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THE NATIONAL HURRICANE CENTER NHC83 MODEL

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ABSTRACT

This document describes the development and operational performance of the statistical-dynamical NHC83 model. NHC83 was developed at the National Hurricane Center (NHC) in the early 1980's and introduced operationally for the 1983 Atlantic hurricane season. The model was developed in the "perfect-prog" mode with principal predictors being deep-layer-mean geopotential heights as derived from U.S. National Meteorological Center (NMC) operational analyses for the years 1962-1982. In the operational mode, NHC83 derives these deep-layer-mean forecast geopotential heights (through 72 h) from the NMC Medium Range Forecast (MRF) model. Additional predictors are derived from the output of the NHC CLIPER (CLImatology and PERsistence) model as well as from the current NMC initial analysis or a "first-guess" to the initial analysis.

Based on five years of operational verification statistics, 1983-1987, NHC83 has outperformed other NHC track prediction models by a rather wide margin. In addition, the model has other utilitarian features such as being available to forecasters four times daily in ample time to meet operational advisory schedules. Also, output from the NHC83 model is available in a graphical format which portrays both the numerically forecast height fields through 72 h and the forecast tropical cyclone track.

1.0 INTRODUCTION

1.1 TROPICAL CYCLONE PREDICTION MODELS

The National Hurricane Center (NHC) uses a number of computer models as objective guidance preparatory to the issuance of tropical cyclone advisories. The great majority of these models, including the NHC83 model, the focus of this paper, concern themselves with forecasts of tropical cyclone motion. Other models provide forecasts of tropical cyclone intensity while still others provide the forecaster with diagnostic information relative to the given forecast situation.

Tropical cyclone prediction models are either <u>statistical</u> or <u>dynamical</u> and both types of models, each having distinct spatial, temporal and utilitarian advantages and disadvantages, are in use at the major tropical cyclone forecast centers. Depending on the type of developmental data and how this information is processed, statistical models are classified as being <u>analog</u>, <u>CLIPER-class</u>, <u>statistical-synoptic</u> or <u>statistical-dynamical</u> while the dynamical models, depending on the basic physical assumptions, are classified as being <u>baroclinic</u> or <u>barotropic</u>. Further discussion of the models in use at the NHC is provided by Neumann and Pelissier (1981a, 1981b). A more general discussion of tropical cyclone prediction models is provided by McBride and Holland (1987) and Elsberry et al. (1987).

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[1] Prepared for the National Hurricane Center, Coral Gables, FL 33146: Contract No. 50-DGNC-6-00209

A problem common to most forecast centers is that guidance from the various models is often contradictory rather than complementary. Also, model performance tends to be inconsistent such that tropical cyclone forecasting is typically associated with a subjective evaluation of many objective products.

1.2 STATISTICAL-DYNAMICAL MODELS

Models which combine statistical and dynamical processes are known as statistical-dynamical models. Typically, such models use the output from a numerical model but process this output in a statistical prediction framework. Conceptually, statistical-dynamical models are very appealing in that they purport to combine individual advantages of statistical and dynamical models into a single prediction package. Until recently, however, their success has been limited due to a number of often unrealistic assumptions which must be made in structuring such models. One of these assumptions is that the statistical attributes of developmental data will always be similar to that of the data used when activating the model in an operational mode. The NHC statistical-dynamical NHC73 model (Neumann and Lawrence, 1975), for example, performed quite well for several years after its introduction in 1973. However, procedural changes at the National Meteorological Center (NMC) and the inability of NHC73 to withstand these changes has led to degraded performance of that model in recent years. This event underscored the necessity of designing statistical-dynamical models with sufficient flexibility to accommodate procedural changes in the dynamical side of the model.

The limitations of NHC73 and other NHC models led to the development of the statistical-dynamical NHC83 model. Work on NHC83 began in early 1981 and the model was first tested in a semi-operational mode in 1983. The scarcity of storms during that season prompted another year of operational testing in 1984. The model, for all practical purposes, became fully operational the following year, 1985. As will be shown, NHC83 performed exceptionally well[2] in each of the five years, 1983 through 1987.

1.3 PURPOSE OF STUDY

Although NHC83 has become the principal operational model at the NHC, it has never been formally documented. Fragmented descriptions appear in various NHC quarterly progress reports and Conference summaries (for example, Neumann, 1988), but these have fallen short of providing scientific documentation. The objective of this Technical Memorandum is to provide a comprehensive description and evaluation of the NHC83 model.

2.0 OVERVIEW OF EARLIER NHC MODELS

2.1 HISTORICAL PERSPECTIVE

Objective models for the prediction of tropical cyclone motion have been is use at the NHC for over 30 years and a complete historical perspective

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[2] The term exceptionally well is used in the relative sense and does not imply that further improvements are not needed in the NHC83 model or in any other model.

can be found in World Meteorological Organization (1979). The brief chronology given here is intended only as background for better understanding of NHC83 methodology.

2.1.1 Early Steering Models

Statistically based "rules of thumb" have long been used in tropical cyclone forecasting. The first really objective system for predicting 24 h Atlantic tropical cyclone motion is generally attributed to Riehl et al. (1956). The method, often referred to as Riehl-Haggard, was based on the principle that the tropical cyclone moved or was "steered" in accordance with the vertically integrated flow surrounding the tropical cyclone. The 500 mb level was used to approximate this flow and the geopotential height difference across the storm was found to be significantly correlated with subsequent storm motion.

Another early steering model, referred to as Miller-Moore, was developed by Miller and Moore (1960). Those authors, after examining other levels, selected 700 mb as the best "steering" level. Both "Riehl-Haggard" and "Miller-Moore" used a relatively small domain grid to forecast tropical cyclone motion through 24 h.

2.1.2 Evolution of Operational Models

Following the late 1950's initial operational use of the above objective methods by the NHC, the U.S. Navy and the National Hurricane Research Laboratory (predecessor to the current Atlantic Oceanographic and Meteorological Laboratory/Hurricane Research Division), there has been a more or less gradual evolution of models over the Atlantic basin. Through 1973, some noteworthy events in the evolution of statistical models include: (1) the introduction of a larger domain grid system than that used by earlier modelers (Veigas et al., 1959); (2) the development of stepwise screening regression analysis (Miller, 1958), (3) the use of objective analysis beginning in 1965; (4) the use of multiple pressure levels in statistical models (Miller and Chase, 1966), (5) experimentation with statistical-dynamical models in tropical cyclone prediction (Veigas, 1966); (6) the introduction of analog models (Hope and Neumann, 1970); (7) the introduction of "CLIPER-class" models (Neumann, 1972) and (8) operational use of statistical-dynamical models (Neumann and Lawrence, 1975).

2.1.3 Development of NHC83

Although the NHC83 model can be thought off as a continuation of the developmental process referred to above, many of the features of the model are complete breaks with the past. After the development of the NHC73 model (Neumann and Lawrence, 1975), which began in 1971 and ended when NHC73 became operational in 1973, there was an extended period during which Atlantic model development was suspended. During that period, many studies (to be reviewed in subsequent sections) were conducted which critically examined some of the accepted practices in statistical modeling. As a result of these studies and as a further result of operational experience with earlier models, the NHC83 model was designed with many radically different approaches than its predecessors.

2.2 PROBLEMS WITH EARLIER MODELS

As discussed above, the development of the NHC83 model was prompted and guided by lessons learned from operational experience with other models. These problems, taken collectively, had led to inconsistencies in model performance and resultant forecaster apathy toward models. Without being specific as to the particular model or models at fault, these problems, not listed in order of importance, include:

(1) Too much reliance on a single-level, notably 500 mb;

(2) A grid system that was too coarse and did not take into account the change of map scale with latitude;

(3) Geographical restrictions in activating a model;

(4) Inability of model to produce a forecast of anomalous situations;

(5) Delivery of forecast product to user too late for use in latest advisory;

(6) Slow speed bias;

(7) Over-reliance on sometimes erroneous initial motion vectors;

(8) Lack of proper statistical significance. This was typically manifest by model having too many predictors;

(9) Use of poorly analyzed geopotential height fields in the tropics;

(10) Inconsistencies between model track projection and current trends in synoptic "steering" pattern;

(11) Inconsistencies among models. This is related to the use of too many models;

(12) Unavailability of model as guidance for 1000 and 2200GMT advisories;

(13) Poor performance of statistical models at extended projections and poor performance of baroclinic models at short range projections;

(14) Lack of visual access to analysis and numerical prognoses which provide input to a statistical model.

