A Diagnostic Study on the Statistical Predictability of Tropical Cyclone Motion

CHARLES J. NEUMANN AND JOHN R. HOPE
National Hurricane Center, Miami, Fla. 33124

(Manuscript received 10 April 1972, in revised form 25 August 1972)

ABSTRACT

Statistical tropical cyclone prediction systems typically fall into one of three categories: 1) those using meteorological predictors derived from observed synoptic data; 2) those using purely empirical predictors such as climatology, present motion, past motion, analogs, etc.; and 3) those using combinations of both synoptic and empirical predictors. The variance-reducing potential of each of these prediction systems on given sets of dependent data is examined in detail. In general, it is found that empirical prediction systems are always superior in the shorter range forecast periods and even for extended forecast periods before storm recurvature. During and after storm recurvature, however, the synoptic-type predictors provide a better means of reducing the variance of tropical cyclone motion. It is shown that statistical tropical cyclone forecasting systems should make judicious use of both synoptic and empirical predictors.

1. Introduction

The National Hurricane Center (NHC) currently uses four semi-independent, computerized techniques to provide objective guidance preparatory to the issuance of tropical cyclone forecasts. These systems, known as NHC-67, HURRAN, CLIPER, and SANBAR, provide estimates of storm displacements over forecast intervals extending out to 72 hr.

The NHC-67 system (Miller *et al.*, 1968) or its predecessor, NHC-64 (Miller and Chase, 1966), has been in use at NHC for a number of years. Zonal (E–W) and meridional (N–S) components of storm displacements are computed from a series of regression equations which use predictors derived from the observed heights and 24-hr height changes of the 1000-, 700-, and 500-mb surfaces. Additionally, persistence is used as a predictor in the shorter forecast periods.

HURRAN (Hope and Neumann, 1970) is an analog system. All recorded tropical cyclone tracks back to the year 1886 are computer scanned and those with time and space characteristics similar to the current storm are identified and translated to a common origin. The cluster of analog storm positions at the various forecast intervals is then fitted to a bivariate normal distribution, the centroids of which represent the forecast track. HURRAN, like NHC-67, uses some persistence in the early forecast periods.

CLIPER (Neumann, 1972) is a new technique used for the first time during the 1971 hurricane season. The system makes explicit use of climatology and persistence through a series of nonlinear multiple regression equations fitted essentially to the same predictors used 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 times.

SANBAR (Sanders and Burpee, 1968) is a filtered barotropic model with input derived from grid-point values of the current 1000- to 100-mb pressure-weighted winds. 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 for the 1971 hurricane season.

These four systems are procedurally different approaches to the problem of tropical cyclone forecasting. Each is capable of producing displacement forecasts with errors ranging from near zero to over 1000 n mi for the 72-hr forecast period. It is not at all unusual for one or more of the systems to predict widely differing forecast 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 on decision making are currently being used (Simpson, 1971), the problem of which of these objectively computed tracks to follow, if any, remains one of the critical decisions for the hurricane forecaster.

2. Purpose

Conceptually, a solution to the problem outlined above would be to make temporal and spatial error analyses of the four forecast systems and combine their better features into a single system. Corzine (1964), used statistically derived weighting factors to combine

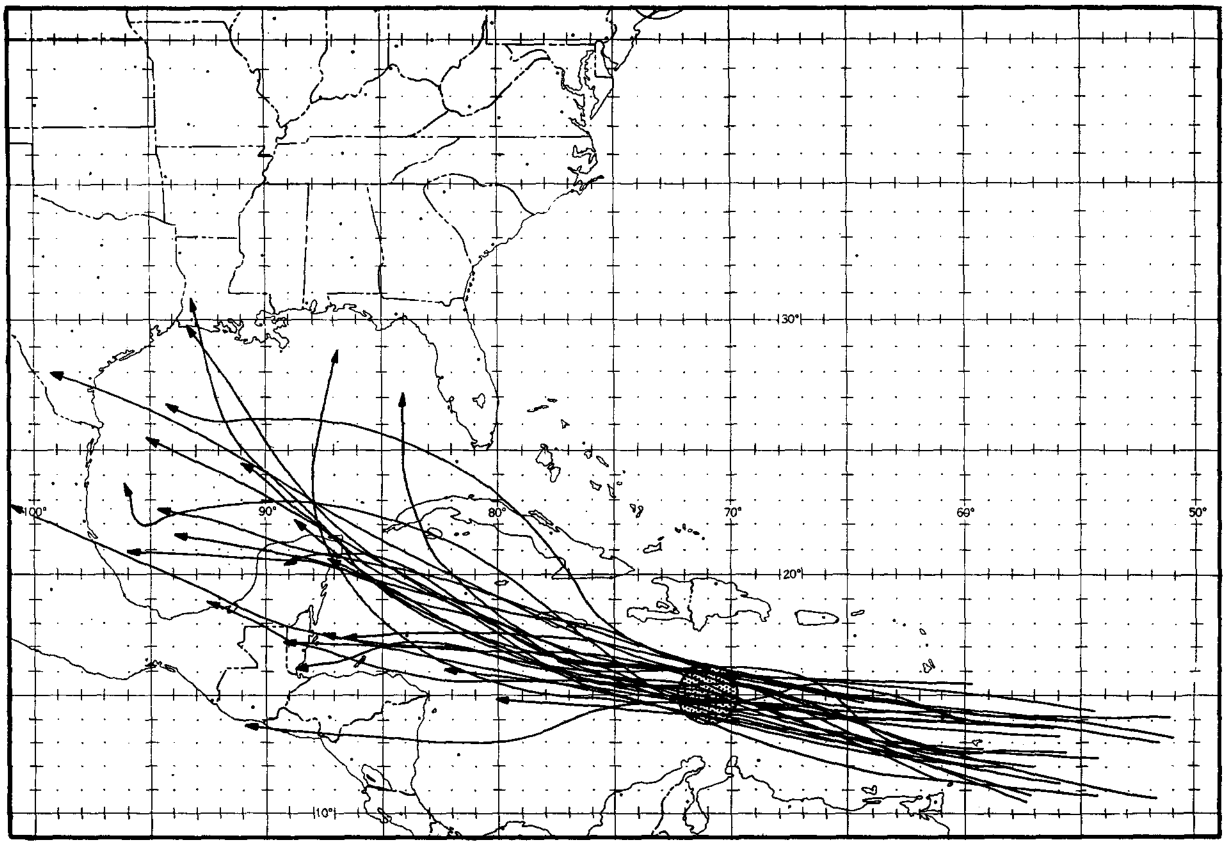

FIG. 1. Tracks of all recorded tropical cyclones which passed within 75 n mi of 15N, 71W, 16 July through 20 September, 1886–1970.

