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An Operational Experiment in the Statistical-Dynamical Prediction of Tropical Cyclone Motion

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ABSTRACT

Current statistical models for the prediction of tropical cyclone motion use predictors derived from climatology, persistence, and observed geopotential height data. This paper describes an operational experiment conducted during the 1973 and 1974 Atlantic hurricane seasons whereby prognostic 500 mb height data from the National Meteorological Center's primitive equation model were also included as statistical predictors. Both the "perfect-prog" and a "simulated-model-output-statistics" (SMOS) approach were utilized to introduce the prognostic height data into the statistical prediction equations. Compared to the current "state-of-the-art" of tropical cyclone forecasting, the perfect-prog technique gave relatively poor displacement forecasts for the first half of the 72 h forecast period but excellent forecasts for the latter half. The SMOS method performed well over the entire period but the 72 h displacement error was somewhat greater than that of the perfect-prog equations.

The results of the test are extremely encouraging and suggest that independent predictive information obtained from the numerical prognoses can be objectively used to improve the performance of current statistical tropical cyclone prediction models.

1. Introduction

A number of techniques for the objective determination of tropical cyclone motion are either in operational use or under development at the National Hurricane Center (NHC) in Miami, Fla. Three statistical models, NHC67 (Miller *et al.*, 1968), NHC72 (Neumann *et al.*, 1972), and CLIPER (Neumann, 1972) use the classical stepwise screening regression approach while a fourth statistical system, HURRAN (Hope and Neumann, 1970) uses analog concepts. Another operational system, SANBAR (Sanders and Burpee, 1968), as modified by Pike (1972), is a filtered barotropic model with input derived from 1000 to 100 mb pressure-weighted winds.

In recent years the large number of Atlantic area tropical cyclones with anomalous motion characteristics have highlighted inherent weaknesses in the purely statistical systems and given impetus to the development of dynamical and statistical-dynamical models. Accordingly, Miller *et al.* (1972) are experimenting with a seven-level primitive equation model, while Neumann and Lawrence (1973) describe a statistical-dynamical model known as NHC73 which uses the output from an existing numerical model such as the NMC primitive equation (PE) model (Shuman and Hovermale, 1968) as input to a statistical prediction system. Two versions of NHC73 were tested under operational conditions during the 1973 and 1974 hurricane seasons. This paper reviews the development of NHC73, describes results of the two year test, and suggests avenues of approach for further development of the statistical-dynamical concept as applied to tropical cyclone forecasting.

2. Statistical use of numerically derived prognostic data

Klein and Glahn (1974) discuss two techniques which have been successfully used to introduce numerically derived prognostic data into statistical prediction frameworks. One of these techniques, the so called "perfect-prog" method, is perhaps best exemplified by the work of Klein (1966) in maximum and minimum temperature forecasting. The other method, known as MOS for Model Output Statistics, is gradually supplanting the earlier concept.

In the perfect-prog method, observed values of a predictor at time $T_o+\Delta T$ are used along with current data to derive a statistical relationship between predictors and predictand at the same time $T_o+\Delta T$. In actual practice, observed values of the predictors are simulated imperfectly by the forecast values. Such a procedure results in the perfect-prog predictors being overweighted in the statistical prediction equations. This "over-weighting" (see Subsection 7c) is a major problem with a perfect-prog approach and in some cases can completely offset any benefits that the prognostic data may offer.

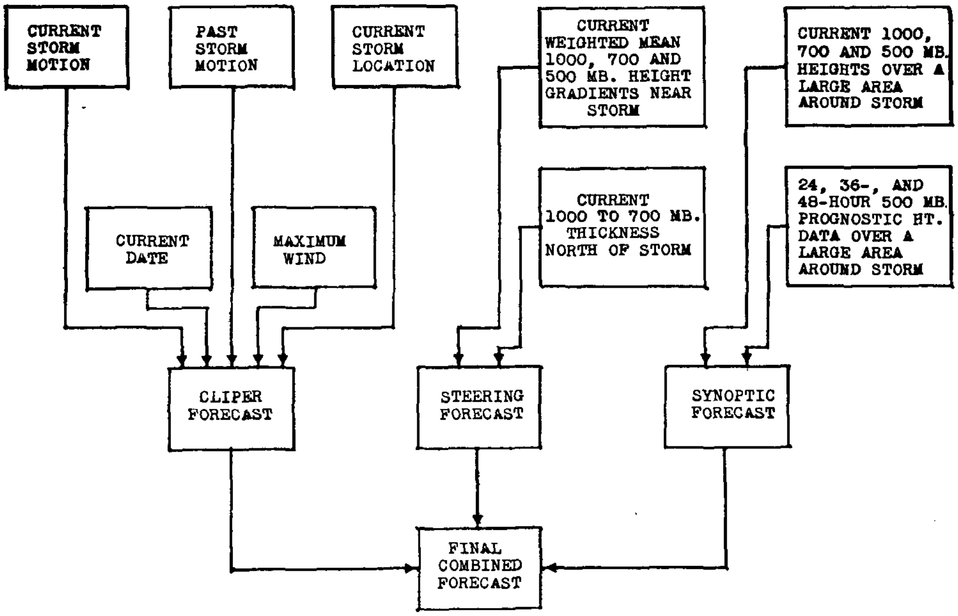

FIG. 1. NHC73 prediction algorithm.

