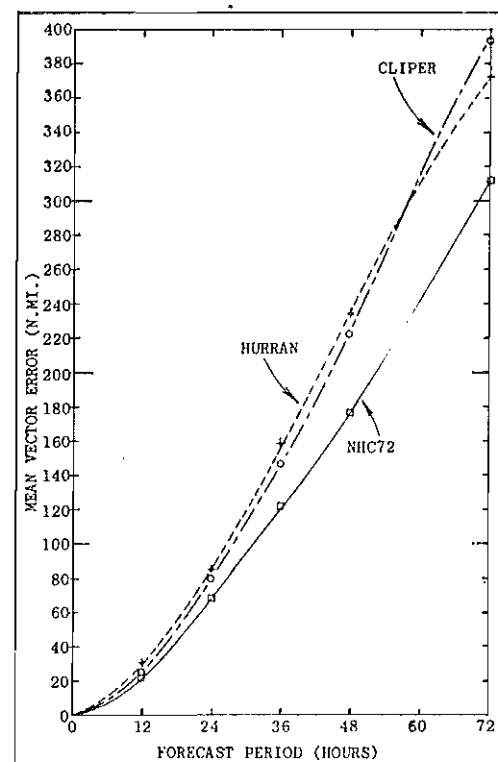


Figure 10. Mean vector errors of CLIPER, HURRAN and NHC72.

1 and 2 while figure 12 includes data from quadrants 3 and 4. The smooth curves connecting data points were objectively drawn using a technique suggested by Akima (1970). The first three of the four panels in each chart show, respectively, the percentage reduction in variance, the multiple correlation coefficient and the standard error of estimate for the CLIPER forecast, the SYNOPTIC forecast and the combined NHC-72 forecast. The fourth right-hand panel shows the standard deviation of the observed displacements. This latter quantity is identical for all the systems since the dependent data set is homogeneous. The mathematical relationship between the four quantities is given by (2).

As an example of interpretation of the data on these charts, consider meridional motion in quadrant 2 on Figure 11. Here, the SYNOPTIC forecast is seen to explain only 40 percent of the 12-hour motion variance while