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-hr forecast, the results of Corzine's study were encouraging enough to suggest further evaluation of the principle when sufficient data became available.

Practical considerations preclude such a direct approach to the problem. Since SANBAR is a relatively new system, there are insufficient dependent data; furthermore, SANBAR forecasts are not available early enough to be combined with the other systems on a real-time basis. HURRAN forecasts are not always available. Also, since all three statistical systems use some persistence in the early forecast periods, the forecasts are not independent. Furthermore, the three statistical systems were developed from different dependent-data sets. For these reasons, a more basic approach was conceived.

In the broad sense, the three statistical schemes in use at NHC derive their variance-reducing potential from either synoptic or empirical[1] sources. The purpose of this study is to examine in some detail the relative reduction in variance of tropical cyclone motion which can be expected from a synoptic approach as opposed to an empirical approach. It will be shown that statistical tropical cyclone forecasting systems must make judicious use of predictors from both sources. Such a finding is not new; Miller and Moore (1960), for example, in referring to 24-hr forecasts, stress the importance of persistence in reducing forecast errors. The current study attempts to examine the time-space contributions of the different predictors in greater detail than has heretofore been accomplished.

The study is purely diagnostic; although forecasting equations using the concepts presented herein have been developed, they will be reported in a separate paper. Reasons for inadequacies of the various predictors will not be discussed. The intent here is to establish guidelines from which further development of statistical forecasting techniques can proceed in a logical and orderly fashion. As stated by Mills (1955), in referring to multivariate regression analysis, "Wisdom in the selection of functions, time units, strategic periods, etc., requires some understanding of the ground plan of nature in the particular field of study, as well as competence in the application of statistical techniques. The task of analysis is never purely mechanical."

[1] In the sense used here, synoptic predictors refer to those derived from observed upper air data, whereas empirical predictors refer to climatology, persistence, analogs, etc.

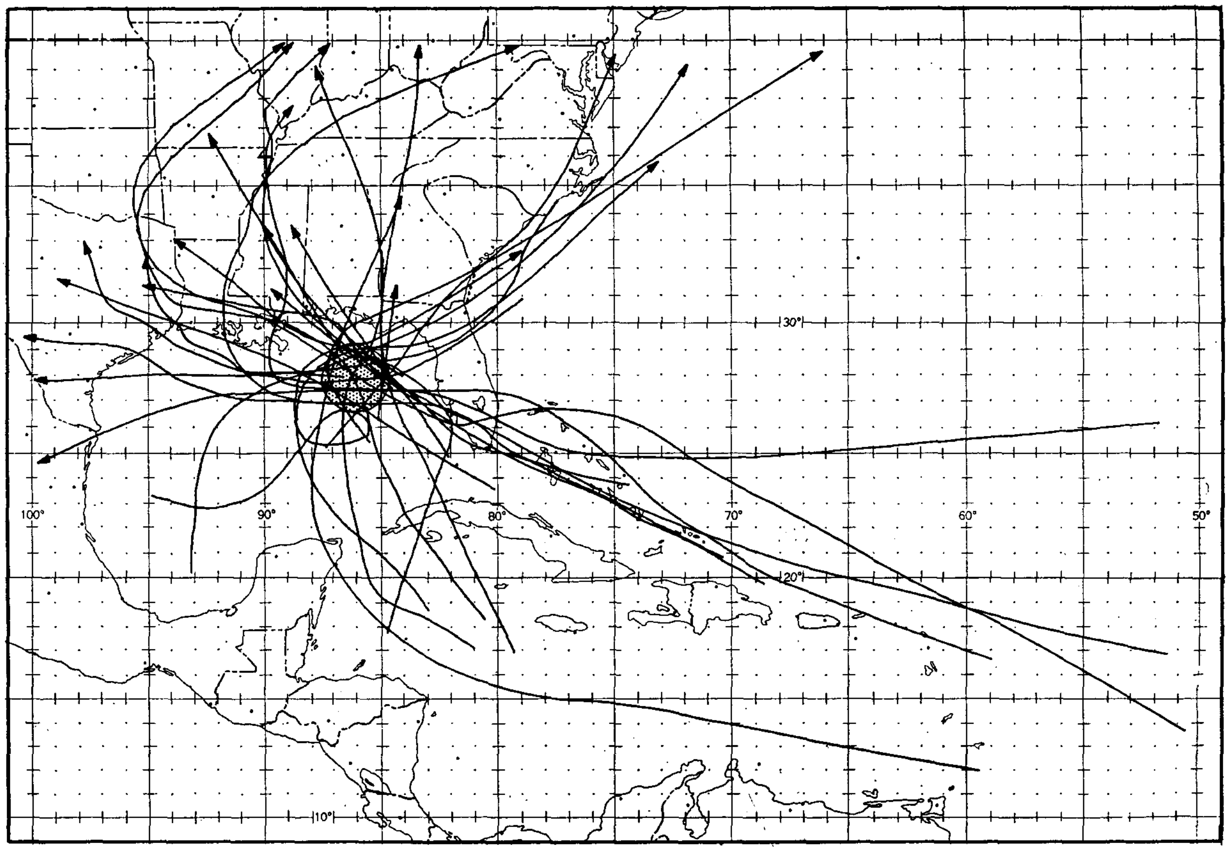

FIG. 2. Same as Fig. 1 except for 28N, 86W.

3. Empirical prediction systems

Neither HURRAN nor CLIPER requires any direct synoptic data input and in this sense they are purely empirical. Both of the systems do, however, require initial storm motion (in the form of U and V components of motion) as initial predictors. Current storm motion reflects the instantaneous integrated effect of the synoptic steering environment. It should be expected, therefore, that both HURRAN and CLIPER would out-perform prediction systems based on synoptic data in both the short-range forecast and also for longer range forecasts in areas where the synoptic patterns show little variation.

The two latter conditions are illustrated in Fig. 1. Each of the tropical cyclones passing through this designated area during this portion of the season is most likely associated with a somewhat similar synoptic steering pattern and the eventual location of storms passing through this area can be predicted with skill using only empirical predictors. Therefore, HURRAN and CLIPER perform well in such areas. For example, the 72-hr mean displacement error, using independent CLIPER forecasts on Hurricane Edith, 1971, which passed near this area, was only 230 n mi, which is well below the long-term average 72-hr error.