In the MOS approach, direct output from a numerical prediction model is used to develop the statistical prediction equation; thus, both developmental and operational data assume similar error characteristics and overweighting is not a problem. The use of MOS, however, like any other statistical system, requires a minimum amount of developmental data to insure statistical stability. Since Atlantic area tropical cyclones are a relatively rare event, the collection of a sufficient data sample of tropical cyclone tracks and attendant PE prognostic grid-fields is impracticable at this time.

3. Veigas' experiment

Veigas (1966) describes experiments on the use of both the MOS and the perfect-prog concept to introduce 1960 vintage barotropic forecasts of 500 mb height fields into statistical tropical cyclone prediction schemes. Both the overweighting and the small-sample-size problem cited in the preceding section were encountered by Veigas. Nevertheless, with the perfect-prog approach, partial success in the prediction of zonal motion led him to conclude that the numerical progs did contain independent predictive information which should be incorporated into the statistical models. Veigas further concluded that improvements in large-scale circulation prediction would lead to significant increases in the accuracy of future statistical hurricane displacement models.

As a mutual solution to the problem of predictor overweighting in the perfect-prog concept and lack of sufficient data in the MOS approach, Veigas suggests a simulated MOS (SMOS) approach whereby the covariance matrix obtained from the perfect-prog data is contaminated with known error characteristics of the numerical model. A modification of this suggestion was incorporated into the experimental NHC73 system.

4. General description of the model

The results of Veigas experiment, the available data, available computer time, and experience with previous statistical prediction models led to the design of the new system. Most of the variance reduction associated with any statistical tropical cyclone prediction model is drawn from three sources: a) climatology and/or persistence, b) some type of "steering," and c) the position and intensity of the synoptic scale features which surround a storm. In Fig. 1, these three predictor classes are identified respectively as a CLIPER forecast, a steering forecast, and a synoptic forecast. Each may be considered to be a kind of independent subsystem in the prediction algorithm and, as such, yields a zonal and meridional displacement for each of the five projections, 12, 24, 36, 48, and 72 h. There is, of course, some overlap between sub-systems 2 and 3 since both use observed fields. The main difference is that the steering sub-system uses a predetermined height function as given by Eq. (2). In addition, the synoptic grid length is 300 n mi, whereas the grid length for the steering computations is one-half this value. Testing indicated that this finer grid resolution gave increased variance reducing potential to the steering sub-system.

The intermediate step of obtaining multiple sets of forecasts, one from each of the sub-systems, departs from traditional statistical concepts. Typically, all of the available predictors would have been analyzed in a stepwise procedure of the type described by Efroymson (1964). However, retaining the three sets of forecast displacements as separate entities provides the hurricane forecaster with important diagnostic information. It also permits maximizing the size of the development data set used by each sub-system. Finally, it provides for the ability to assign weighting factors to each sub-system based on operational rather than on dependent data (see Section 8.)

Another feature of the new model is the use of an expanded areal stratification system. The Atlantic, Caribbean, and Gulf of Mexico are subdivided into 52 zones. Using overlapping sets of data, a separate set of prediction equations was developed for each of these zones. Details on the stratification system follow in Section 7.

TABLE 1. The eight basic predictors of the CLIPER system together with their means and standard deviations.

P(I)	Predictor	Mean	Standard deviation
P(1)	Initial longitude (degrees)	68.4	15.4
P(2)	Initial latitude (degrees)	24.1	7.3
P(3)	Initial zonal motion (kt, E to W neg.)	−3.4	8.8
P(4)	Initial meridional motion (kt, S to N pos.)	−5.1	5.2
P(5)	Zonal motion 12 h ago	4.2	8.5
P(6)	Meridional motion 12 h ago	4.9	4.9
P(7)	Maximum wind near storm center (mph)	71.4	32.7
P(8)	Day number (135 through 334)	248 (Sep. 5)	37.0

5. Forecast derived from climatology and persistence (sub-system 1)

The CLIPER (CLImatology and PERsistence) system (Neumann, 1972) incorporates a sample of 3156 events to develop a prediction system based on climatology and persistence. The variance reducing potential is derived from eight predictors as listed in Table 1. An additional 156 secondary predictors are generated by considering all the possible second- and third-order products and cross-products of the 8 basic predictors. Standard stepwise screening regression techniques were used to eliminate those predictors which failed to contribute a 1% incremental variance reduction. Equation (1), for example, gives the 72 h zonal CLIPER forecast (DX_{72}) displacements in n mi with the units of the predictors (P_i) as given in Table 1.

$$\begin{aligned}DX_{72}=&-60.2+46.26(P_3)-8.81(P_5)\\&+29.12(P_2-24)+32.91(P_4)-0.022(P_4)^2(P_5)\\&-0.086(P_2-24)(P_4)(P_5)+3.29(P_1-68).\end{aligned}\quad(1)$$

For a complete description of the set of prediction equations, i.e., one for each component of motion at 12 h intervals out to 72 h, along with a description of their derivation and the usual variance analysis, the reader is referred to Neumann (1972).