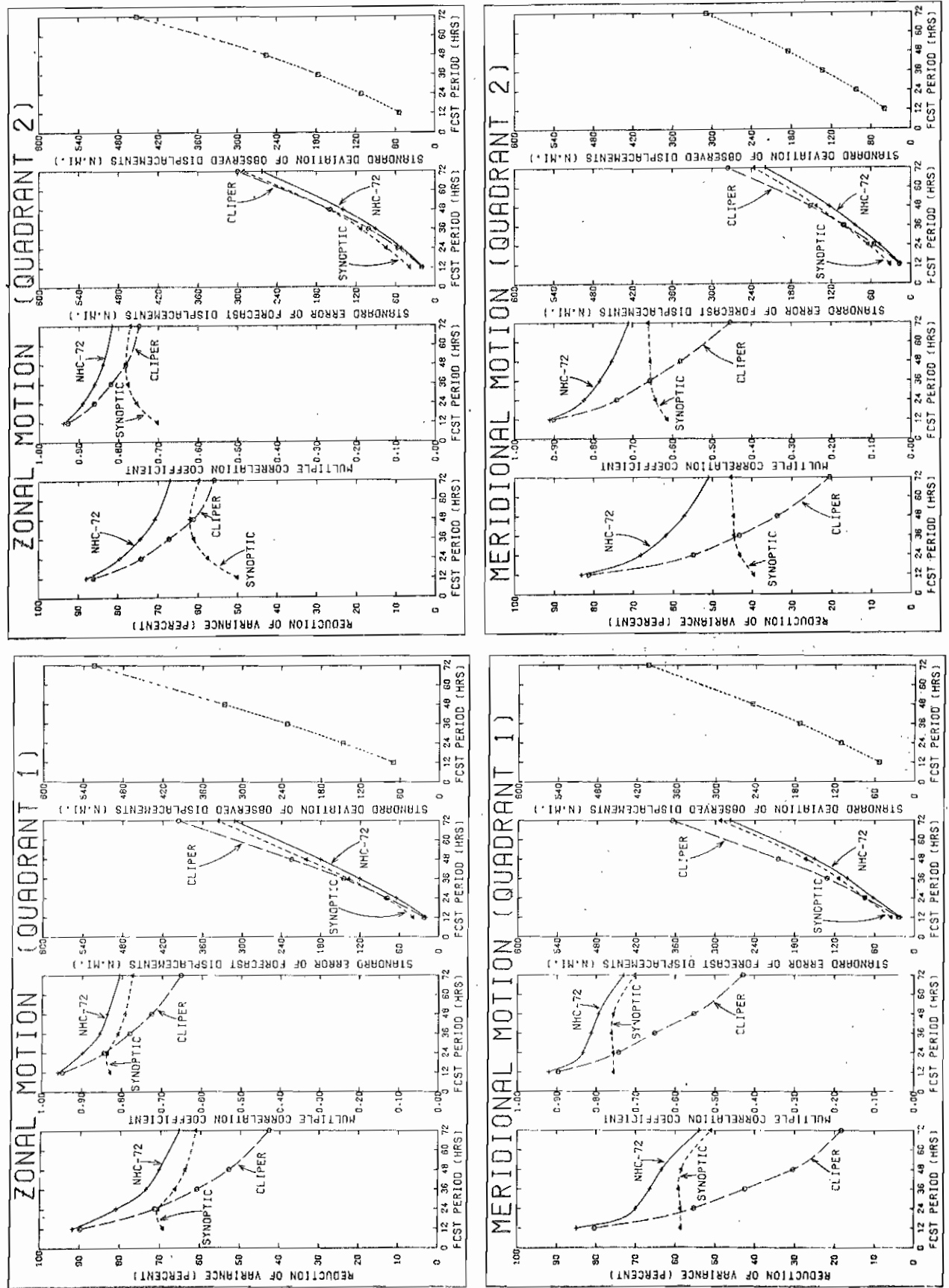
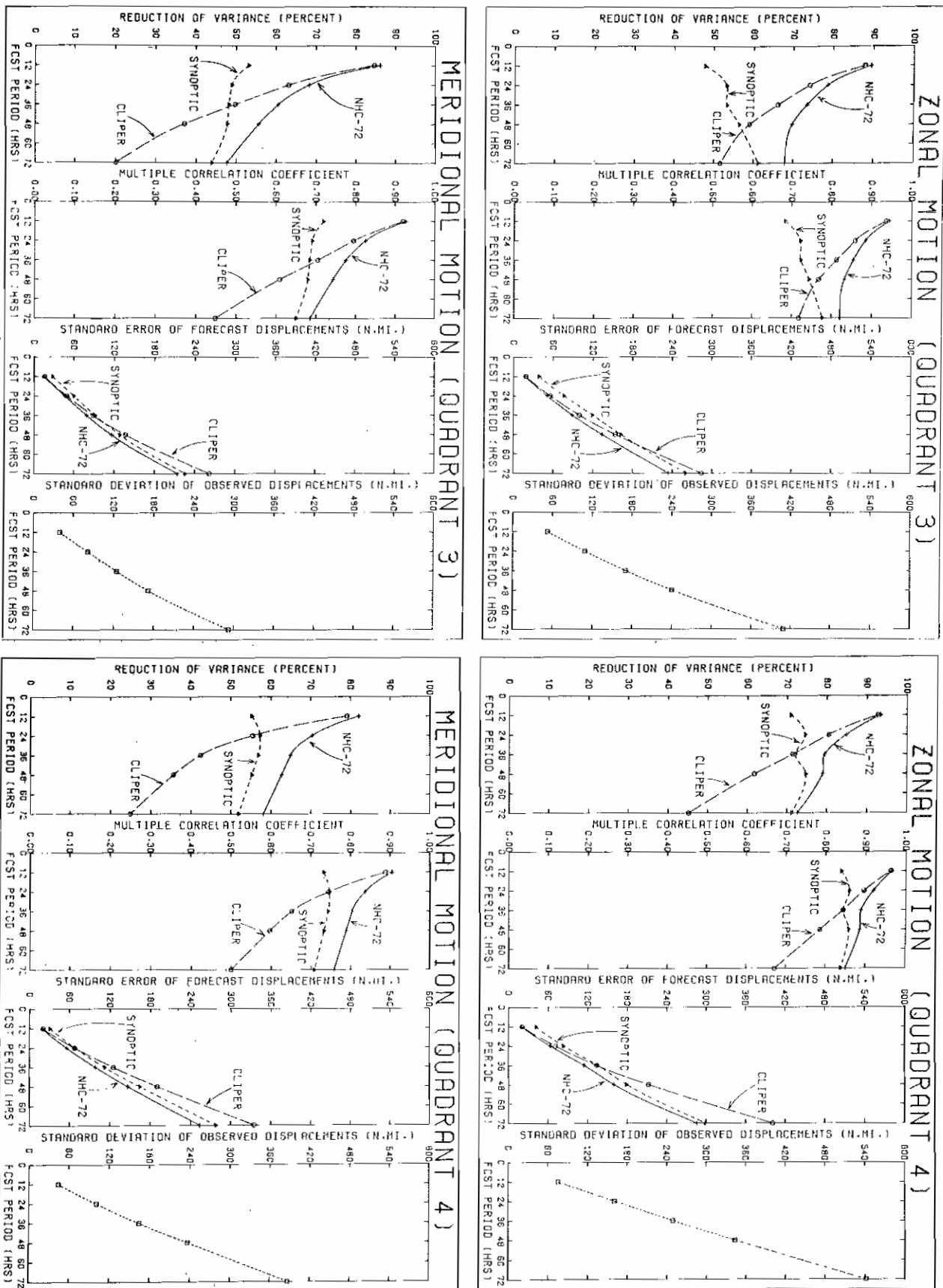