In contrast, the circular area in Fig. 2 for the same portion of the season is a region where a variety of hurricane-associated synoptic steering patterns must have existed. In such areas, empirical systems, even with initial motion as predictors, do not normally do so well as those based on synoptic predictions in anticipating eventual storm locations. In these areas, therefore, prediction systems sensitive to the existing (or forecast) synoptic environment can be expected to give better results than those based on empirical predictors.

Detailed error analysis on both the HURRAN (Neumann and Hope, 1972) and CLIPER (Neumann, 1972) systems support this hypothesis. Fig. 3, extracted from these sources shows the 36-hr mean displacement error (E_{36}) as a function of the initial westward (U) and initial northward (V) component of storm motion given by the third-order polynomial

$$E_{36}(U,V)=C_1+C_2U+C_3V+C_4UV+C_5U^2+C_6V^2 +C_7U^3+C_8U^2V+C_9UV^2+C_{10}V^3, \quad (1)$$

where the constants C_1 through C_{10} are determined from the simultaneous solution of the 10 normal equations formulated from (1) by standard least-squares techniques. Fig. 3 clearly demonstrates the relatively low residual errors of the two empirical systems when

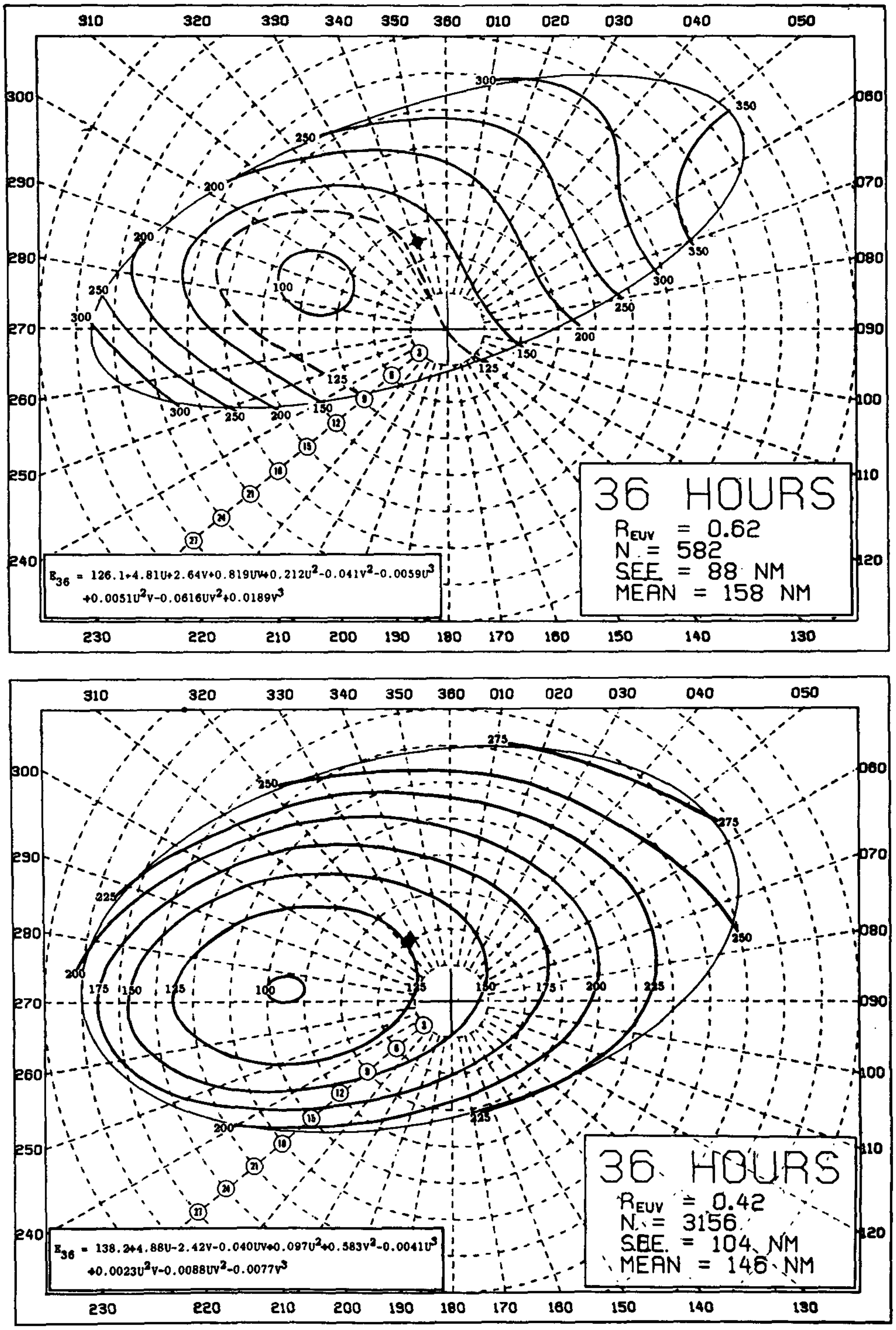

FIG. 3. Thirty-six hour HURRAN (top) and CLIPER (bottom) displacement errors (n mi) (solid curves) as a function of the initial storm heading and speed. The dashed radials are storm headings in degrees and the concentric dashed circles are spaced at 3-kt intervals. The outer ellipse encloses the 99% data envelope. R_{euv} is the multiple correlation coefficient, N the number of observations, and *SEE* the standard error of estimate.