Although current synoptic data are not considered by the CLIPER system, a kind of stratification into synoptic data-types is implied by the nature of the predictors. In this respect, the CLIPER system simulates a purely analog approach. Operational usage of the CLIPER and analog HURRAN (Hope and Neumann, 1970) systems has shown that each gives almost identical forecast tracks.

6. Forecast based on the steering concept (sub-system 2)

The second sub-system of the prediction algorithm produces a tropical cyclone track forecast based on steering principles. Miller and Moore (1960), in a paper dealing with the steering concept, point out that the motion of a tropical cyclone is not determined solely by forces acting at any one level but rather by the mean wind flow integrated through a deep layer and over a substantial area surrounding the storm. The authors also point out that internal forces, propagation, and probably some other factors contribute to storm motion.

Due to the uncertainties of the above cited variables in an operational environment, numerical treatment of the steering principle has met with only limited success. These same data limitations suggest that steering, by itself, will probably not produce a satisfactory statistical forecast. However, since some independent predictive information is provided, the steering principle was included as one of the components of the NHC73 system.

Prior to the adoption of a suitable steering function, considerable testing and pre-screening runs were made. Available for a statistical screening analysis were 317 hurricane forecast situations with concurrent 1000, 700, and 500 mb heights at the 81 points in the 9×9 storm centered grid illustrated in Fig. 2. Initial test screenings using meridional and zonal gradients taken over various distances established that, on the average, most of the steering "information" was contained in the row of grid-points 450 n mi around the storm (numbered grid-points 1 through 24 in Fig. 2). This is in general agreement with the findings by Miller and Moore (1960) and by Miller *et al.* (1968) in the NHC67 tropical cyclone prediction system. The testing further indicated, however, that somewhat better results were obtained by considering the height difference across a 300 n mi distance centered on a single grid-point rather than averaging across the storm, as was done in the above cited references.

It was also found that greater variance reductions were realized by vertically weighting the grid data before computing any horizontal height differences where the vertical average height ($\overline{HT}$) at grid-point

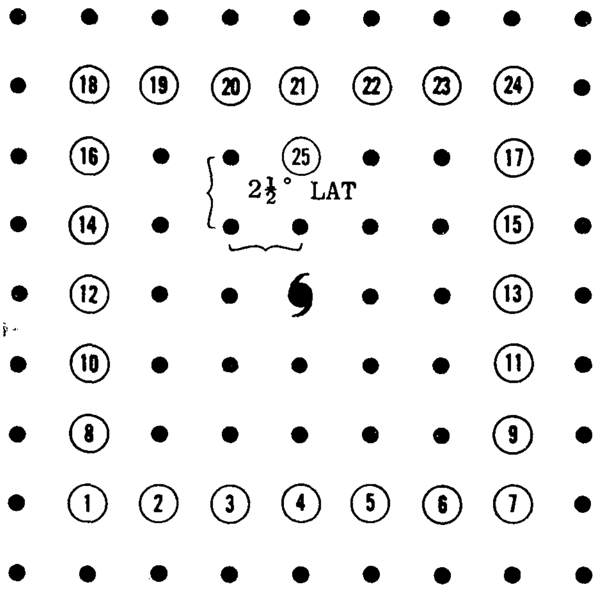

FIG. 2. Storm centered grid used for steering computations.

j was given by,

$$\overline{\mathrm{HT}}(j)=[\mathrm{CH10}(j)+2\mathrm{CH07}(j)+3\mathrm{CH05}(j)]/6 \quad (2)$$

and where the designators CH10, CH07, and CH05 refer respectively to the current heights at 1000, 700, and 500 mb. This particular weighting function was selected after testing numerous other combinations. Poorest results were obtained from a function which weighted the 1000 mb level 100%. It is of interest to note that no additional variance reduction was obtained by dividing the height differences by the sine of the latitude as is typically done to make the predictors proportional to a geostrophic wind. Accordingly, the simpler differences themselves were retained as predictors.