Figure 11. Error analysis for quadrants 1 and 2

Figure 12. Error analysis for quadrants 3 and 4



CLIPER (assuming, of course, that the empirical data are perfectly known) explains 81 percent of the variance. The reduction of variance of the SYNOPTIC forecast increases slightly with time whereas, that of the CLIPER forecast decreases rapidly with time, crossing the SYNOPTIC curve in slightly less than 36 hours. The combined effect of the two systems (upper curve) results in an initial reduction of variance of 83 percent with a gradual decrease to about 51 percent in 72 hours.

Examination of the various panels of Figures 11 and 12 reveal large time and space variations in the inherent ability of the empirical forecast system and the SYNOPTIC system to forecast tropical cyclone motion. Note, for example, in the case of meridional motion in quadrant 1 (Figure 11), that the SYNOPTIC curve crosses the CLIPER curve in less than 24 hours whereas in the case of zonal motion in quadrant 3 (Figure 12), the crossing point is about 54 hours. The weighting factors used to combine CLIPER and SYNOPTIC as listed in the APPENDIX, Table 19, reflect this variability.

Test on 1971 independent data- Tests were run on 1971 tropical cyclones for that portion of the season for which CLIPER forecasts had been made, and for which the appropriate synoptic grid data were available at the National Hurricane Center. The tests were restricted further to the upper air synoptic times, 0000 and 1200 GMT. The NHC-72 forecasts were run with the initial position, speed and direction of movement the same used in real time by the forecaster in order to simulate operational conditions as closely as possible. The number of such forecasts ranged from 51 at 12 hours to 29 at 72 hours. A summary of NHC-72 mean vector errors compared to a homogeneous sample of official and NHC-72 forecasts is shown in Table 21.

Table 21. Mean vector error (n.mi.) of NHC-72 forecasts compared to homogeneous sets of NHC-67 and official forecasts of independent data.

	FORECAST INTERVAL (HRS)			
	12	24	48	72
NHC-72	44	94	182	292
NHC-67	47	95	292	575
OFFICIAL	44	99	232	356
No. of Cases	51	46	37	29

The results of the evaluation on this limited sample of independent data are encouraging, especially at 48 and 72 hours, where there was considerable improvement over both the NHC-67 and the official forecasts. Evaluation of these independent data verification suggested the need of a separate set of equations for the Gulf of Mexico and the Western Caribbean. Analysis has indicated that the presence of the summertime semi-permanent heat low over southwestern United States and northwestern Mexico produces anomalous grid-point values, especially at lower levels, over the western portion of the grid when a storm is located in these areas.