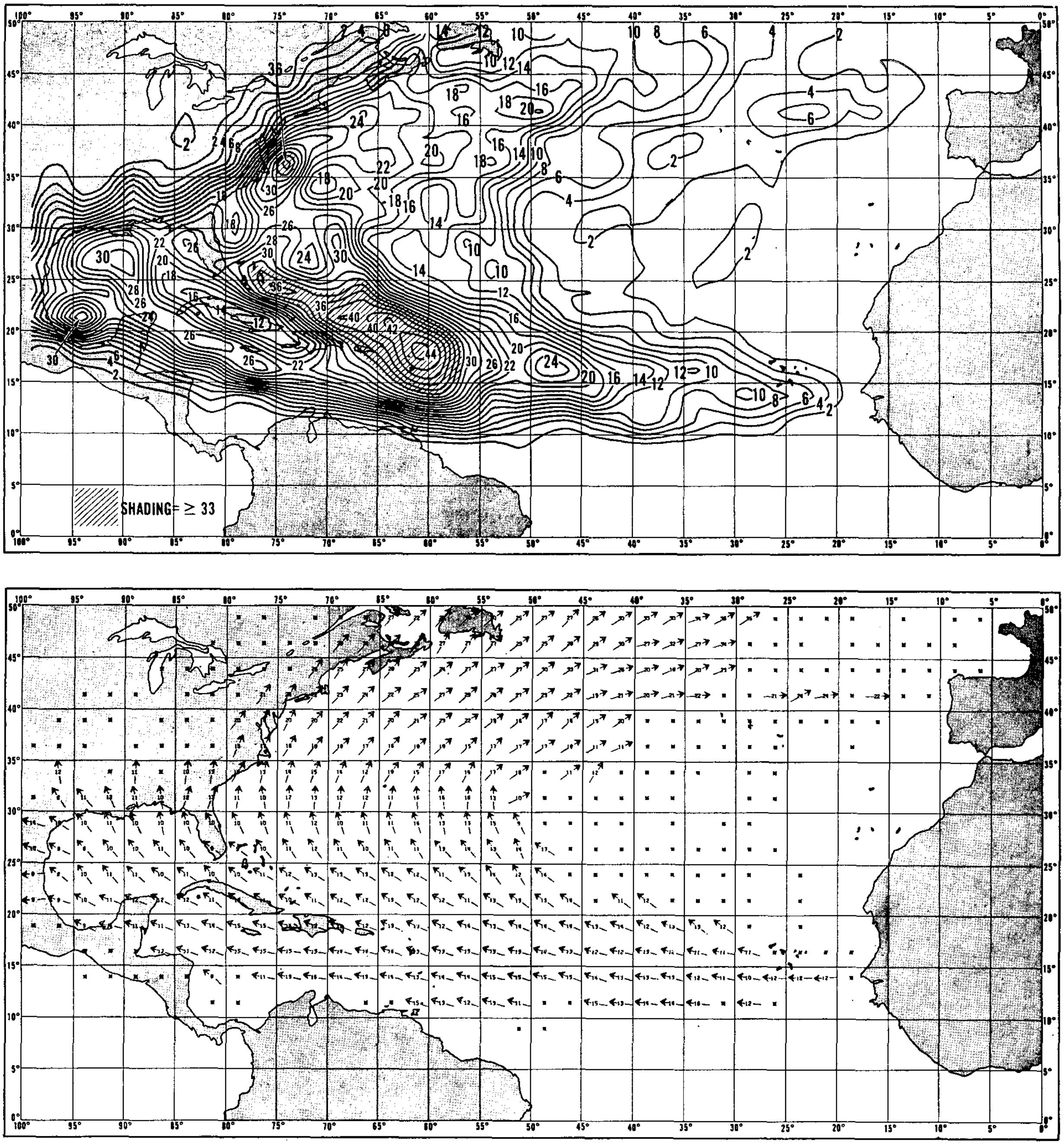

FIG. 4. Number of tropical cyclones passing through each $2\frac{1}{2}$ latitude-longitude box (top) and resultant direction and mean scalar speed (kt) for each box (bottom) over the period 16 July through 20 September, 1886–1968. Boxes marked with asterisks have insufficient data for analysis.

the initial storm motion is in a westerly or northwesterly direction with speeds generally between 8 and 16 kt. Fig. 4, from Hope and Neumann (1971), shows that such motion is not only typical of a large portion of the Atlantic tropical cyclone belt south of 27N during the main portion of the hurricane season, but also that most tropical cyclones occur in this belt. Furthermore, with the exception of the east coast of the United States north of Florida, most tropical cyclones striking North America and the West Indies have a westerly component of zonal motion. Maximum advantage should be taken of systems which excel in the prediction of this type of motion.

Fig. 3 also demonstrates that storms on general northerly through northeasterly headings are relatively poorly forecast by the empirical systems. Such move-

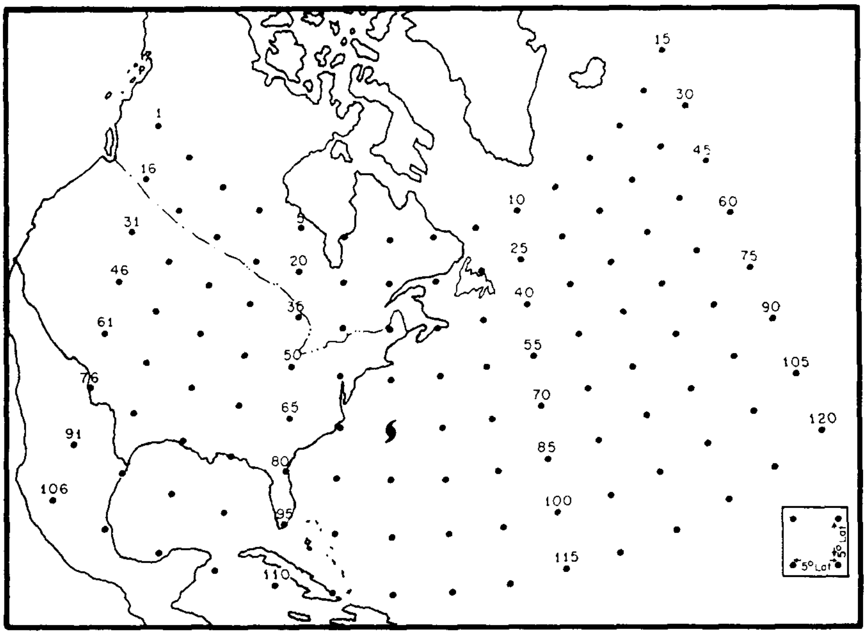

FIG. 5. The moving grid system used in deriving prediction equations from synoptic data.

ment is typical of higher latitudes where, as will be shown, the variance-reducing potential of a forecast system must be derived principally from synoptic sources.

4. Synoptic prediction systems

The original NHC-67 system derived its variance-reducing potential from both empirical (persistence) and synoptic (observed upper-air data) predictors. To study the predictability of hurricane motion using purely synoptic predictors, it was necessary to formulate revised prediction equations eliminating the persistence term. For this purpose, the moving 8×15 storm-centered grid (Fig. 5) used in developing the original NHC-67 equations was again employed. The dependent data set was extended to include the period through the 1969 hurricane season, thus providing 999 forecast situations dating back through 1945. For each case, in addition to the usual storm displacement and bookkeeping data, the master data tape lists the geopotential heights, the 24-hr height changes, and the departures from normal at each of the 120 grid points at 1000, 700 and 500 mb. Also included for each case are the precomputed CLIPER and HURRAN forecasts.