Two differences were computed for each of the grid-points labeled 1 through 24 in Fig. 2. The east/west difference (G_{ew}) at grid-point 21, for example was given by,

$$G_{ew}(21)=\overline{\mathrm{HT}}(20)-\overline{\mathrm{HT}}(22); \quad (3)$$

while the north/south difference (G_{ns}) at grid-point 13 was given by,

$$G_{ns}(13)=\overline{\mathrm{HT}}(11)-\overline{\mathrm{HT}}(15). \quad (4)$$

Thus, a total of 48 predictors were available for the steering screening analysis.

The variance analysis, prediction selection order and regression coefficients for the final steering prediction equations are given in Neumann and Lawrence (1973) wherein, for example, the 12 h meridional displacement (DY_{12}) in n mi is given as,

$$DY_{12}=46.4-1.308G_{ew}(17)-2.371G_{ew}(12) \\ -1.511G_{ew}(2)+1.539G_{ns}(8)-1.750G_{ns}(19) \quad (5)$$

and the 12 h zonal displacement (DX_{12}) is given as

$$DX_{12}=-10.3-1.703G_{ns}(21) \\ -3.002G_{ns}(4)-1.377G_{ew}(9) \quad (6)$$

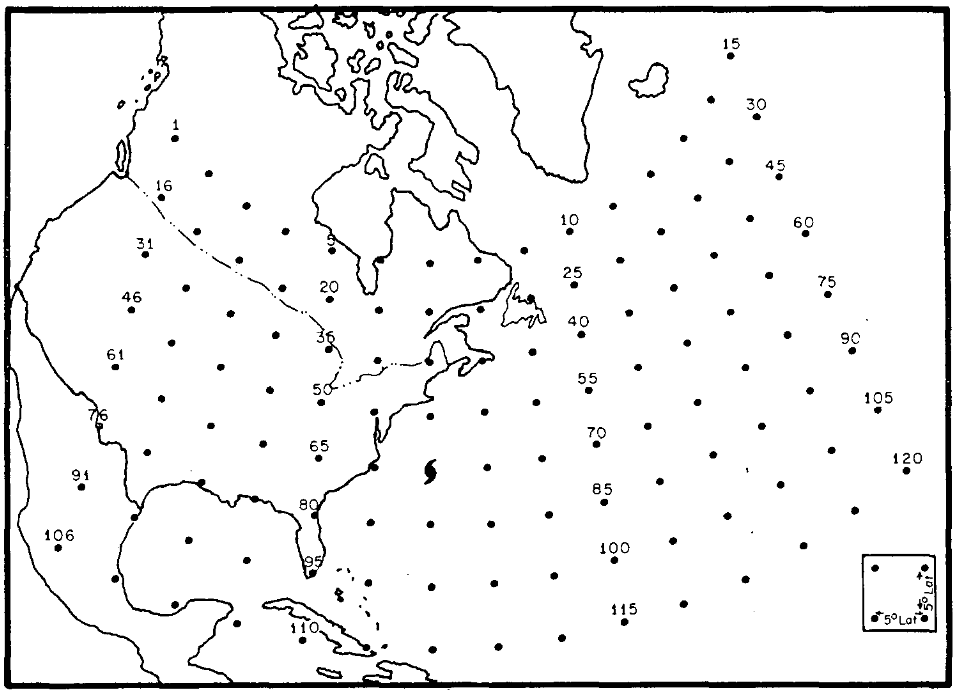

FIG. 3. Storm centered grid used for synoptic data.

where the indices refer to the grid-points given in Fig. 2 and the height differences are in meters. It can be noted from (5) and (6) that contributions to the reduction of variance are derived from both the zonal and the meridional height differences.

7. Forecast based on synoptic data (sub-system 3)

The third and final sub-system of the prediction algorithm is based on the current 1000, 700, and 500 mb analyses and the 24, 36, 48 h 500 mb prognostic height fields. Two methods of introducing the prognostic data into the statistical prediction equations were tested. One method uses the perfect-prog concept with 127 data cases per areal stratification zone. The other method uses what is referred to as a simulated model output statistics (SMOS) approach, with 200 data cases included in each stratification zone.

The question arises as to the statistical significance of the prediction equations developed in the various sub-sections. Miller (1962) points out that the significance of a particular predictor or set of predictors may not be tested by the usual F-ratio since the significance criteria must be established for the problem at hand. Accordingly, a Monte Carlo technique suggested by Lund (1970) was used to estimate the number of data cases needed to insure statistical significance. It was found, for example, in developing the sub-system 3 prediction equations, that by using 127 dependent data cases, multiple correlation coefficients as high as 0.68 and never lower than 0.45 could be obtained by repeatedly allowing the stepwise screening computer program to select 12 out of 120 possible 500 mb height values as predictors of randomly selected tropical cyclone displacements. The test was repeated 100 times. For significance at approximately the 1% level the correlation coefficients therefore had to exceed 0.68 when the program was run on real rather than on random data.

TABLE 2. Synoptic predictors included on master data tape. The subscripts (I) refer to one of the 120 grid-point addresses as specified in Fig. 3.