Many of these fourteen problem areas were addressed in specific studies which were completed before commencement of development work on the NHC83 model itself. These studies are described in the following section. Further prompting these NHC83 pre-development studies was the knowledge that the ability to forecast the important 24 h tropical cyclone motion was improving at a slow rate or not at all (Neumann, 1981).

3.0 NHC83 PRE-DEVELOPMENT PHASE

3.1 USE OF DEEP-LAYER-MEAN GEOPOTENTIAL HEIGHT FIELDS

In developing the barotropic SANBAR model for the prediction of tropical cyclone motion, Sanders and Burpee (1968) pointed out the advantages of using a deep-layer-mean wind and demonstrated how to use the data in an operational environment. An earlier study by Miller (1958) had also investigated some aspects of this concept. Although it would have been desirable to use deep-layer-mean winds rather than heights in NHC83, a long-term sample of sufficiently reliable winds needed for a developmental (dependent) data set did not exist at the time NHC83 was designed.

Accordingly, Neumann (1979) tested deep-layer-mean heights as to their ability in explaining the variance of tropical cyclone motion. His study clearly showed that there was more predictive information contained in layer averages than contained is any single level. Many different methods of computing these layer averages were tested and his conclusion was that the Sanders method of mass-weighting the 10-standard levels from 1000 to 100 mb gave the best results in regard to explaining the variance of short-term tropical cyclone motion. Later studies such as Pike (1985), Dong and Neumann, 1986, also addressed the utility of deep-layer-mean height fields in statistical prediction and confirmed earlier findings of Neumann.

Table 1. Assigned weights and standard heights for NHC83 deep-layer-mean geopotential height computations.

Level Number	1	2	3	4	5	6	7	8	9	10
Level (Millibars)	1000	850	700	500	400	300	250	200	150	100
Weight (mbs/mbs)	75/900	150/900	175/900	150/900	100/900	75/900	50/900	50/900	50/900	25/900
($0 \leq$ Weight ≤ 1)	.083333	.166667	.194444	.166667	.111111	.083333	.055555	.055555	.055555	.027778
Mean September standard height (meters)	122	1539	3176	5883	7593	9683	10939	12405	14185	16569

The actual deep-layer-mean function f(H) adopted for use in NHC83 was,

$$f(H) = \sum_{i=1}^{i=10} (W_i H_i) \qquad (1)$$

where H_i is the geopotential height for each of the 10 levels, 1000 through 100 mb and W_i are assigned weighting factors as specified in Table 1. In practice, the geopotential heights are stated in terms of departures from Jordan's (1957) mean September tropical atmosphere, also given in Table 1. Initially, Eq. (1) was defined in terms of departure from daily normals. However, tests on dependent data disclosed no particular advantage to that added complexity. Weighting the tabular standard heights in accordance with Eq. (1) yields an NHC83 "reference" geopotential height of 6060.5 meters.

3.2 GRID CONSIDERATIONS

3.2.1 Grid Spacing

Neumann (1979) examined the utility of various grid-spacings in statistical prediction models. The statistical models developed for or by the NHC prior to NHC83 used a 15 column by 8 row zonal/meridional grid-system for representing geopotential height fields. The grid-spacing was 300 nautical miles (556 km). An illustration of the grid can be found in Miller and Chase (1966). In that the grid was designed with manual data retrieval as an important consideration, there were many simplifications. The storm was always positioned near the center of the grid. Another consideration was that the number of grid points be limited to an amount commensurate with storage capacity of contemporary computer systems and stepwise screening regression programs.

Neumann concluded that the 300 n mi spacing was too coarse and that the optimal grid size for present-day statistical model development was about 150 n mi. While a smaller grid spacing of 120 n mi provided for somewhat greater variance reduction (allowing for the generation of artificial skill through increased number of predictors) the actual number of grid points in the required grid domain (see Section 3.2.3) became too large for efficient numerical manipulation of the covariance matrices.

3.2.2 Grid Orientation

All grids in the NHC83 model are rotated according to the initial motion of the storm as defined by the initial storm position and the position 12 h earlier. Forecast storm motion is stated in terms of continued motion along this (persistence) track or across (at right angles) to the track using Taylor (1982) map projection software.

The original motivation for grid rotation (Shapiro and Neumann, 1984) was to alleviate slow speed bias, a phenomena common to most statistical models. The tests conducted by Shapiro and Neumann were on best-track[3] data where storm motion is "perfectly" known. Under this condition, the authors demonstrated a definite advantage to the rotated system in regard to reducing forecast error and slow-speed bias. As stated by the authors, however, the effect of using "imperfect" operationally determined initial motion vectors to orient the grid was unknown. Although, operational use of NHC83 suggests that grid mis-alignment is not a serious problem, other innovations in the NHC83 prediction algorithm obscure the effect of grid-rotation.

3.2.3 Grid Domain

Fig. 1 shows the grid systems used in the NHC83 model. Grid points are separated by 150 n mi (278 km). There are three grid systems.

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[3] The term <u>best-track</u> refers to the accepted track and intensity of a storm after a post-analysis of all available data. This analysis is conducted as soon as possible after discontinuance of advisories on the given storm.

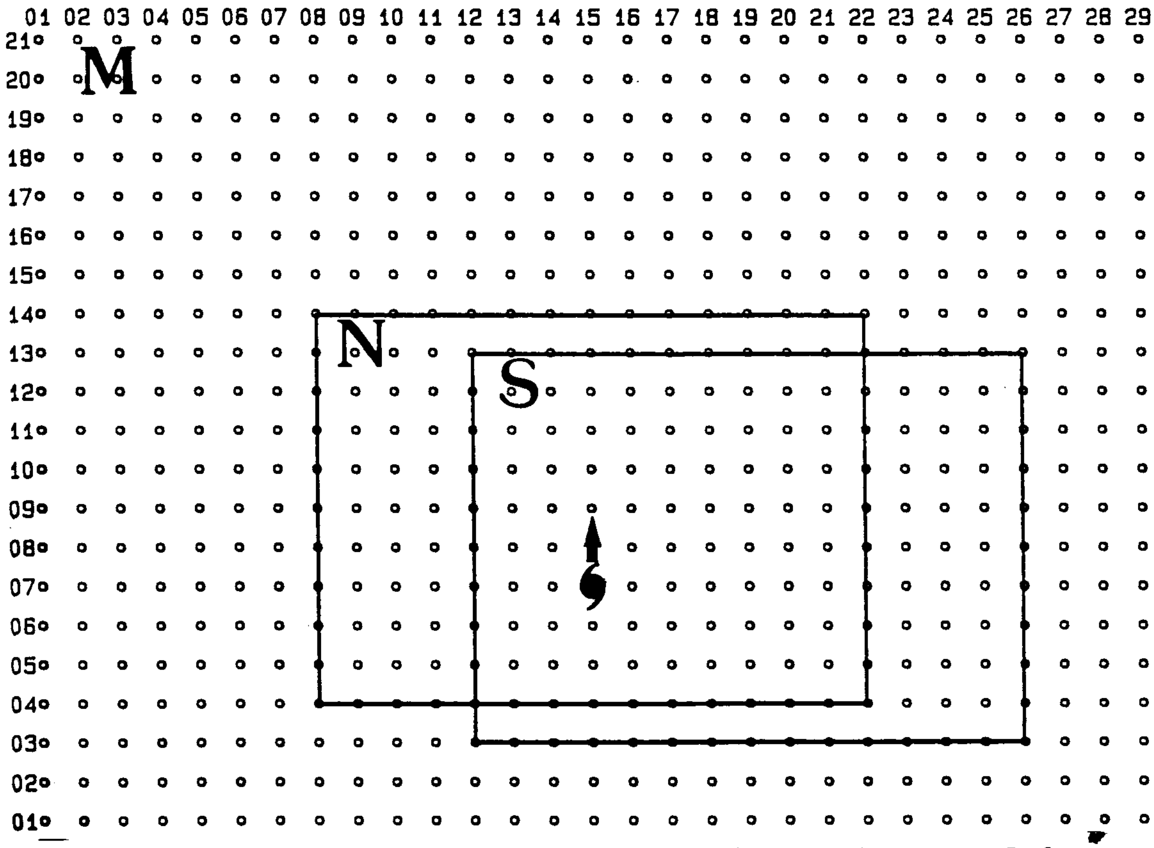

Fig. 1. NHC83 grid systems. Storm is always positioned at column 15, row 7 of large grid M, as shown. Grid alignment is given by the heading of the storm from the -12h position to the current position. Sub-grids N (North-zone) and S (South-zone) were used in developmental mode of model while grid M is used in operational mode.