Prior to the actual computer screening run, the dependent data set was stratified into four groups of storms. Fig. 6 illustrates the stratification scheme. The initial 12-hr components of motion of the 999 cases comprising the dependent data set were fitted to a bivariate normal distribution. The new (A,B) coordinate axes through the centroid of the distribution were rotated counterclockwise through an angle of 12° from the original axes. At this angle, components of motion along the new coordinate system are uncorrelated. Details concerning this fitting process are discussed in Hope and Neumann (1970). The new (A,B) coordinate system conveniently divides the data set into four approximately equal sub-sets, with the storms in each sub-set having similar motion characteristics.

Separate screening runs of the type described by Efroymson (1964) were made for each of the four quadrants. Screening of the grid-point data was continued until the addition of another predictor (excluding persistence) failed to reduce the variance of tropical cyclone motion an additional 1%. Further screening runs were then made for each quadrant with the appropriate CLIPER forecast as an allowable predictor. In order to make the forecasts comparable to the CLIPER system, the forecast time steps were taken as 0–12, 0–24, 0–36, 0–48 and 0–72 hr rather than in the shorter component time steps as used in the original NHC-67 system. Since the actual prediction equations are not pertinent to the purpose of this study, they will not be presented here. The completed operational prediction system will be the subject of a separate paper.

5. Synoptic or empirical predictors

An analysis of the variance-reducing potential of 1) purely synoptic predictors, 2) purely empirical predictors, and 3) a combination of both predictor types was made for each of the four quadrants defined in Fig. 6. The modified NHC-67 system discussed in the previous section was used as the synoptic system and the CLIPER equations were used to represent the purely empirical approach. Figs. 7–10 present a graphical depiction of the relative superiority of the

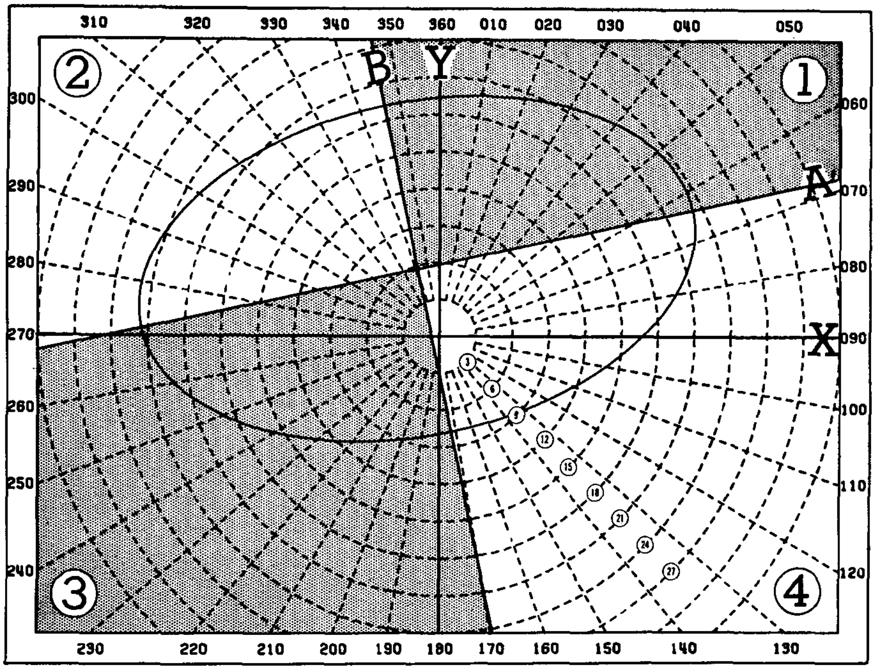

FIG. 6. Quadrants into which storms were stratified according to initial motion. The radials are direction of storm movement and the concentric circles give speed at 3-kt intervals. The ellipse is the 99% data envelope assuming a bivariate normal distribution of the initial U and V components of motion.

different prediction systems for each of the five forecast periods. The smooth curves drawn between data points in the figures were objectively derived using the technique suggested by Akima (1970).

Reduction of variance (RV), multiple correlation coefficients (R_m), standard errors (SE), and standard deviations (SD) are interdependent and are related according to

$$RV = R_m{}^2 = 1 - \frac{(SE)^2}{(SD)^2}. \tag{2}$$

A time plot of each of these four related quantities are included in Figs. 7–10. Where applicable, the correction for lost degrees of freedom has been applied to each quantity. It should be noted that the reduction of variance depends not only on the standard error but also on the standard deviation of the original observed data. Since the standard deviation of observed tropical cyclone motion is greater at the higher latitudes where storms have an eastward component of motion (quadrants 1 and 4), similar reduction of variance in these quadrants are associated with greater standard errors.

a. An overview

A large amount of diagnostic information is apparent upon study of Figs. 7–10. In the broad sense, the figures point out that meridional motion is associated with greater unexplained variance than is zonal motion. This is particularly true when considering CLIPER forecasts by themselves. On a percentage basis, the addition of synoptic predictors contributed more to improving the forecast of meridional motion than of zonal motion. However, the combined effect of both synoptic and empirical predictors still fails to explain more than half of the variance of 72-hr meridional motion in either quadrant 2 or 3. Such a situation is quite discouraging when one considers that these two quadrants contain the great majority of storms which strike populated areas of North America and the West Indies. The addition of predictors derived from numerical prognostic charts, using techniques described by Klein (1971), may serve to improve this situation.

Without exception, the variance explained by the CLIPER system falls off rapidly with time. This is particularly true with meridional motion. Such is not the case using synoptic predictors and in some cases, the variance-reducing potential of these predictors actually increases with time. This latter result is in contrast to what one might expect on purely *a priori* grounds.

b. Individual quadrants

The point in time at which the synoptic curve crosses the CLIPER curve on each figure is of prime importance since this determines the time that the synoptic predictors become better suited than empirical predictors to predict tropical cyclone motion. Table 1 shows that depending on quadrant and initial component of motion, there is considerable variation of this crossover point.