Number	Predictor description	Symbolic reference
1	1000 mb ht at time $T+00$ h	(H0010(I), I=1, 120)
2	700 mb ht at time $T+00$ h	(H0007(I), I=1, 120)
3	500 mb ht at time $T+00$ h	(H0005(I), I=1, 120)
4	500 mb ht at time $T+24$ h	(H2405(I), I=1, 120)
5	500 mb ht at time $T+36$ h	(H3605(I), I=1, 120)
6	500 mb ht at time $T+48$ h	(H4805(I), I=1, 120)

a. Data sources

The source of data for both experiments was similar to that used in previous statistical forecasting systems

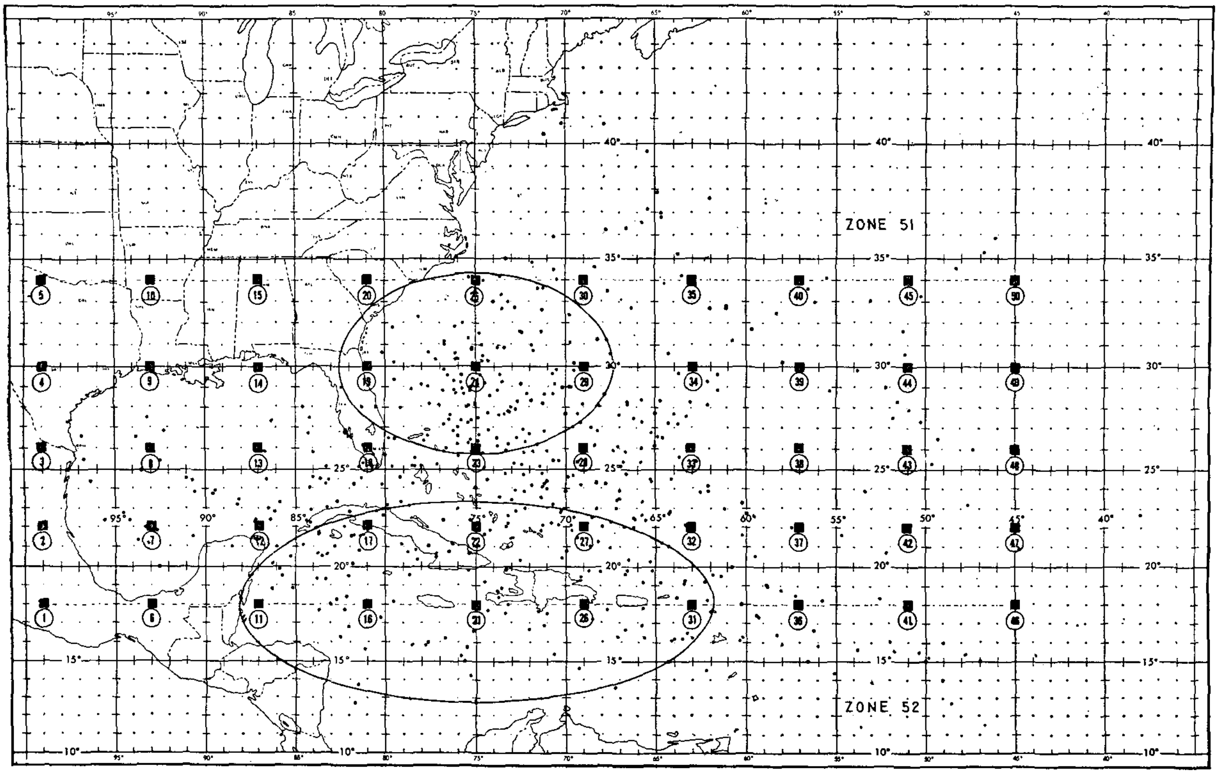

FIG. 4. NHC73 stratification system. Dots show the initial location of the 530 storms comprising the dependent data set. Ellipses contain the dependent data subsets for zones 21 and 24.

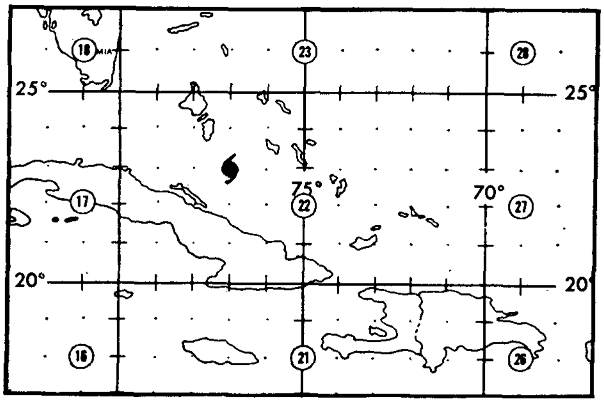

FIG. 5. An enlarged portion of Fig. 4, illustrating operational usage of stratification system.

developed for the National Hurricane Center. A master tape contains data from 1000 tropical cyclone forecast situations between the years 1945–1969. Geopotential height data at 1000, 700, and 500 mb are recorded on an 8×15 storm-centered grid as illustrated in Fig. 3.