Grid M is a large grid having 29 columns and 21 rows with the storm always centered at point (15,7)[4] and with the grid columns aligned precisely along the initial motion of the storm. This motion is defined by the heading of the storm from its position at T-12 h to its position at T-0 h where T refers to the starting time of the 72 h forecast cycle. In the developmental data set, to be discussed later, this motion is based on the best-track (see footnote 3) of the storm while in the operational mode, it is based on the operational track. The grid orientation is kept constant throughout the entire 72 h forecast cycle but the grid continually translates with the storm (at 12-hrly time steps) throughout the cycle. Rationale for this procedure is discussed in a later section.

Stepwise screening regression computer programs require a considerable amount of matrix manipulation. The number of grid points in Grid M is far too large for efficient computer manipulation of such a matrix. Accordingly, the smaller sub-grids N and S, each having 15 columns and 11 rows were used for this purpose. This smaller grid yields a 165 x 165 matrix

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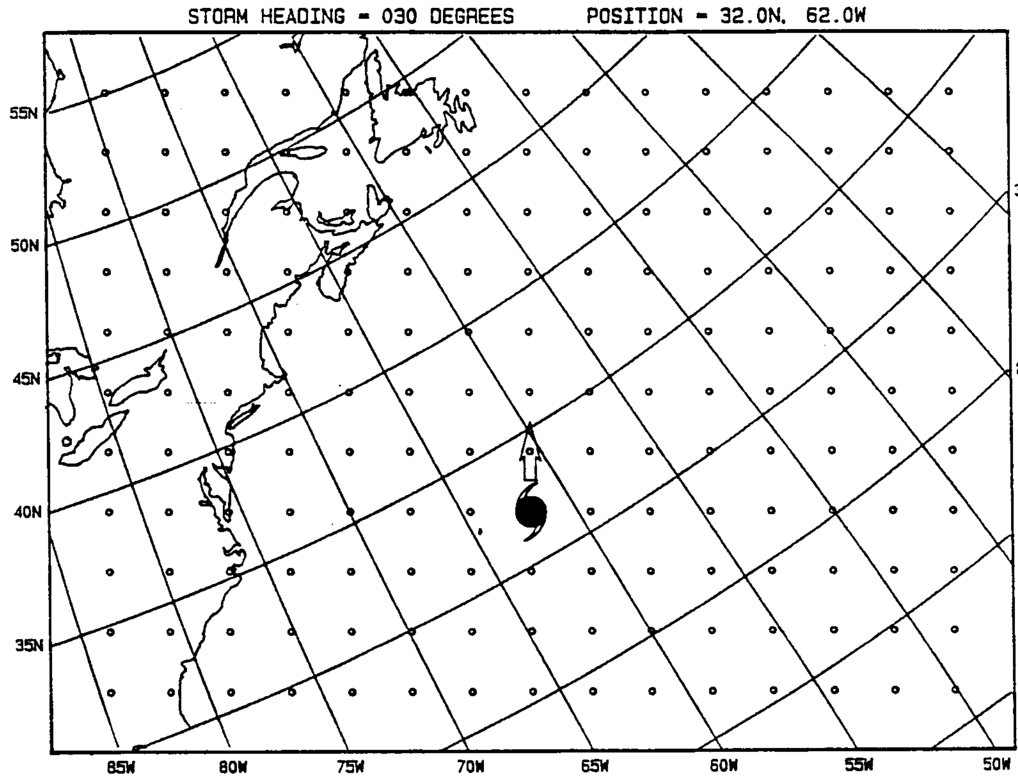
[4] The (I = COLUMN, J = ROW) grid numbering convention used here has the origin at the lower-left grid point.



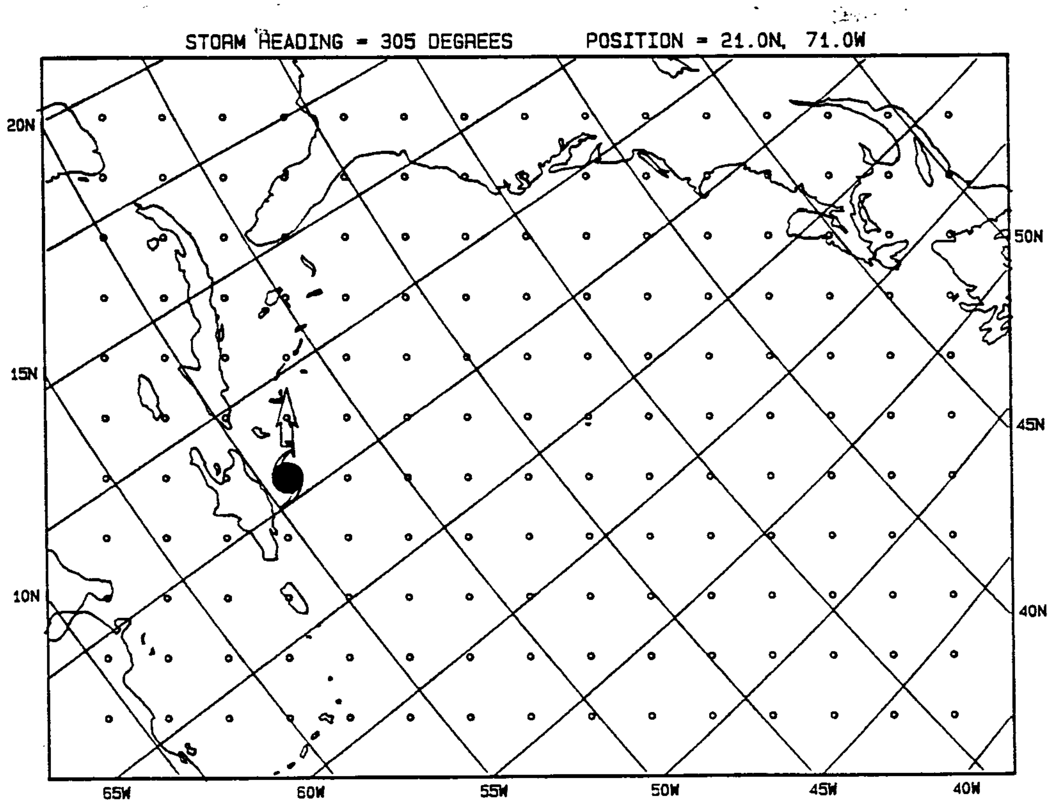


Fig. 2 (top) and Fig. 3 (bottom) showing example of developmental grids for North-zone and South-zone, respectively. Examples are for a typical storm position and heading in respective zone. Storm heading remains constant throughout forecast cycle and is defined by initial best-track position and -12h position.

which is manageable. Effectively, the storm can be repositioned in these grids by shifting in the along (J) or across (I) track directions. This shift allows the smaller grid domain to encompass maxima and minima in the correlation and partial correlation fields. These smaller grids were used in the developmental mode of the model whereas the larger grid is used in the operational mode.

Grid S is used for storms initially located in the southern portion of the basin whereas grid N is used for storms initially located in the northern portion. Figs. 2 and 3 are examples of these sub-grids with coast-line reference shown. In these examples, the storms were positioned near their average position in the developmental data set and the grids were rotated in accordance with typical initial storm motion for the given zone.

3.2.4 Map Projection Considerations

Grid-point positioning relative to the storm was determined using a technique developed by Taylor (1982). It is based on an oblique equidistant cylindrical map projection oriented along the track of the storm. The I-coordinate of a point represents the distance, left or right, from that point to the great circle through the storm position. The J-coordinate of the point represents the distance along the same great circle to the projection of that point on the circle. Scale distances are strictly uniform in the I-direction. The same scale holds in the J-direction only along the storm track. Elsewhere, distances in that direction are exaggerated by a factor inversely proportional to the cosine of the angular distance from the track. The scale is correct to 1 percent within a distance of 480 n mi from the great circle through the tropical cyclone.

3.3 STATISTICAL-SIGNIFICANCE LEVELS

3.3.1 Artificial Skill

The number of predictors entering the NHC83 model were governed by the findings of Neumann et al. (1977) and of Shapiro (1984). Those authors, using Monte-Carlo methods, addressed the generation of artificial skill resulting from the practice of offering a stepwise screening regression program a large number of predictors and selecting only a few. Adherence to their recommendations resulted in a dramatic reduction in the number of geopotential height predictors retained by the NHC83 model as compared to those retained by earlier models. As will be noted, as few as two geopotential height predictors were retained for a given projection and a given component of motion.