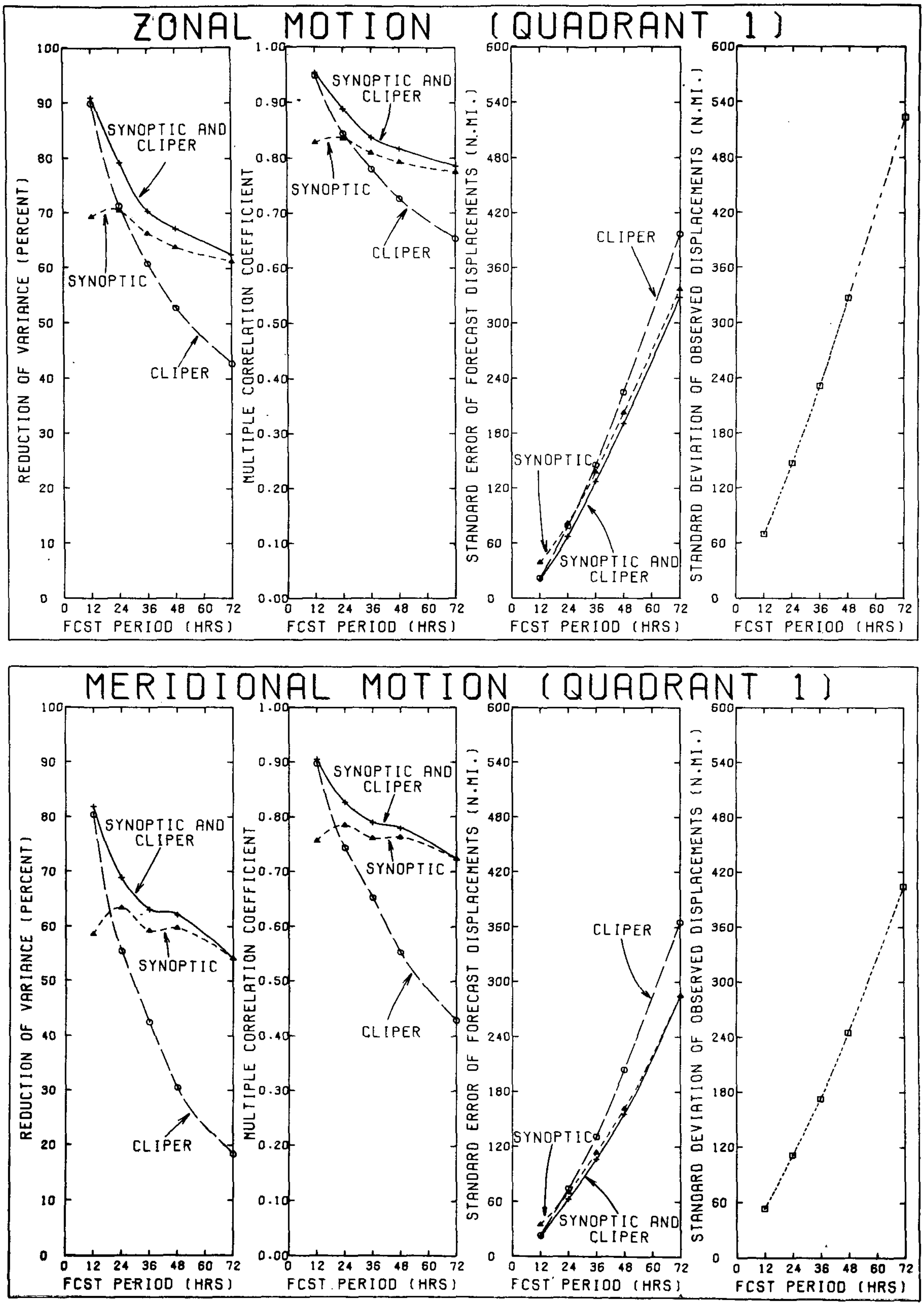

FIG. 7. Residual error analysis of forecast tropical cyclone displacement with initial motion in quadrant 1.

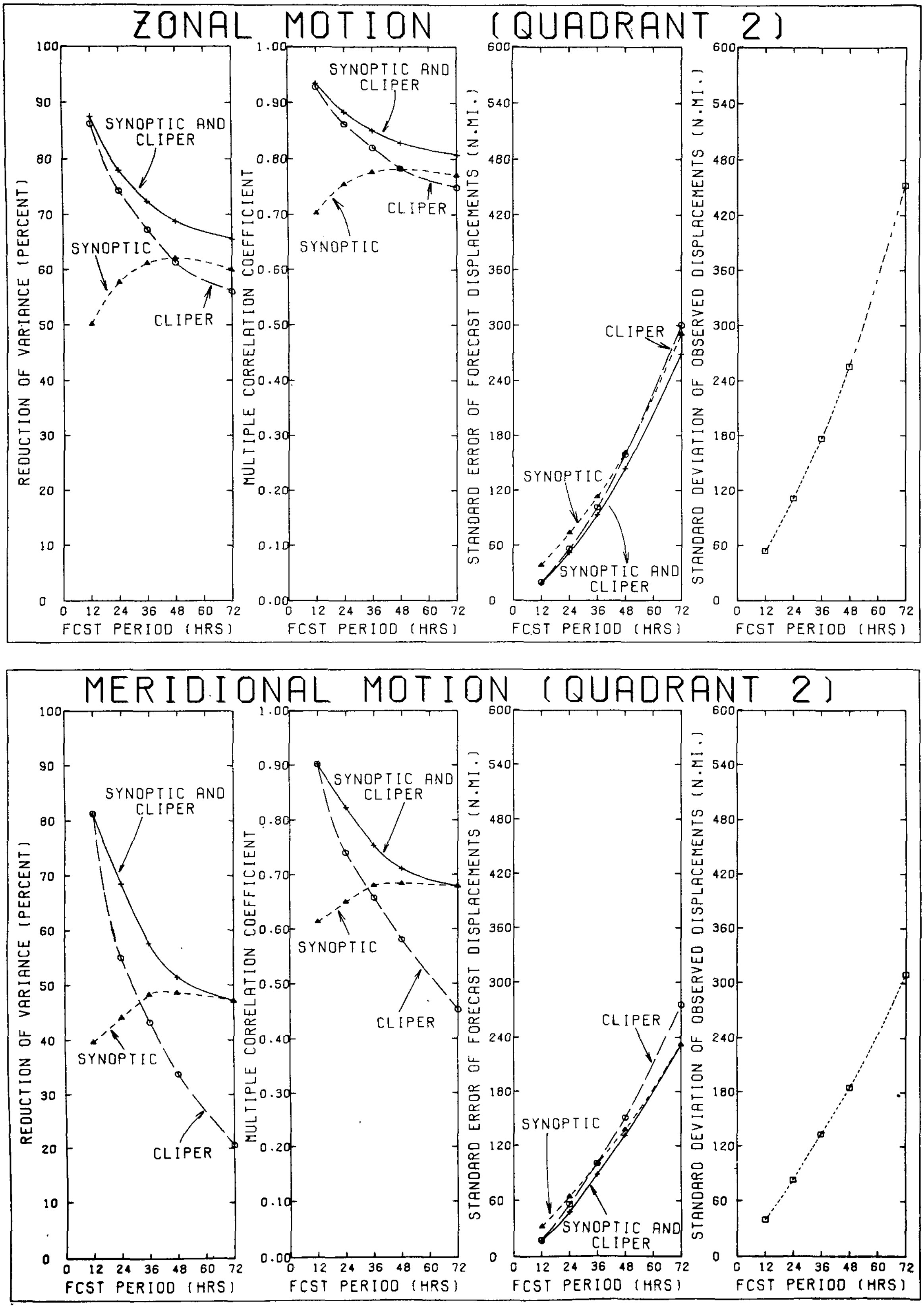

FIG. 8. Same as Fig. 7 except for quadrant 2.