In order to meet the data requirements of the NHC73 system, it was necessary to restructure the data tape so that each individual forecast situation contained not only the current ($T+0$) grid data but also the later observed 500 mb heights after 24 h ($T+24$), after 36 h ($T+36$) and after 48 h ($T+48$). Missing sequential data sets eliminated many cases and the final restructured tape contains 530 forecast situations containing data from the six fields identified in Table 2.

b. The stratification scheme

Experience with previous objective prediction systems has shown that improved performance can be attained by stratifying the data set into some type of homogeneous sub-sets of data. The NHC73 model uses an overlapping geographical stratification, details of which are illustrated in Fig. 4. The size of an elliptical scanning area centered on each of the 50 zones was increased in stepwise fashion until the area included the desired number of data cases. The major (east/west) elliptical axis was increased at a faster rate than the minor (north/south) axis according to

$$A=(B-3)^{2.5}+B, \qquad (7)$$

where A is the length of the major axis and B is the length of the minor axis. Two such elliptical areas are illustrated on Fig. 4. An elliptical scan was used in preference to a circular scan since the latter would, for some of the zones, necessitate including storms too far north or south of the zone center. Such storms would likely be associated with synoptic patterns atypical of the given zone, thus defeating the purpose of the area stratification.

A separate set of screening equations was developed for each of the 52 zones shown in Fig. 4. In operational practice, the prediction equation sets from the four zones nearest the current storm position are used to compute the synoptic displacement. The forecast motion of the storm illustrated in Fig. 5, for example, is determined by equation sets 17, 18, 22, and 23, each being weighted 25%. The rationale for this procedure is discussed in Neumann and Lawrence (1973).

c. Predictor screening using the perfect prog approach

Each of the six predictor fields identified in Table 2 was pre-screened to reduce the number of available predictors from each field to 20. Because of the nature of the perfect-prog method and the desire to incorporate only large-scale circulation features in the synoptic sub-system, the eight grid points surrounding the storm were not included in the regression analysis.

Final screenings included twenty predictors from each of the six fields. Examination of the results showed that more predictors were being chosen from the perfect-prog data (fields 4, 5, and 6 of Table 2) than from the observed data fields. The high reductions of variance one obtains from these synoptic screening runs compared to the reductions obtained from the other sub-systems is shown in Table 3. However, these high values are misleading, since the actual forecast height fields used operationally will not be as accurate as the perfect-prog development data. This, of course, is the primary disadvantage of the perfect-prog method in that the operational performance of the prediction scheme will always fall short of the success suggested by the reduction of variance as described in Table 3. Accordingly, an alternative method, described in the following sub-section, was used to render the perfect-prog data less attractive to the screening program.

d. Predictor screening using the SMOS approach

Most screening programs require the computation of a covariance matrix containing the sums of the

TABLE 3. Percentage reduction of variance provided by specified sub-system.

	Zonal motion					Meridional motion				
Forecast interval (h)	12	24	36	48	72	12	24	36	48	72
CLIPER sub-system	89	82	73	66	53	74	57	42	30	16
Steering sub-system	60	59	54	51	40	26	26	11	10	12
Synoptic (perfect-prog) sub-system	91	93	93	94	94	78	83	84	89	88

cross-products of all possible combinations of variable pairs. It is from this matrix, along with an array representing the sums of the same variables, that the correlation fields, eventual predictor selections and regression coefficients are determined. Veigas (1966) suggests a procedure whereby the perfect-prog covariance matrix is modified by introducing an error component derived from a relatively short period of record of actual prognostic data fields. The purpose is to simulate the covariance matrix one would obtain from a long period of record of the prognostic data.

A similar, but more elementary, approach was undertaken in the current experiment. A certain percentage of the perfect-prog fields were contaminated by the inclusion of 500 mb height fields randomly selected from the master data tape. Although the required amount of contamination is probably both time and space dependent, the current experiment varied the amount of contamination in the spatial sense only, ranging from 10% of the dependent data cases for the northernmost stratification zone (zone 51 on Fig. 4) to 22% of the cases for the southernmost zone 52. These percentages were selected after conducting test screening runs with varying amounts of randomization. The percentage values finally selected appeared to give the proper reductions of variance when compared to other operational statistical prediction schemes. The percentages are in no way to be considered optimal; the purpose of the experiment was merely to see if such an approach would at least partially correct the tendency for the screening program to select too many predictors from the perfect-prog data. The predictive scheme just described which results from the use of "contaminated" data fields is what is identified as SMOS (Simulated Model Output Statistics).