3.3.2 Use of 99% Significance Levels

In choosing predictors, significance levels, for the most part, were set at the 99% level using a sample size corrected for degrees of freedom loss due to serial correlation (World Meteorological Organization, 1979). This rather strict cutoff criteria was selected with the believe that there are likely additional and unknown degrees of freedom loss due to the use of uncertain objective analyses over the tropics. The latter, with attendant analysis conventions, lack of data and the use of "first-guess" fields likely results in a restriction to "freedom of choice" in sampling from the parent distributions.

3.3.3 Pairing of Predictors

The use of geopotential heights rather than winds as statistical predictors of tropical cyclone motion typically results in "pairs" of heights, located asymmetrically either side of a storm, being initially selected in stepwise screening regression computer programs. These two predictors typically provide for most, if not all, of the variance reduction provided by the heights for the given forecast interval and the given component of motion.

A shortcoming of the type of forward stepwise screening regression program used is that optimal pairing of functionally related predictors is not guaranteed. The program examines and selects only one predictor at a time and has no knowledge of future predictor selection. This initial predictor becomes "locked-in" and incremental variance reduction (partial correlation coefficients) govern the next selection. This presents a problem in that the pair selected may not be optimal insofar as variance reduction is concerned. Neumann (1979) experimented with this problem and concluded that there was a significant gain in variance reduction by providing a priori guidance to the screening program in the selection of the two initial predictors. Although there was likely some attendant gain in artificial skill, the gain in real skill appeared to be greater.

In general, these "forced" predictor pairings resulted in their location being closer to the storm than would have been the case without the forcing. Also, the combined reduction of variance was often large enough that additional predictors, located farther from the storm, failed to provide additional statistically significant variance reduction.

3.4 INITIAL ANALYSES

Generation of statistical prediction equations from a set of developmental data and eventual use of these equations on operational data assumes that the two data sets will have similar statistical attributes. The current trend to constantly improve on analyses methodology often leads to violations of this assumption, particularly in the tropical data-void areas. The real problem here is not related so much to analysis accuracy as it is to the different statistical attributes of the analysis systems and numerical prognoses made therefrom. A related problem concerns the relatively low standard deviations of geopotential heights in the tropics. These problems, as they relate to statistical models, were studied by Leftwich, et al. (1977) and by Neumann et al. (1979). Until analyses methodology is stabilized, there is no simple solution to this problem. NHC83 rationale was to avoid, as much as possible, the use of predictors in the deep tropics.

4.0 DEVELOPMENT OF THE MODEL

4.1 GENERAL DESIGN OF MODEL

4.1.1 Use of "Perfect-prog" Methodology

In general, there are three methods to develop statistical-dynamical models: "Perfect-Prog" (PP), Model Output Statistics (MOS) and Simulated Model Output Statistics (SMOS). These three methodologies, as they relate to tropical cyclone models, are discussed by Neumann et al. (1975).

Each method is associated with certain advantages and disadvantages. Although MOS is conceptually more appealing that the other two methods, its use would require access to archived output from a given numerical model for at least a 10-year period. It would also require that the same numerical model used in developing the statistical model would also be continually used in the operational running of the model--an unlikely event. The use of SMOS methodology is also dependent on the availability of a given numerical model. Accordingly, the PP approach, wherein actual analyses are substituted for numerical prognoses, was used in developing NHC83. One of the advantages of that method is that the statistical prediction equations are not tuned to a given model. Another advantage is that a long period of analyses is usually available. Still another advantage is that improvements in the numerical model will be passed on to the statistical side of the model.

There are also disadvantages to the PP approach. Since analyses are "perfect" and numerical prognoses are "imperfect", predictors from the latter, but assuming the former, are overweighted in the statistical prediction equations. Also, any biases in the numerical model could impact negatively upon the performance of the statistical side of the models. Indeed, a bias problem did occur with the NHC83 model for the 1987 Atlantic season. This is discussed in Section 5.4.

4.1.2 Some Additional Features of the Model

4.1.2.1 Sub-systems - The NHC83 model consists of various components which can be thought of as sub-systems. This feature of model structure is illustrated in Fig. 4. There are five separate models utilized in various stages of the NHC83 prediction cycle with each model producing a "stand-alone" forecast track through 72 h. Model 1 is represented by the CLIPER (Neumann, 1972) model. CLIPER is a regression equation model based on eight basic predictors and additional predictor functions derived from climatology and persistence.

Model 2 is based on current deep-layer-mean geopotential height fields only. It does not utilize CLIPER-type predictors.

Model 3 is based only on numerically forecast and initial geopotential heights. CLIPER predictors are, likewise, not included in Model 3.

Model 4 is an entirely separate model developed from the output of Models 1 and 2 (in the form of along and across track displacements) as a developmental data set. In this respect, Model 4 can be thought of as a

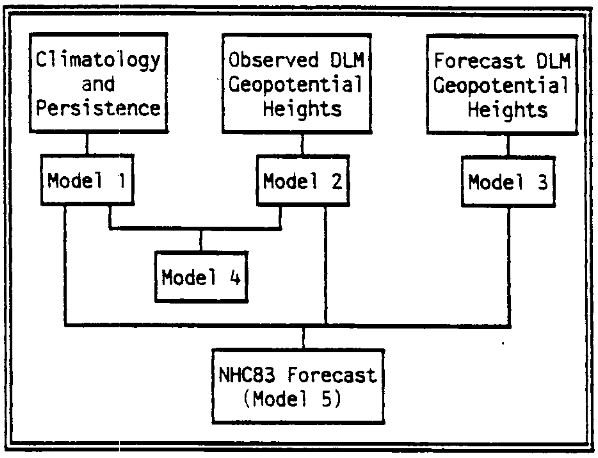


Fig. 4. Schematic diagram of NHC83 prediction algorithm. The term DLM refers to Deep-Layer-Mean. Model 1 consists of CLIPER model. Model 2 is based on observed geopotential height data only. Model 3 is based on numerically forecast geopotential height data only. Model 4 consists of Models 1 and 2 combined while Model 5 consists of Models 1, 2 and 3 combined. Final NHC83 forecast is based on Model 5.

statistical-synoptic model since it includes predictors from climatology, persistence and current synoptic data only. The need for this intermediate Model 4 is discussed in Section 4.1.1.2.

Model 5 (the final NHC83 forecast product) is based on the output from Models 1, 2 and 3 such that,

$$D_{j,k} = C_{0,j,k} + \sum_{\substack{i=1,3\\ j=1,2\\ k=1,6}} (C_{i,j,k})(P_{i,j,k}) \tag{2}$$

where array D is the new combined displacement forecast, C is an array of constants determined by least-squares fitting and P is an array of individual forecast displacements from Model 1, 2 and 3. For the indexing subscripts, $\underline{i}$ refers to Model 1, 2 or 3, $\underline{j}$ refers to along or across track component while $\underline{k}$ refers to one of the 6 projections, 12 through 72 h. Because of the large number of regression equation constants contained in the NHC83 program, the decision was made to not include actual values of such constants in this documentation. They can be found in adequately documented block data subprograms of the NHC83 FORTRAN source code maintained by the National Hurricane Center, Coral Gables FL 33146.

An alternative and simpler procedure than that shown in Fig. 4 would have been to initially combine all possible predictors into a single model. However, the added complexity involved in keeping the models as separate entities throughout the forecast cycle serves three important functions. First, it provides the forecaster (who has access to the intermediate Models 1 through 4) with considerable diagnostic information on the forecast track which, otherwise, would have been lost. A forecast which suddenly accelerates, for example, is likely due to input from the numerical side of the model. This can be verified by reference to the output from Model 3 alone. Or, large differences between models 1 and 2 would suggest an incorrect initial motion vector, etc.

Another reason for structuring the model as shown in Fig. 4 is that it provides for a potentially easy way to reassign the regression coefficients used in combining Models 1, 2 and 3. These coefficients were originally determined from developmental (perfect-prog) data and thus, Model 3 is apt to be overweighted. These weights can eventually be reassigned, without altering the basic model framework, from knowledge gained in operational runs of the model. Here, operational forecast displacements from each of the model sub-systems would constitute the dependent sample in Eq. (2).

This can be thought of as a type of Simulated Model Output Statistics (Neumann et al., 1975) approach. It is considered likely that the five years of independent operational data which are now available from the NHC83 model (275 forecast situations over the 5-year period, 1983-1987) are sufficient to activate such a procedure. This procedure has <u>not</u> been incorporated into the version of the model described herein.