Although not shown here, a separate set of equations was developed for the area west of longitude 81.5° , and preliminary tests on dependent data have shown significant improvement. Tests on a small independent data sample, which included the three 1971 storms passing through this area, Edith, Fern, and Laura, showed that the new equations produced forecasts with a 24-hour mean vector error about 10 percent less than the values obtained using the general equations for the same forecast situations.

Since these results have been so promising, the new equations will be incorporated in the operational system prior to the onset of the 1972 hurricane season. Also the other equations will be revised somewhat

since they no longer will include information obtained from grid-height values over the western portion of the Gulf and Caribbean and adjacent areas.

9. ANTICIPATED REFINEMENTS IN THE SYSTEM

The 20 percent reduction in the mean vector error of the NHC-72 over the CLIPER and HURRAN forecasts based on the dependent data set and the encouraging results on independent data for the 1971 hurricane season suggest that the approach taken in the NHC-72 system has considerable merit. Accordingly, the work will continue towards further refinements in the system. It is the opinion of the authors that such efforts should be channeled toward further modifications in the stratification scheme discussed in Section 4. An optimum statistical forecasting system, for example, might derive a completely new set of regression equations each time the program is run using a circular or elliptical scanning technique to select homogeneous cases. Additional efforts will be made to study the effects of using predictors derived from prognostic grid-height data in conjunction with the observed grid-height data as currently used. However, it is not anticipated that the basic design of the NHC-72 system will be altered.

10. ACKNOWLEDGEMENTS

The authors are grateful to Dr. Robert H. Simpson, Director, National Hurricane Center, for his continued encouragement during the course of this and other research efforts currently underway at the National Hurricane Center.

Retrieval of current and 24-hour old height data from the computer data files maintained by NMC required considerable programming and engineering, ably accomplished by Mr. Elbert Hill of NHC with some assistance from Mr. Fred Zbar, Tropical Program Coordinator of NMC.

Programming Akima's (1970) curve-fitting technique for an X-Y plotter was accomplished by Mr. Peter Chase of the National Hurricane Research Laboratory (NHRL). The latter organization also supplied the magnetic tape which contains the synoptic grid data.

REFERENCES

- Akima, H., 1970: "A New Method of Interpolation and Smooth Curve Fitting Based on Local Procedures," Journal of the Association For Computing Machinery, Vol. 17, No. 4, pp. 589-602.
- Burington, R.S. and D.C. May, 1958: Handbook of Probability and Statistics, Handbook Publishers, Inc., Sandusky, Ohio, pp. 276-277.
- Corzine, H.A., 1964: "A Comparison of Objective Hurricane Forecasting Methods and Attempts to Combine Two or More of These Methods," U. S. Navy Weather Research Facility, Norfolk, Va. (NWRF 12-1164-098), 19 pp.
- Efroymson, M.A., 1964: "Multiple Regression Analysis", Mathematical Methods for Digital Computers, edited by A. Ralston and H. S. Wilf, John Wiley and Sons, Inc., New York, pp. 191-203.
- Hope, J.R. and C.J. Neumann, 1970: "An Operational Technique for Relating the Movement of Existing Tropical Cyclones to Past Tracks," Monthly Weather Review, Vol. 98, No. 12, pp. 925-933.
- Hope, J.R. and C.J. Neumann, 1971: "Digitized Atlantic Tropical Cyclone Tracks," NOAA Technical Memorandum, NWS SR-55, 145 pp.
- Miller, B.I. and P.P. Chase, 1966: "Prediction of Hurricane Motion by Statistical Methods," Monthly Weather Review, Vol. 94, No. 6, pp. 399-406.
- Miller, B.I., E.C. Hill and P.P. Chase, 1968: "Revised Technique for Forecasting Hurricane Motion by Statistical Methods," Monthly Weather Review, Vol. 96, No. 8, pp. 540-548.
- Miller, B.I., P.P. Chase and B.R. Jarvinen, 1972: "Numerical Prediction of Tropical Weather Systems," Submitted to Monthly Weather Review.
- Neumann, C.J., 1972: "An Alternate to the HURRAN Tropical Cyclone Forecast System," NOAA Technical Memorandum NWS SR-62, 24 pp.
- Neumann, C.J., and J.R. Hope, 1972a: "A Performance Analysis of the HURRAN Tropical Cyclone Forecast System," Monthly Weather Review, April, 1972.
- Neumann, C.J., and J.R. Hope, 1972b: "A Diagnostic Study on the Statistical Predictability of Tropical Cyclone Motion," (Submitted for publication)
- Pike, A.C., 1972: "Improved Barotropic Hurricane Track Prediction by Adjustment of the Initial Wind Field, Submitted to NWS Southern Region as NOAA Technical Memorandum.