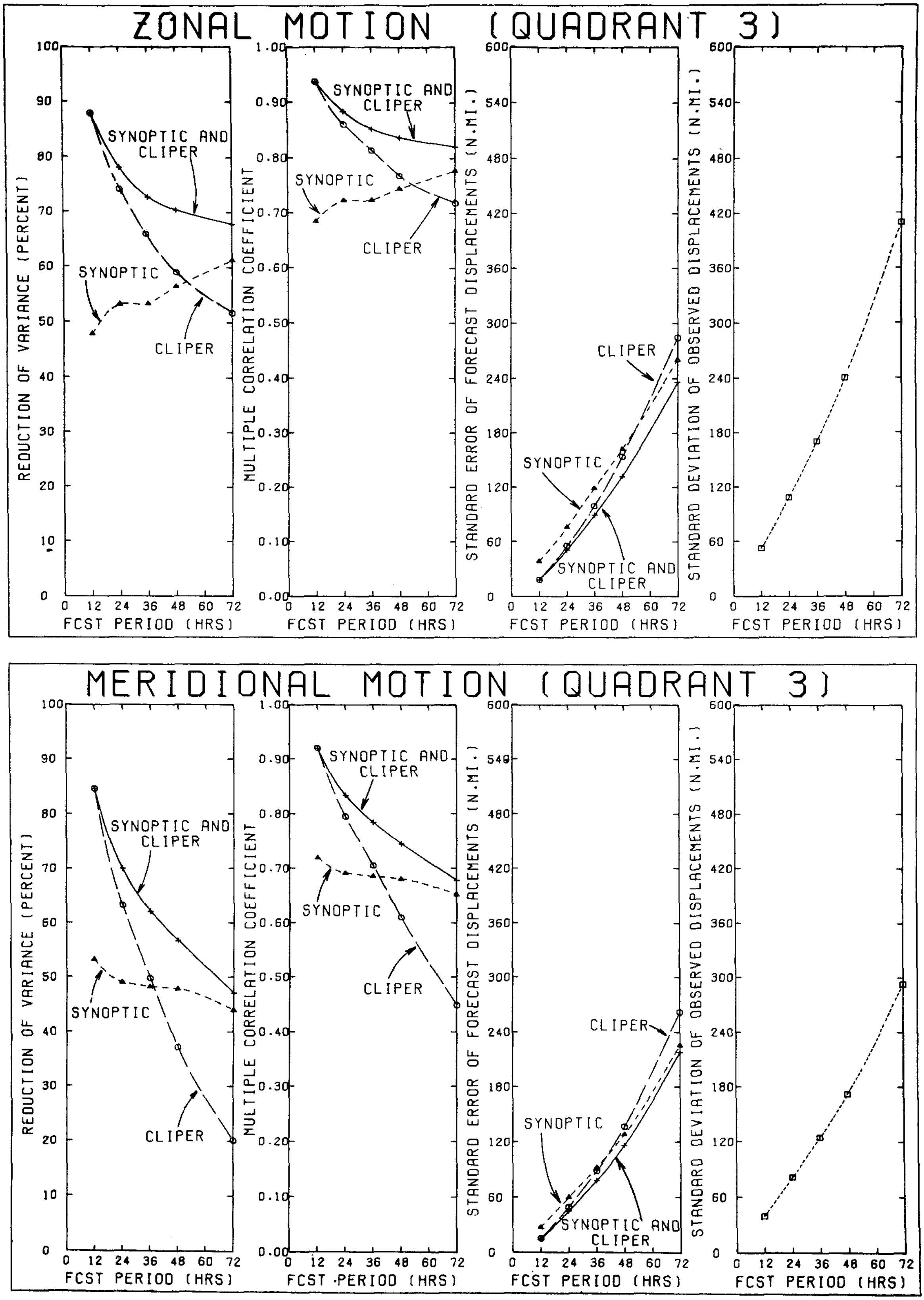

Fig. 9. Same as Fig. 7 except for quadrant 3.