4.1.2.2 <u>Forecast "recycling"</u> - To understand the third and perhaps most important reason for structuring the model as depicted in Fig. 4, it needs to again be pointed out that the NHC83 grid system translates with the storm. Accordingly, to make a 24 h forecast from Model 3, the position of the grid at +24 h must be known in advance. Model 4 provides a convenient "first-guess" to this position and the initial Model 5 forecast becomes a new estimate of an updated Model 5 forecast, etc. These iterations are continued until the forecast from Model 5 stabilizes.

The effect of this forecast "recycling" in reducing errors of the NHC83 model at the extended projections is demonstrated in Table 2. These data were obtained by re-running the entire series of NHC83 operational forecasts for the period 1983-1987 with different settings of the forecast recycle option. It can be noted from the table that recycling twice is sufficient to provide a reasonable stable forecast--on the average. Accordingly, the prediction algorithm is currently structured to allow only two iterations through the forecast cycle.

Table 2. Forecast error (nautical miles) realized by NHC83 model with specified number of iterations through the forecast cycle. Sample consists of all NHC83 operational forecasts over 5-year period, 1983-1987.

	Forecast error at hour:					
	12	24	36	48	60	72
Iterations = 1	48.3	94.7	154.8	211.1	281.4	345.8
Iterations = 2	48.2	93.6	148.9	195.3	256.9	302.7
Iterations = 3	48.2	93.5	148.3	196.6	259.5	309.4
Iterations = 4	48.2	93.5	148.3	196.3	260.0	309.0
Sample size	245	241	209	178	152	128

The improvement achieved through the recycling process varies from one forecast situation to another and it is emphasized that the data in Table 2 represent average condition only. It may be profitable to restructure the model to allow the number of iterations to be a function of the given forecast situation. The number of iterations needed to stabilize the forecast in any given situation appears to depend on the consistency between the initial motion vector supplied by the forecaster and the direction of motion as indicated by the numerical forcing fields. If these quantities vary widely, then additional iterations appear to be needed in order to arrive at a stable forecast. Thus, the recycling process provides a mechanism for correcting for errors in operational initial motion vectors. Additional research into the feedback mechanism might further benefit NHC83 as well as other models.

4.2 DEVELOPMENTAL DATA

4.2.1 Availability of Deep-Layer-Mean Geopotential Heights

The National Hurricane Center routinely archives all National Meteorological Center analyses and prognoses relevant to NHC statistical prediction over the Atlantic and the Eastern Pacific Tropical Cyclone Basins. Portions of these data, through the year 1981, were utilized in developing the NHC83 model. In accordance with Eq. (1), deep-layer-mean geopotential height fields were constructed from the 10 standard levels, 1000 to 100 mb whenever these data were available. In general, 500 mb data are available back through 1946. However, it is not until 1962 that data from the other levels were sufficient for construction of a deep-layer-mean. Although some levels (notably 400 mb) were occasionally missing after that date, a deep-layer-mean height, in the context of Eq. (1), was still constructed by adjustment of the weighting factors. If more than two levels were missing, the case was not used. The latter procedure was considered an acceptable "trade-off" to increase the sample size. In general, however, construction of a deep-layer-mean with less than 10 levels, is not recommended.

4.2.2 Missing Data over Deep Tropics

Archived data referred to above are represented on the National Meteorological Center standard 4225 (65 x 65) grid system on a polar stereographic map projection. However, prior to 1975, data were not available over portions of the grid south of about latitude 10 to 13 North[5]. This presented a problem for modeling storms located in the deep tropics. Methods of dealing with this problem are discussed in Section 4.5.

4.2.3 Additional Constraints to Sample Size

In addition to the constraints noted above, the sample did not include cases when the storm became extratropical or weakened to below tropical storm intensity either at the initial time of the forecast or at verification time. Also, there is a CLIPER model requirement for at least 24 h of storm history. With these additional constraints, a total of 1,050 12 h forecast situations over the 20-year period 1962-1981 were available from which to develop the model. This amount decreased to 489 cases for the 72 h projection. The loss at the latter time frame is due to storms dissipating, weakening, or becoming extratropical between 12 and 72 h after the initial time. These 1,050 forecast situations are from a total of 141 tropical cyclones, tracks or track segments of which are shown on Fig. 5.

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[5] The region of available data is referred to as the National Meteorological Center "Octagonal" grid.

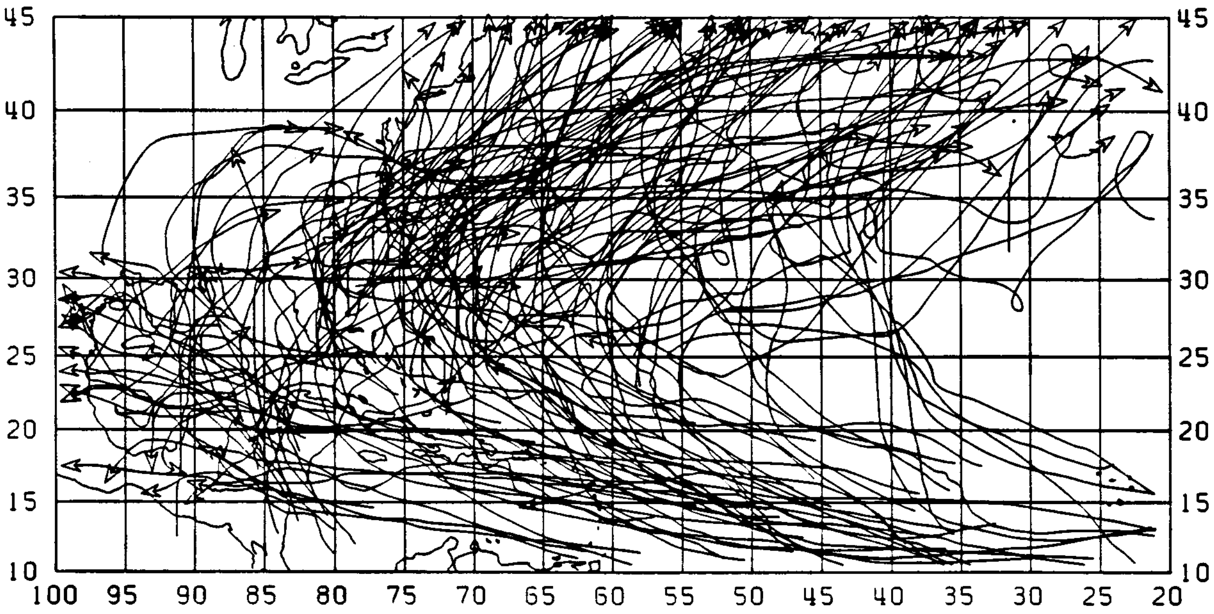

Fig. 5. Tracks of the 141 tropical storms and hurricanes, 1962-1981, used in developing NHC83 model. Portions of storm tracks having initial position ≤25°N were used as data set for "South-zone" storms while portions of storm tracks having initial positions >25°N comprised the "North-zone" set.

4.3 TEMPORAL AVERAGING OF GEOPOTENTIAL HEIGHTS

Early NHC models using geopotential heights as predictors incorporated one of two methods for advancing forward in time. The NHC67 model (Miller and Chase, 1966; Miller, et al., 1968) produced forecasts in discrete time steps. That is, forecasts are made over periods 0 through 12 h, 12 through 24 h, 24 through 36 h, 36 through 48 h and 48 through 72 h. In later models such as NHC72 (Neumann et al., 1972 and NHC73 (Neumann and Lawrence, 1975), forecasts were made over the entire forecast interval, i.e., 0 through 12 h, 0 through 24 h, 0 through 36 h, etc.

Tests, conducted prior to the development of NHC83, showed that best results (in terms of reduction of variance on dependent data) were obtained by averaging the geopotential height fields over time such that the 12 h forecast of tropical cyclone motion was based on an average of the initial analysis and the 12 h forecast[6] analysis, the 24 h forecast was based on an average of the initial analysis, the 12 h forecast analysis and the 24 h forecast analysis, etc. The method of accomplishing this averaging is described below. Note that this is not a simple linear average of the NMC gridded fields in the 65 x 65 format for the 7 projections zero through 72 h but rather, is an average relative to the storm position at each projection and the initial storm motion. Specifically:

(1) On the appropriate "perfect-prog" NMC analysis field, the large grid (M) shown on Fig. 1 was positioned at the best-track position of the storm for the appropriate projection; i.e, the initial position of the

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6 Note that the use of the term "forecast" in reference to the developmental mode of the model signifies actual analysis being substituted for the forecasts in accordance with the "perfect-prog" concept.

storm was positioned on the initial grid, the +12 h position of the storm was positioned on the +12 h "perfect-prog" grid, etc.