REFERENCES (Continued)

- Sanders, F. and R.W. Burpee, 1968: "Experiments in Barotropic Hurricane Track Forecasting," Journal of Applied Meteorology, Vol. 7, No. 3, pp. 313-323.
- Simpson, R.H., 1971: "The Decision Process in Hurricane Forecasting," NOAA Technical Memorandum NWS SR-53, 35 pp.

TABLE 11 REGRESSION COEFFICIENTS FOR MERIDIONAL MOTION IN QUADRANT 1					
PREDICTOR NUMBER (J)	12HR FCST	24HR FCST	36HR FCST	48HR FCST	72HR FCST
J=0	84.1900	-1318.7000	-3206.7800	-15629.8000	-21802.0700
1	-0.6326	-0.6721	-1.1803	-1.2432	0.5749
2	0.2085	0.8779	1.1057	0.9318	0.6155
3	0.2869	1.2525	-2.1807	-3.7490	1.4928
4	0.2973	-0.7716	1.2362	1.2730	3.4557
5	0.2186	0.3690	0.3691	2.3792	-3.3164
6	-0.1631	0.3597	1.0491	-1.4537	1.2267
7	-0.1692	-1.2913	-1.4791	1.3189	1.5625
8	-0.3486	0.9108	1.8869	0.4286	3.0217
9	0.3920	0.4436	1.2036	0.5538	-2.3809
10	-0.5247	-0.2480	0.2954	2.1650	2.6571
11	0.2602	-0.2227	-0.8666	-1.2558	2.7098
12	0.3609	-0.6741	--	1.5760	-1.9359
	K=1	K=2	K=3	K=4	K=6

TABLE 12 REGRESSION COEFFICIENTS FOR MERIDIONAL MOTION IN QUADRANT 2					
PREDICTOR NUMBER (J)	12HR FCST	24HR FCST	36HR FCST	48HR FCST	72HR FCST
J=0	-1460.8500	-5288.7200	-2184.9900	-9980.1000	-7513.8900
1	0.3394	0.5305	0.6304	2.0591	2.6052
2	-0.3285	-0.8718	-1.3496	-1.4134	-2.6256
3	-0.0616	-0.3052	-0.8176	1.9699	1.5720
4	0.2862	-1.3040	1.1998	-0.7251	-0.7912
5	0.2424	0.6722	0.8943	0.4367	2.2102
6	-0.1105	0.6610	-1.1914	0.3416	-1.6561
7	-0.2695	-0.2593	0.7053	-1.1628	-1.0721
8	-0.0791	-0.5691	-1.3581	-3.7577	1.6841
9	0.3760	0.5711	1.1708	2.1814	0.7030
10	0.3218	-1.2176	-1.8641	-0.4325	-1.5145
11	-0.3889	0.7017	-0.2446	1.4554	2.6364
12	-0.2177	0.6471	0.6640	-1.0409	-3.1371
	K=1	K=2	K=3	K=4	K=6

TABLE 13 REGRESSION COEFFICIENTS FOR MERIDIONAL MOTION IN QUADRANT 3					
PREDICTOR NUMBER (J)	12HR FCST	24HR FCST	36HR FCST	48HR FCST	72HR FCST
J=0	-1627.8100	-2623.4600	-3727.0700	-10486.5200	-13480.4600
1	0.0542	0.3957	0.7465	0.9318	1.3604
2	-0.1656	-0.3331	-0.4678	-0.9216	1.8071
3	-0.0916	-0.4366	-1.3739	-1.7113	-1.3363
4	-0.2167	0.5357	0.8346	1.4618	0.1487
5	0.2184	-0.1654	0.4734	0.7420	2.4280
6	-0.1196	0.1534	-0.2772	-0.2332	-2.6765
7	-0.2159	-0.3713	-0.7454	-1.3098	0.7620
8	0.0955	-0.5022	-0.9526	0.3800	1.0357
9	-0.2494	-0.1620	0.3324	-1.0554	-2.4506
10	0.4556	0.4497	0.6748	1.7763	-1.0369
11	-0.3694	--	--	-1.3458	-3.3532
12	0.1248	--	--	-0.3231	--
	K=1	K=2	K=3	K=4	K=6