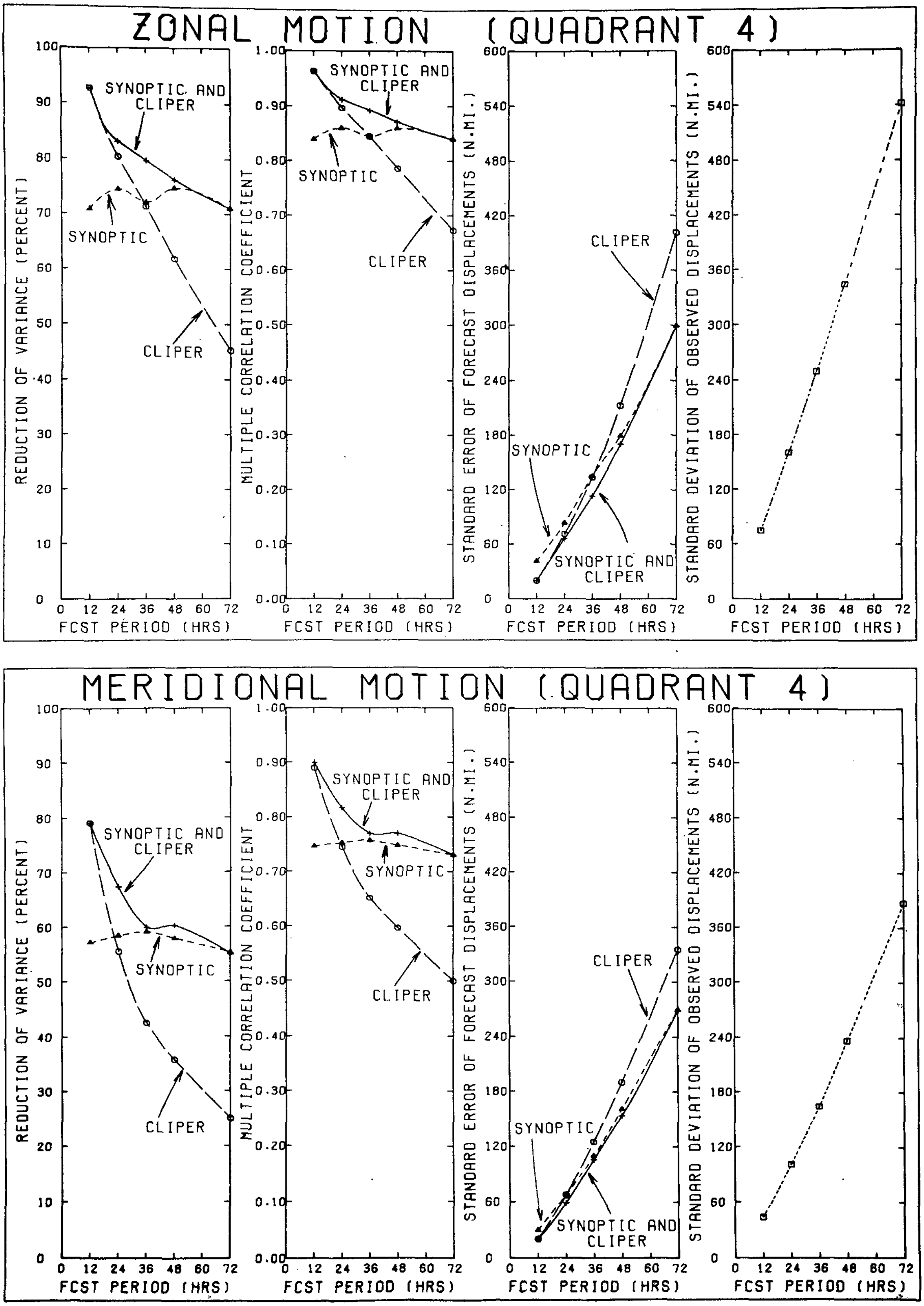

FIG. 10. Same as Fig. 7 except for quadrant 4.

TABLE 1. Crossover point (hours) between synoptic and CLIPER curves

Quadrant number	Type of motion	Crossover point
1	Zonal	25
1	Meridional	17
2	Zonal	46
2	Meridional	32
3	Zonal	54
3	Meridional	38
4	Zonal	35
4	Meridional	22
Average 1–4	Zonal	40
Average 1–4	Meridional	27

The synoptic predictors become better in only 17 hr in the case of meridional motion in quadrant 1, but CLIPER predictors are superior to synoptic for the first 54 hr in the case of zonal motion in quadrant 3. On the average, the CLIPER approach works considerably better with zonal motion than it does with meridional motion. Considering individual quadrants, CLIPER shows up better in quadrants 2 and 3 (westerly component of motion, before storm recurvature) than in quadrants 1 and 2 (after recurvature). These results are in complete accord with the error analyses presented in Fig. 3 and point out that empirical type predictors used in the CLIPER system offer the best means of reducing variance before storm recurvature for periods up to 36 or 48 hr. However, during and after storm recurvature, they give better results up to 12–36 hr only.

6. Conclusions

This diagnostic study leads to the following conclusions:

1. On the average, the synoptic predictors as used herein explain only about 50% of the variance of meridional motion.
2. Any statistical forecasting scheme used to predict tropical cyclone motion should consider both synoptic and empirical predictors.
3. The empirical predictors provide the best single means of reducing variance in the early forecast periods and even in extended forecast periods before storm recurvature. Any weighting of the forecast displacements must therefore be both time and space dependent.
4. After 24 hr, during and after storm recurvature, the synoptic predictors contribute more to the reduction of variance than do the empirical predictors.
5. In the statistical sense, zonal motion is easier to predict than meridional motion.
6. The variance-reducing potential of the empirical prediction systems decreases rapidly with time whereas that of the synoptic system changes only slightly, and in some cases increases, with time.

Acknowledgments. The authors are grateful to Dr. Banner Miller of the National Hurricane Center for encouragement and advice during the study.

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 upon which the synoptic grid data reside.

REFERENCES

Akima, H., 1970: A new method of interpolation and smooth curve fitting based on local procedures. *J. Assoc. Computing Mach.*, **17**, 589–602.

Corzine, H. A., 1964: A comparison of objective hurricane forecasting methods and attempts to combine two or more of these methods. NWRF 12-1164-098, U. S. Navy Weather Research Facility, Norfolk, Va. 19 pp.

Efroymson, M. A., 1964: Multiple regression analysis. *Mathematical Methods for Digital Computers*, A. Ralston and H. S. Wilf, Eds., New York, Wiley, 191–203.

Hope, J. R., and C. J. Neumann, 1970: An operational technique for relating the movement of existing tropical cyclones to past tracks. *Mon. Wea. Rev.*, **98**, 925–933.

——, and ——, 1971: Computer methods applied to Atlantic area tropical storm and hurricane climatology. *Mariners Wea. Log*, **15**, 272–278.

Klein, W. H., 1971: Computer prediction of precipitation probability in the United States. *J. Appl. Meteor.*, **10**, 903, 915.

Miller, B. I., E. C. Hill and P. P. Chase, 1968: Revised technique for forecasting hurricane motion by statistical methods. *Mon. Wea. Rev.*, **96**, 540–548.

——, and P. P. Chase, 1966: Prediction of hurricane motion by statistical methods. *Mon. Wea. Rev.*, **94**, 399–406.

——, and P. Moore, 1960: A comparison of hurricane steering levels. *Bull. Amer. Meteor. Soc.*, **41**, 59–63.

Mills, F. C., 1955: *Statistical Methods*. New York, Holt, Rinehart and Winston, 625 pp.

Neumann, C. J., 1972: An alternate to the HURRAN tropical cyclone forecast system. NOAA Tech. Memo. NWS SR-62, 32 pp.

——, and J. R. Hope, 1972: A performance analysis of the HURRAN tropical cyclone forecast system. *Mon. Wea. Rev.*, **100**, 245–255.

Pike, A. C., 1972: Improved barotropic hurricane track prediction by adjustment of the initial wind field. NOAA Tech. Memo. NWS SR-66, 16 pp.

Sanders, F., and R. W. Burpee, 1968: Experiments in barotropic hurricane track forecasting. *J. Appl. Meteor.*, **7**, 313–323.

Simpson, R. H., 1971: The decision process in hurricane forecasting. NOAA Tech. Memo. NWS SR-53, 35 pp.