(2) The (M) grids were rotated according to the average storm heading over the period from the 12 h old position to the initial storm position. This, too, was based on best-track storm motion. Note that this rotation remains constant throughout the entire 72 h forecast cycle.

(3) The location of each of the 609 grid points in the (M) grid were determined according to the Taylor (1982) map-projection algorithm. Geopotential height values were then interpolated from the NMC 65x65 hemispheric grid.

(4) Steps 1, 2 and 3 were accomplished for each of the seven time periods, zero through 72 h. This resulted in seven sets of (M) grids, one for each of the time periods zero through 72 h.

(5) Grids 1 and 2 were then averaged to represent average forcing over the period zero through 12 h; grids 1, 2 and 3 were averaged to represent averaging forcing zero through 24 h, etc.

(6) Sub-sets (grid S or N) of the final 609 x 7 grid were used for all subsequent screening runs.

The question arises here as to the rationale behind keeping grid rotation constant throughout the forecast cycle. For consistency, grids should have been rotated at each time step in accordance with storm motion at that time step. Experimental grids were, indeed, constructed in this manner. However, it was found that continually changing both grid rotation and location gave inferior results, in terms of variance reduction, than did the method actually adopted of accounting only for translation. The reason or reasons for this are not fully understood.

Experiments were also conducted whereby one of the grids was omitted in the averaging process. For example, the final 72 h geopotential height fields used for the prediction of 72 h motion is an average of seven relative fields; one for each of the time periods zero through 72 h. Removal of only one of these seven grids produced larger errors for that projection. This suggests that the procedure is sound. It is again pointed out that these results are based on dependent data. However, the relatively good performance of the NHC83 model over the past 5-years on operational data further suggests that the averaging process has merit. In that grid rotation adds considerable complexity to the model, additional research in this area is warranted. Pike (1987b), for example, suggests an alternate and simpler method of grid rotation.

4.4 FINAL STRUCTURING OF DATA SET FOR SCREENING RUNS

As discussed in Section 4.2.3, 1,050 forecast situations were available for analysis. Since the goal was to predict along and across track motion relative to the persistence track, it was necessary to resolve all best-track tropical cyclone displacements into this component system. Also, since CLIPER forecasts were used as Model 1 (see Fig. 4), those forecast displacements were precomputed and resolved into along and across track components. Attempts to redesign the CLIPER model so as to directly produce along and across track components, were not successful.

The final developmental data set, for each of the 1,050 cases contained:

(1) Seven geopotential height fields defined on the 29 x 21 grid system shown in Fig. 1. These fields were for the initial analysis and the 6 "projections", 12 through 72 h.

(2) Positions of storms from -24 h to +72 h at 12 hourly intervals.

(3) Storm displacements for (2) resolved into along and across track components.

(4) Forecast CLIPER storm positions 12 through 72 h.

(5) CLIPER forecast displacements resolved into rotated coordinate system.

(6) Various "bookkeeping" items at each of the time periods, -24 h through +72 h. These included datetimes, maximum winds, pressures, directions of motion, translational speeds and stages (tropical, extratropical or sub-tropical) of storm.

4.5 STRATIFICATION OF DATA SET

The data set was subdivided into a North-zone set of storms and a South-zone set. This stratification was prompted by unavailability of geopotential height data in the deep tropics prior to 1975 (see Section 4.2.2) and the necessity for separate treatment of storms in this zone insofar as predictor location is concerned. Another reason was low standard deviations of heights in the deep tropics and the often adverse effect of this condition on statistical prediction equations (Neumann et al.,1979).

Experiments were conducted on stratification schemes based on direction of motion and based on latitude. Since the latter provided somewhat greater variance reduction on dependent data, it was selected over the former. Storms initially at or south of 25N were assigned to the South-zone whereas those initially north of 25N were assigned to the North-zone. This resulted in South- and North-zone data sets having 317 and 733 cases, respectively, for the 12 h forecast. Although the interzonal difference in sample size is rather large, this diminishes with increased projection. At 72 h, for example, there are 220 cases for the South-zone and 269 cases for the North-zone. The explanation here is that North-zone storms are more likely than South-zone storms to be dropped from the data set during a 72 h period due to the storm dissipating, moving over land or becoming extratropical.

During the five-year operational phase of the model, it had been noted that a few storms, assigned to the South-zone because of their initial latitude, were associated with motion characteristics more typical of North-zone storms. An example of such a storm was late season Hurricane KLAUS, 1984. Re-running forecasts of these storms after the 1987 season using North-, rather than South-zone equations, almost always produced better forecast verification. Accordingly, a modification was made to the prediction algorithm prior to the beginning of the 1988 season whereby South-zone storms poleward of latitude 20N with distinct North-zone motion characteristics were re-assigned to that zone. This was defined as having a speed of at least 5 knots and with initial motion between 340 degrees, clockwise through 150 degrees. Changes were <u>not</u> made to the prediction equations themselves.

4.5.1 South-zone Grid Structure

The lack of sufficient archived geopotential height data in the deep-tropics necessitated the development of a screening grid-structure as depicted in Fig. 3 where the storm is positioned well to the left of the grid-center. Since typical motion for storms in this zone was towards the west-northwest, grid point data near the lower left corner of the grid were often missing and it was necessary to insert climatological deep-layer-mean geopotential height values at those locations in order for the stepwise screening regression program to function properly. However, actual selection of these climatological predictors was disallowed; it having been determined earlier that there was no significant predictive information in this corner of the grid for South-zone storms.

4.5.2 North-zone Grid Structure

In the North-zone, the storm was positioned closer to the center of the grid in the left/right sense than it was in the South-zone (see Figs. 2 and 3). This was to allow for the inclusion on the grid of correlation centers (see Figs. 6 through 9) which appeared on <u>both</u> sides of the storm. For South-zone storms, as will be shown, the correlation center is primarily to the <u>north</u> (right) of the storm; there appears to be little predictive information on the equatorward side (to the left of the storm). It was also advantageous, as will be shown, to position the storm farther toward the bottom of the grid in the North-zone than in the South-zone. This was to allow for the inclusion of correlation centers which typically appeared well to the north of the storm in the case of across track motion in the analysis mode.

4.6 <u>METHOD OF PREDICTOR SELECTION</u>

The selection of appropriate predictors is extremely important and considerable time was spent on this task. Both objective and subjective procedures were used in the selection process. On the objective side, there was strict adherence to Monte-Carlo determined statistical significance levels as discussed earlier in Section 3.3.1. On the subjective side, attempts were made to select a set of predictors, consistent from one forecast period to another. This necessitated relaxation of the significance guidelines in some cases. Predictor selection was also governed by "forced-pairing" of predictors, discussed earlier in Section 3.3.3.

Prior to selecting final predictors, about 150 sets of correlation and partial correlation fields between a given component motion and the deep-layer-mean geopotential heights were objectively analyzed and examined. Examples of these fields which guided selection of predictors for Model 3 (perfect-prog mode--see Fig. 4) are shown in Figs. 6 through 10.

4.6.1 Along-Track Motion, North-zone (Perfect-Prog mode)

Fig. 6 shows a contoured linear (zero-order) correlation field between +12 h along track motion and the geopotential height field (see Section 4.3). A maximum correlation (in the negative sense) of -0.76 is clearly shown well to the left and ahead of the storm; grid point (5,6), closest to this point, is selected as the single predictor which explains most of the variance between +12 h along track motion and deep-layer-mean geopotential height. Therefore, low heights in this region are associated with large along-track storm displacements, irrespective of future predictor selection.