TABLE 14 REGRESSION COEFFICIENTS FOR MERIDIONAL MOTION IN QUADRANT 4					
PREDICTOR NUMBER (J)	12HR FCST	24HR FCST	36HR FCST	48HR FCST	72HR FCST
J=0	-14.0700	-159.8900	-1219.2400	-5175.2800	1060.5500
1	0.1180	0.2058	0.1785	-0.5315	-0.3973
2	-0.3209	-0.2221	0.5276	-0.8601	-1.4220
3	0.4553	1.0320	-0.7827	1.5623	-3.1792
4	-0.2657	0.1398	1.4015	0.2332	3.4207
5	0.4477	-0.5210	0.9691	-2.3132	3.0850
6	0.2578	0.4596	-0.5803	2.1756	-1.9964
7	0.1653	-0.3217	-1.0550	0.4656	0.4665
8	0.2145	0.7814	1.0266	-0.9626	0.9571
9	-0.4468	-0.6372	-1.2375	-0.8463	2.2142
10	-0.2002	-0.8353	0.3160	0.5167	3.0570
11	0.3446	0.1421	-1.1409	0.6127	-2.3327
12	0.0418	0.1856	0.7889	1.0133	0.7371
	K=1	K=2	K=3	K=4	K=6

TABLE 15 REGRESSION COEFFICIENTS FOR ZONAL MOTION IN QUADRANT 1					
PREDICTOR NUMBER(J)	12HR FCST	24HR FCST	36HR FCST	48HR FCST	72HR FCST
J=0	-3217.2300	-4437.6900	-3894.6100	-1591.9500	5707.2300
1	0.7910	1.8303	1.9332	0.6087	1.1380
2	-0.9214	-0.7772	-1.9615	-3.9473	-5.4228
3	0.2531	0.5491	1.0730	3.3984	1.1874
4	-0.4460	-1.8328	0.8378	0.4705	-1.5415
5	0.3125	0.6131	-2.0042	-3.2640	1.8050
6	-0.1768	-1.0959	-1.7771	-0.5060	-2.5634
7	-0.2890	-0.6457	0.7606	-3.4409	-0.8738
8	--	-0.2473	-0.9711	2.1678	3.2587
9	--	--	--	1.6013	-3.7184
10	--	--	--	-0.9613	5.4041
11	--	--	--	--	-4.3315
	K=1	K=2	K=3	K=4	K=6

TABLE 16 REGRESSION COEFFICIENTS FOR ZONAL MOTION IN QUADRANT 2					
PREDICTOR NUMBER(J)	12HR FCST	24HR FCST	36HR FCST	48HR FCST	72HR FCST
J=0	-4599.1500	-8355.8600	-9996.7600	-7629.9000	-9251.3900
1	0.4747	0.2846	0.4936	0.8063	1.5365
2	-0.4619	0.2056	0.3487	-2.2289	0.9657
3	-0.7932	0.9553	-1.4208	0.5234	-2.7827
4	0.1406	-0.9344	1.3754	1.2749	1.0326
5	0.3581	-1.8130	-2.4599	-3.4333	2.4260
6	0.3446	0.3118	0.5114	0.8443	-2.5092
7	0.0556	0.6477	0.8487	0.5901	0.7477
8	--	0.4701	0.9417	1.0238	--
9	--	--	-0.7750	-1.3338	--
10	--	--	--	1.5484	--
	K=1	K=2	K=3	K=4	K=6