That the desired effect was being achieved is evidenced by Fig. 6. These data give the average number of predictors selected from one of the three available "forecast fields" both before (perfect-prog) and after (SMOS) contamination of these fields. The failure of these percentages to continue increasing after 48 h is probably related to the fact that "forecast" data were not available beyond 48 h.

8. Combining the CLIPER, steering, and synoptic-data forecasts

In the preceding section, the derivation of two sets of synoptic data prediction equations (perfect-prog and SMOS) was described. In accordance with the prediction algorithm of Fig. 1, the synoptic forecasts are combined (using some type of weighting function) with the CLIPER and steering forecasts to produce a single final forecast. Since one of the objectives of this experiment was to test the perfect-prog approach vs the SMOS approach, two completely independent prediction systems were prepared. One system combined the CLIPER, steering, and perfect-prog synoptic forecasts. Another combined the CLIPER and steering forecasts with the SMOS synoptic forecasts.

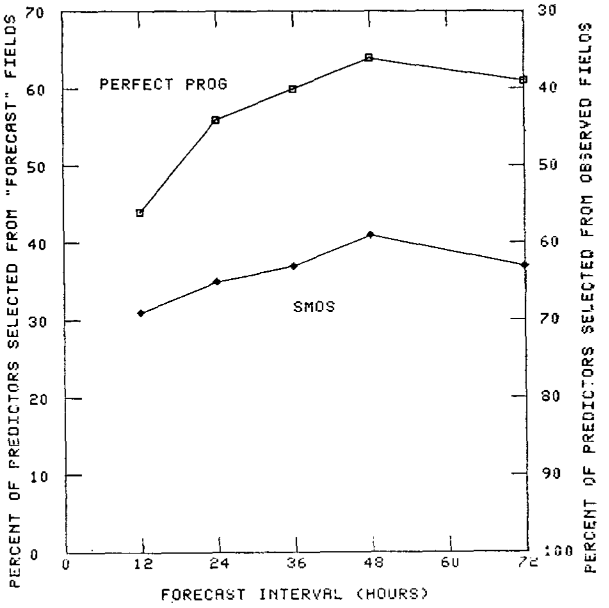

FIG. 6. Percentage of "forecast" and observed predictors used by the perfect-prog and SMOS prediction equations. Usage averaged over all 52 stratification zones.

The evaluation of the performance of any tropical cyclone prediction model is typically based on the magnitude of the average vector displacement error. Therefore, it is desirous that the weighting functions that are used to combine the various sub-systems should minimize this quantity. Furthermore, because of uncertainties involved in the operational specification of some of the predictors used in the CLIPER system (Neumann, 1975), the weighting function should be based on operational rather than on dependent data.

Pending collection of sufficient operational data, an interim weighting function was derived from a linear regression analysis. The dependent data displacement forecasts from the three sub-systems were used as predictors and the observed displacements as predictands. Separate weighting functions were computed for each component of motion, for each of the five forecast projections, 12 through 72 h, and for each of the 52 stratification zones. A subjective analysis of the resultant regression coefficients indicates that for the shorter forecast periods the principal reduction of variance is provided by the CLIPER forecasts, while for the extended forecast periods the synoptic system shows maximum variance reducing potential.

The weightings assigned to the steering sub-system were small and this sub-system could probably have been eliminated from the prediction algorithm. However, preliminary tests suggest that the steering sub-system, at the expense of the CLIPER forecasts, will take on increased significance when a weighting function is derived from operational data. Accordingly, the steering sub-system, at least temporarily, was retained in the prediction algorithm.

9. Performance on operational independent data

Regardless of a system's performance on developmental data, its ultimate evaluation and utility must be based on operational usage. Accordingly, the two final prediction systems, one including the perfect-prog synoptic sub-system and the other including the SMOS synoptic sub-system, were tested on all 0000 GMT and 1200 GMT forecast situations on named tropical cyclones during the 1973 and 1974 Atlantic hurricane seasons. The testing was conducted in a strict operational mode with the required primitive equation (PE) forecast data obtained through a computer terminal linkage between the NOAA computer facility in Suitland, Md., and the National Hurricane Center.

The forecasts were compared to the later observed storm positions and a great circle displacement error (E) in n mi was computed according to a formula derived from the law of cosines,

$$E=\cos^{-1}[\sin Y_o \sin Y_f + \cos Y_o \cos Y_f \cos(X_o - X_f)]60, \quad (8)$$