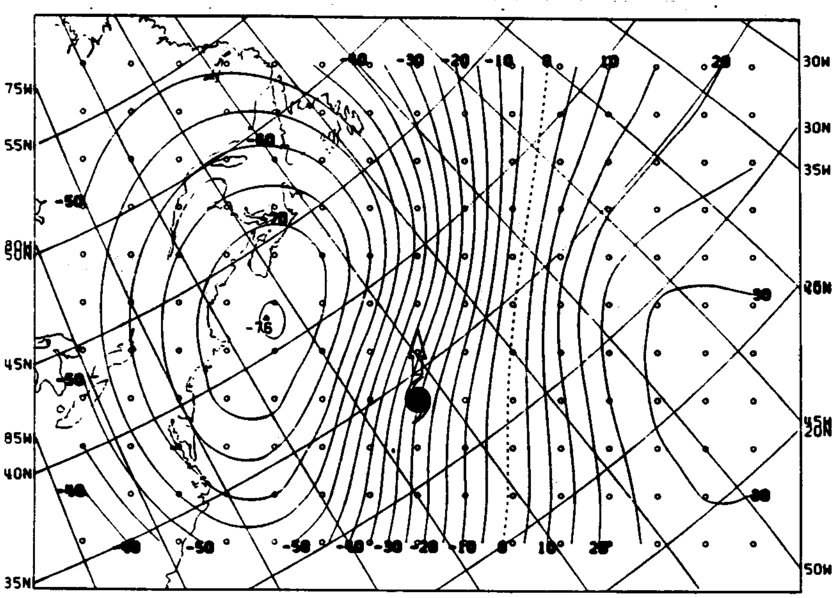

Fig. 6. Linear correlation coefficient field (zero-order partial correlation field) between 12 h along track motion and deep-layer-mean geopotential heights in the North-zone and for "Perfect-prog" mode. Storm is located at average position and is moving towards average motion of the 733 storms comprising developmental data set. Contour labels are in units of correlation coefficient x 100. Dashed line indicates zero correlation coefficient.

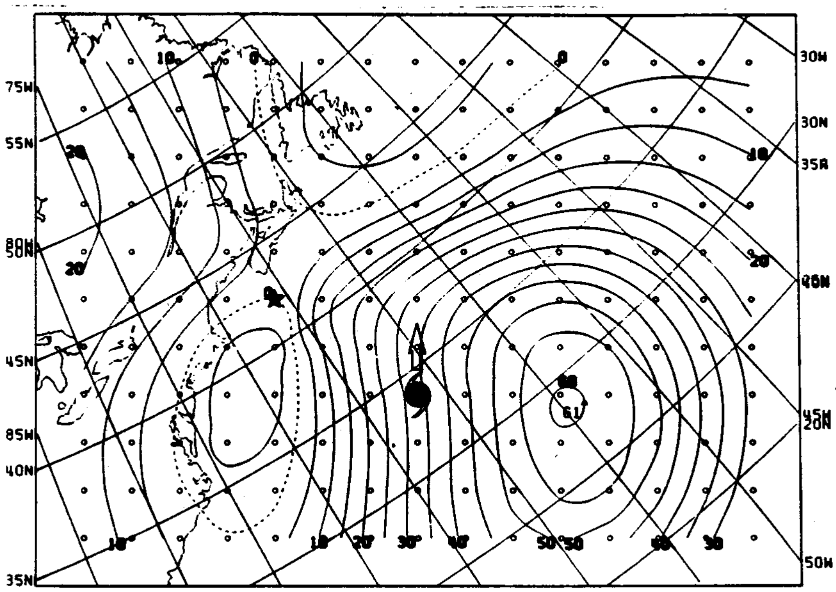

Fig. 7 Similar to Fig. 6 except for first-order partial correlation coefficient field. Star gives location of predictor (gridpoint) selected in previous step.

Fig. 7 shows the first-order partial correlation fields[7] given that predictor (5,6) has already been selected in the screening process. Note that the area to the right of the storm provides additional predictive information and that grid point (11,4), positioned closest to this maximum, was selected. It can also be noted, as expected, that the initially selected gridpoint (5,6) contributes zero incremental variance reduction. However, some residual negative correlation appears to be centered south-southwest of that point, indicating that gridpoint (5,6) was not located at the exact center of negative correlation. It should be noted here that the square of these partial correlation coefficients gives the fractional reduction of the variance from the previous and not the original step. Hence, the squared correlations are not additive in the algebraic sense.

The predictor selection process is discontinued when incremental variance reduction falls below some critical value. As pointed out earlier, the strict statistical significance criteria seldom allowed more than a few predictors (maximum was 4) to be selected in this "stepwise" manner.

The two initially selected predictors, locations of which are shown in Figs. 6 and 7, obviously represent a geopotential height gradient, which, in the geostrophic sense, is indicative of an average wind across the storm. However, as discussed in Section 3.3.3, these two predictors are not optimally located and additional screening runs were required to determine their final location. This "forced-pairing" technique was used whenever pairs of predictors appeared to be acting in concert. In the case of North-zone storms, these were, without exception, the first two predictors selected.

4.6.2 Across-Track Motion, North-zone (Perfect-Prog mode)

Figs. 8 and 9 are similar to Figs. 6 and 7 except that they address 72 h across track motion. As shown on Fig. 8, a "center-of-action" is located well ahead and to the right of the storm and grid-point number (10,9) is initially selected followed by gridpoint number (7,1) (see Fig. 9). It can be noted in this latter figure that the correlation maximum located to the south-southwest of the storm could be off the grid still farther to the south-southwest. However, earlier experiments with the larger (M) grid (see Fig. 1), showed that this was not the case. Similar to along-track motion, these two predictors were likely acting as a "gradient" and additional screening runs were made to determine their optimal location.

4.6.3 Along Track Motion, South-zone (Perfect-Prog mode)

The process of selecting South-zone predictors was considerably different than selecting predictors for North-zone storms. Fig. 10 shows that the main "center-of-action" is to the right of the storm rather than to the left as was the situation for North-zone storms. This reflects the strength of the sub-tropical ridge, typically located to the right of the

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[7] For a discussion of partial correlation fields applicable to tropical cyclone prediction models, see World Meteorological Organization (1979), pages II.4-17 through II.4-19.

storm. The second and third selected geopotential height predictors (not shown) were also indicative of the strength of this ridge in that they were both located to the right of the storm, one "ahead" and the other "behind". A complimentary predictor to the left of the storm, indicative of a "gradient", was either not present or marginally statistically significant.

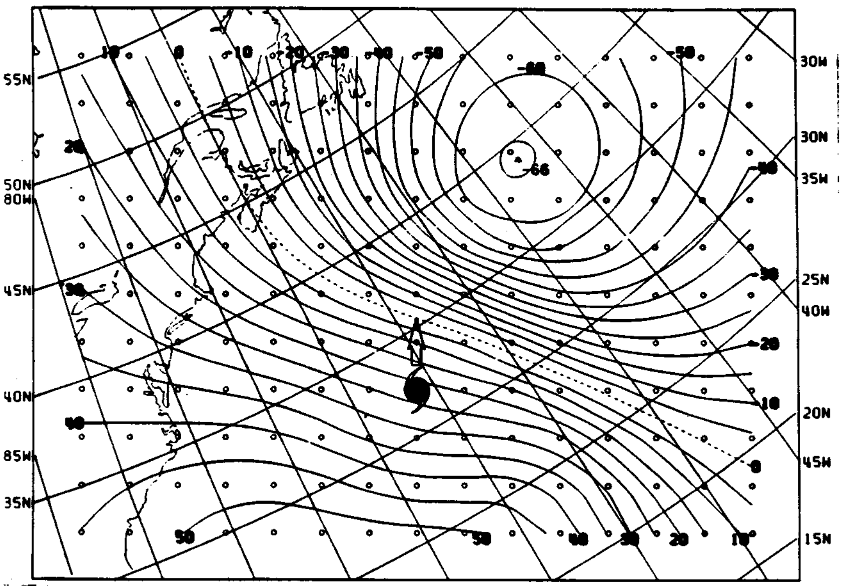

Fig. 8. Linear correlation coefficient field (zero-order partial correlation field) between 72 h across track motion and deep-layer-mean geopotential heights in the North-zone and for "Perfect-prog" mode. Storm is located at average position and is moving towards average motion of the 269 storms comprising developmental data set. Contour labels are in units of correlation coefficient x 100. Dashed line indicates zero correlation coefficient.