TABLE 17 REGRESSION COEFFICIENTS FOR ZONAL MOTION IN QUADRANT 3					
PREDICTOR NUMBER(J)	12HR FCST	24HR FCST	36HR FCST	48HR FCST	72HR FCST
J=0	-4496.2500	-6546.2500	-10451.5600	-8462.0500	5318.2900
1	0.7228	1.4398	0.4872	0.3193	1.8812
2	-0.3194	-0.8317	-1.0173	-1.3982	1.0222
3	0.6069	0.6594	0.3477	0.6335	-3.2945
4	0.6017	0.1611	-0.9736	-0.7087	1.6168
5	-0.3973	-0.7535	1.6529	2.6754	1.8127
6	-0.2905	1.1837	1.5643	0.9852	3.0646
7	-0.6329	-0.8589	0.4491	1.7273	-1.2410
8	0.4443	0.7257	-1.1596	-1.1425	-3.6733
9	--	0.1142	0.8686	0.6542	1.8652
	K=1	K=2	K=3	K=4	K=6

TABLE 18 REGRESSION COEFFICIENTS FOR ZONAL MOTION IN QUADRANT 4					
PREDICTOR NUMBER(J)	12HR FCST	24HR FCST	36HR FCST	48HR FCST	72HR FCST
J=0	-2818.7100	-1776.0200	-2833.0298	1464.8198	5281.4297
1	0.4418	0.6955	0.6135	2.1045	0.7218
2	-0.7884	-0.8417	-1.3803	-2.6085	-3.6882
3	0.4211	0.7089	1.3461	1.3769	1.0989
4	0.3795	-0.3860	1.0294	0.5125	-1.7242
5	0.4369	0.9217	1.1769	0.9891	-3.7276
6	-0.3984	-1.5075	-2.2887	0.9507	1.3670
7	-0.5020	1.4163	1.7655	-1.3869	-2.0970
8	--	0.8608	-1.3402	-0.5087	1.9736
9	--	-1.0812	--	-2.7357	3.0078
10	--	--	--	1.2721	3.0445
11	--	--	--	1.2237	-1.6087
12	--	--	--	-2.4250	--
	K=1	K=2	K=3	K=4	K=6

TABLE 19 Regression coefficients for combining CLIPER forecasts (CF) and SYNOPTIC forecasts (SF) into a final NHC-72 forecast displacement. DYi refer to meridional displacements and DXi to zonal displacements.

	PREDICTAND											
	PREDICTOR	DY12	DY24	DY36	DY48	DY72	DX12	DX24	DX36	DX48	DX72	
QUADRANT 1	Intercept	-2.38	-23.47	-151.91	-294.97	-493.69	3.38	11.74	26.86	53.13	92.89	
	(SF)	0.1237	0.3088	0.5689	0.5690	0.5312	0.2418	0.4497	0.5453	0.4751	0.6209	
	(SF) (SF)	0.0010	0.0002	-0.0001	0.0000	0.0002	-0.0002	-0.0003	-0.0001	-0.0003	0.0000	
	(CF)	0.7813	0.7483	1.1866	1.6390	1.8210	0.9040	0.8283	0.7851	0.7931	0.7425	
	(CF) (CF)	0.0003	-0.0008	-0.0015	-0.0017	-0.0013	0.0006	0.0012	0.0008	0.0007	0.0006	
QUADRANT 2	Intercept	-1.86	-10.69	13.68	75.97	61.50	-1.40	-3.91	-1.22	-1.18	5.20	
	(SF)	-0.0261	0.0011	-0.0206	0.0181	0.0373	0.1040	0.3889	0.5325	0.6064	0.6233	
	(SF) (SF)	0.0020	0.0015	0.0005	0.0000	0.0001	0.0001	-0.0007	-0.0005	-0.0003	0.0000	
	(CF)	0.9116	0.8591	0.6190	0.2089	0.4061	0.9241	0.7044	0.5742	0.5092	0.5899	
	(CF) (CF)	-0.0001	-0.0006	-0.0007	-0.0004	-0.0006	-0.0012	-0.0008	-0.0004	-0.0002	-0.0000	
QUADRANT 3	Intercept	-3.42	-14.57	-27.91	-48.60	-62.27	-0.59	-1.49	0.13	-1.11	-9.87	
	(SF)	0.1881	0.4135	0.6348	0.9287	0.8602	0.3143	0.4876	0.5797	0.6340	0.7412	
	(SF) (SF)	0.0001	0.0007	-0.0001	-0.0003	0.0000	-0.0031	-0.0017	-0.0010	-0.0005	-0.0001	
	(CF)	0.8618	0.7198	0.2985	0.0970	0.7945	0.6814	0.5478	0.5478	0.4607	0.4354	
	(CF) (CF)	-0.0010	0.0004	0.0005	0.0008	0.0005	-0.0016	-0.0010	-0.0003	-0.0001	0.0002	
QUADRANT 4	Intercept	-7.93	-32.72	-48.98	-57.78	-14.22	3.12	11.75	23.04	34.65	52.85	
	(SF)	0.2192	0.4608	0.4758	0.3307	0.3920	0.1842	0.4186	0.5869	0.7349	0.9000	
	(SF) (SF)	0.0023	0.0012	0.0004	0.0000	-0.0001	0.0011	0.0006	0.0005	0.0002	-0.0000	
	(CF)	0.8846	0.7589	0.6721	0.6982	0.1100	0.9281	0.7922	0.6285	0.4880	0.3184	
	(CF) (CF)	0.0008	0.0000	-0.0006	-0.0012	-0.0001	0.0007	0.0009	0.0004	0.0002	0.0000	
	(SF) (CF)	-0.0025	-0.0009	0.0007	0.0019	0.0015	-0.0018	-0.0015	-0.0009	-0.0003	0.0001	