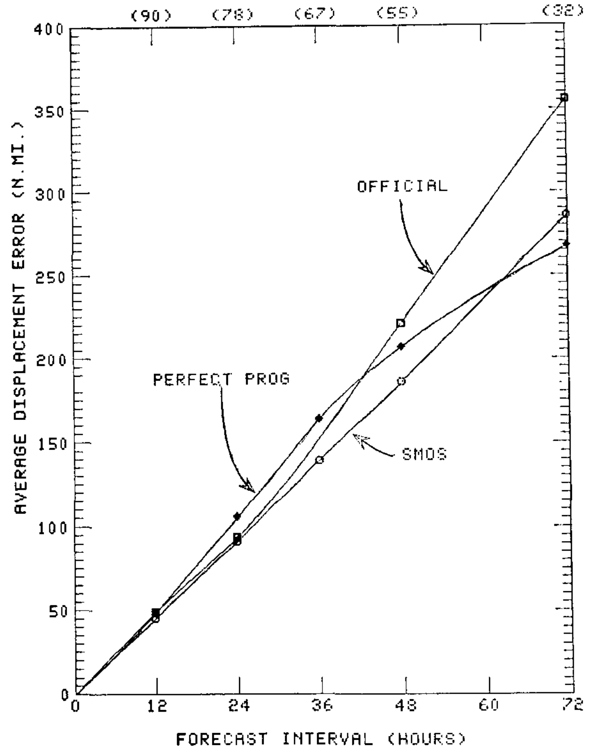

FIG. 7. Independent and homogeneous test results of "perfect-prog," SMOS, and official forecasts for combined 1973 and 1974 Atlantic hurricane seasons. Number of cases given parenthetically along top. Official forecasts are not verified for 36 h forecast period.

where Y_o, X_o are the observed latitude and longitude and Y_f, X_f are the forecast latitude and longitude. The results of the test are graphically depicted in Fig. 7. Also included are the "official" public forecast displacement errors for the same storm sample. These latter forecasts are those released to the public after the forecaster has considered other prediction models in use at the National Hurricane Center. The NHC73 forecasts were not available to the forecaster until after the release of the official forecast.

Certainly, the most noticeable feature of the test results was the relatively small error shown by the models at the extended forecast periods. As expected, the perfect-prog equations performed relatively poorly during the first half of the 72 h forecast period. Predictor over-weighting, as discussed in Subsection 7c, is a probable explanation. The unexpected improvement in the perfect-prog forecasts at the extended periods suggest that the variance reducing potential of the numerically forecast data is greater than that provided by the current data at 48 h and beyond.

In the SMOS experiment, the contamination of the covariance matrix in the shorter range forecast periods allowed for a more realistic blend of current and numerically forecast data resulting in better operational performance. This suggests that additional time-dependent contamination of the perfect prog data would further improve the shorter range forecasts. The unexpected relative increase in the SMOS errors beyond the 48 h forecast period suggests that the contamination should be decreased or even completely eliminated at the 72 h forecast period.

10. Suggestions for further research

It has been demonstrated that information contained in numerically produced 500 mb prognostic charts can be used to improve the performance of statistical tropical cyclone displacement models. Considering the relatively crude simulated model output statistics approach used here, the results suggest that a pure MOS approach would almost certainly further improve the performance of these models. In this respect, the findings reinforce those of Veigas (1966) in his experiments with early barotropic prognoses. Accordingly, every effort will be made to develop a purely MOS system as soon as sufficient dependent data can be collected.

In the interim, two alternative approaches are suggested by the current experiment:

a. *Modification of the SMOS approach*

It was pointed out in the preceding section that improved results can probably be attained by increasing the amount of 500 mb data contamination for the short range forecasts and gradually decreasing the amount of contamination to the point of using a purely perfect-prog approach at the 72 h forecast period. An alternative, suggested by Veigas (1966) would be to contaminate the covariance matrix directly with known error characteristics of a numerical model. Another alternative, suggested by the work of Gringorton (1973), would be the use of a stochastic model to generate 500 mb height error fields with characteristics similar to a given numerical model.

b. Modification of the perfect-prog approach

The results of the experiment clearly show that the perfect-prog equations gave the best results at the extended forecast periods. At the shorter forecast periods, rejection of current data by the screening program leads to overweighting of the numerically forecast data. A possible solution would be to develop one set of prediction equations based only on the perfect-prog data (excluding current data) and another set only on current data. Short-period forecasts would be weighted primarily towards the current data and the extended range forecasts towards the numerically forecast data.

11. Summary of results

The principal findings in this two-year experiment in statistical-dynamical prediction of tropical motion are as follows:

A) Predictors obtained from numerically forecast geopotential height fields can be used to increase the predictive skill of current statistical models.

B) Predictor over-weighting, a problem associated with the perfect-prog approach, can be partially offset by contamination of the covariance matrix with a certain amount of random predictors. Such a procedure better simulates the covariance matrix one would obtain with a model output statistics (MOS) approach. The procedure has been designated simulated model output statistics (SMOS).

C) The two-year experiment showed that the perfect-prog approach gave relatively poor results (presumably from predictor over-weighting) for the first half of the 72 h forecast interval but gave increasingly better results beyond.

D) The SMOS system performed relatively well in all forecast periods but was somewhat inferior to the perfect-prog system at 72 h.

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