Table 22 Standard error, reduction of variance and related statistical data using the NHC72 equations on dependent data set

QUADRANT 1	MERIDIONAL MOTION					ZONAL MOTION				
	12HR	24HR	36HR	48HR	72HR	12HR	24HR	36HR	48HR	72HR
Number of cases	332	332	332	332	332	332	332	332	332	332
Percentage reduction of variance	85	70	67	64	54	92	81	74	70	66
Standard error of forecast displacements	21	62	101	150	278	20	65	121	180	312
Standard deviation of observed displacements	53	111	173	245	404	70	147	232	327	524
Mean absolute forecast error	19	54	87	121	217	15	51	95	147	248
Mean of observed displacements	101	197	292	389	588	-24	-62	-117	-187	-361
QUADRANT 2	MERIDIONAL MOTION					ZONAL MOTION				
	12HR	24HR	36HR	48HR	72HR	12HR	24HR	36HR	48HR	72HR
Number of cases	382	382	382	382	382	382	382	382	382	382
Percentage reduction of variance	83	68	62	57	51	88	80	75	71	67
Standard error of forecast displacements	17	47	84	123	219	19	51	91	140	263
Standard deviation of observed displacements	40	83	134	185	310	54	112	177	256	452
Mean absolute forecast error	13	38	66	100	171	16	40	70	110	211
Mean of observed displacements	74	148	228	309	480	80	140	181	198	162
QUADRANT 3	MERIDIONAL MOTION					ZONAL MOTION				
	12HR	24HR	36HR	48HR	72HR	12HR	24HR	36HR	48HR	72HR
Number of cases	370	370	370	370	370	370	370	370	370	370
Percentage reduction of variance	86	68	61	56	48	89	79	74	70	68
Standard error of forecast displacements	15	47	79	116	214	17	51	89	134	234
Standard deviation of observed displacements	40	82	125	172	293	53	109	171	240	409
Mean absolute forecast error	11	33	60	83	150	13	38	66	100	173
Mean of observed displacements	32	75	126	186	331	70	131	182	219	238
QUADRANT 4	MERIDIONAL MOTION					ZONAL MOTION				
	12HR	24HR	36HR	48HR	72HR	12HR	24HR	36HR	48HR	72HR
Number of cases	324	324	324	324	324	324	324	324	324	324
Percentage reduction of variance	82	70	65	63	58	93	85	80	79	73
Standard error of forecast displacements	19	56	99	147	254	20	63	114	160	286
Standard deviation of observed displacements	44	101	165	237	387	76	161	249	344	542
Mean absolute forecast error	16	43	82	112	189	15	50	95	130	238
Mean of observed displacements	51	113	179	257	434	-37	-77	-121	-171	-299

Note: Displacements are in units of nautical miles with southward and eastward motion negative.