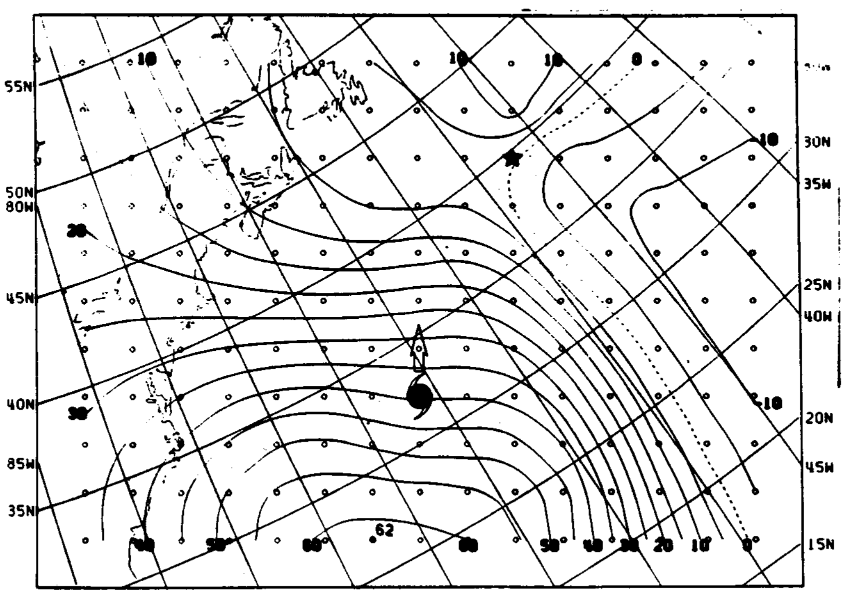

Fig. 9. Similar to Fig. 8 except for first-order partial correlation coefficient field. Star gives location of predictor (grid-point) selected in previous step.

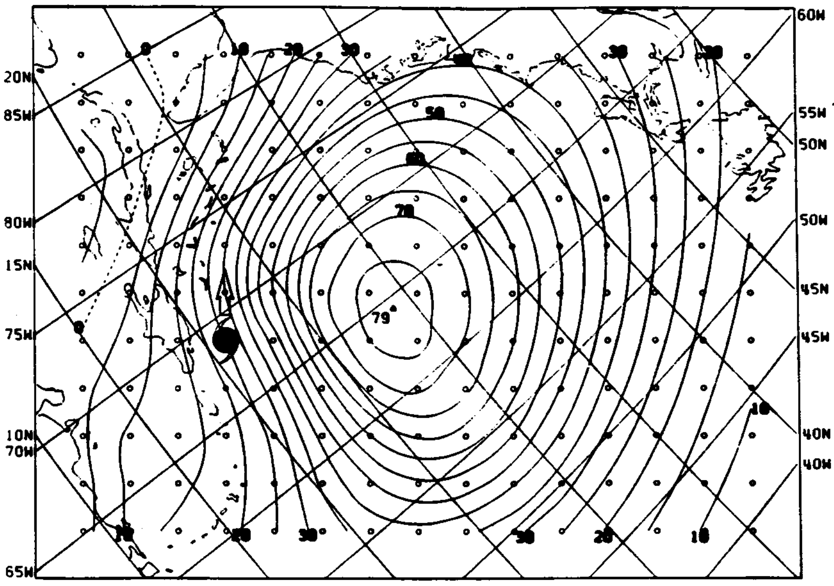

Fig. 10. Linear correlation coefficient field (zero-order partial correlation field) between 72h along-track motion and deep-layer-mean geopotential heights in the South-Zone and for "Perfect-Prog" mode. Storm is located near average position and is moving towards average motion of the 220 storms comprising developmental data set. Contour labels are in units of correlation coefficient x 100. Dashed line indicates zero correlation.

The strength of this sub-tropical ridge, particularly to the right and "ahead" of the storm was also related to across track motion (not shown). Thus, the ridge appears to be the dominant feature for the "steering" or, "implied steering" of tropical cyclones in the deep tropics. This is also true, to a certain extent, for North-zone storms but these storms are steered predominantly by other synoptic-scale features.

4.7 FINAL LOCATION OF PREDICTORS

Figs. 11 and 12 show the final location of predictors for Model 2 (analysis-mode) while Figs. 13 and 14 show final predictor locations for Model 3 (perfect-prog) mode. As discussed in the previous section, these predictors were selected after objective and subjective analyses of partial correlation fields as shown in Figs. 7 through 10 modified by "forced-pairing" methods. Selection was also governed by subjective considerations such as the desire to maintain a reasonably consistent set of predictors for given Model 2 or 3; for each of the two zones and for each of the two components of motion.

It can be noted that the predictors selected in the "perfect-prog" mode (Model 3) are grouped more around the storm than are those selected in the analysis mode (Model 2). In the latter, predictors are based only on an initial analysis and the selection of predictors at greater distances from the storm is an attempt to obtain additional predictive information on later "steering" of the storm from the larger scale synoptic pattern. These more distant predictors are not very efficient, however, and the incremental variance reduction tends to be small. In the "perfect-prog" mode, however, direct rather than implied "steering" information is continually being provided by the "prognostic" fields and this information tends to remain close to the storm area. There is no need for information distant from the storm in the "perfect-prog" mode.

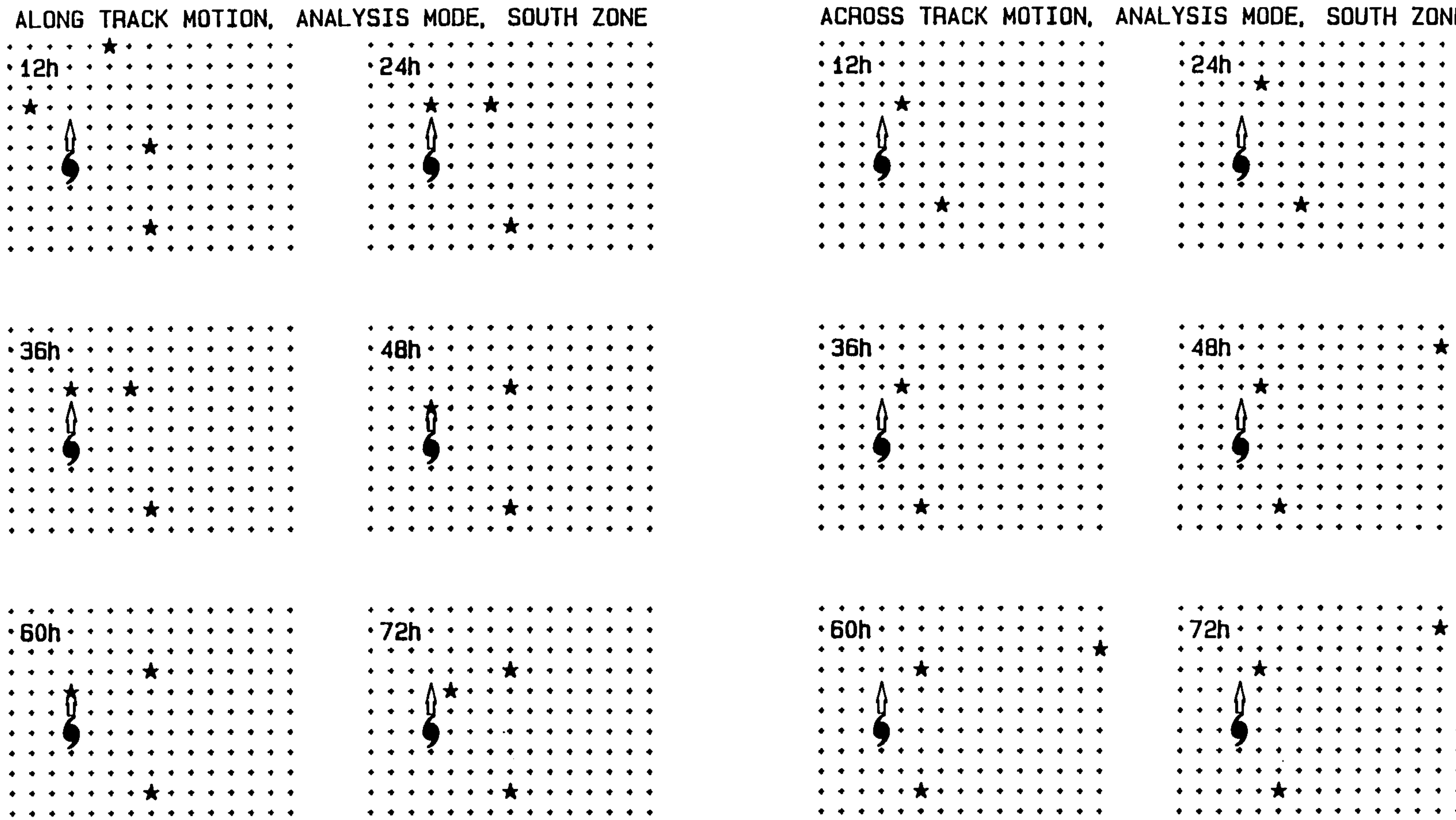

Fig. 11. Predictor location (starred gridpoints) for analysis mode (Model 2) over South-zone.

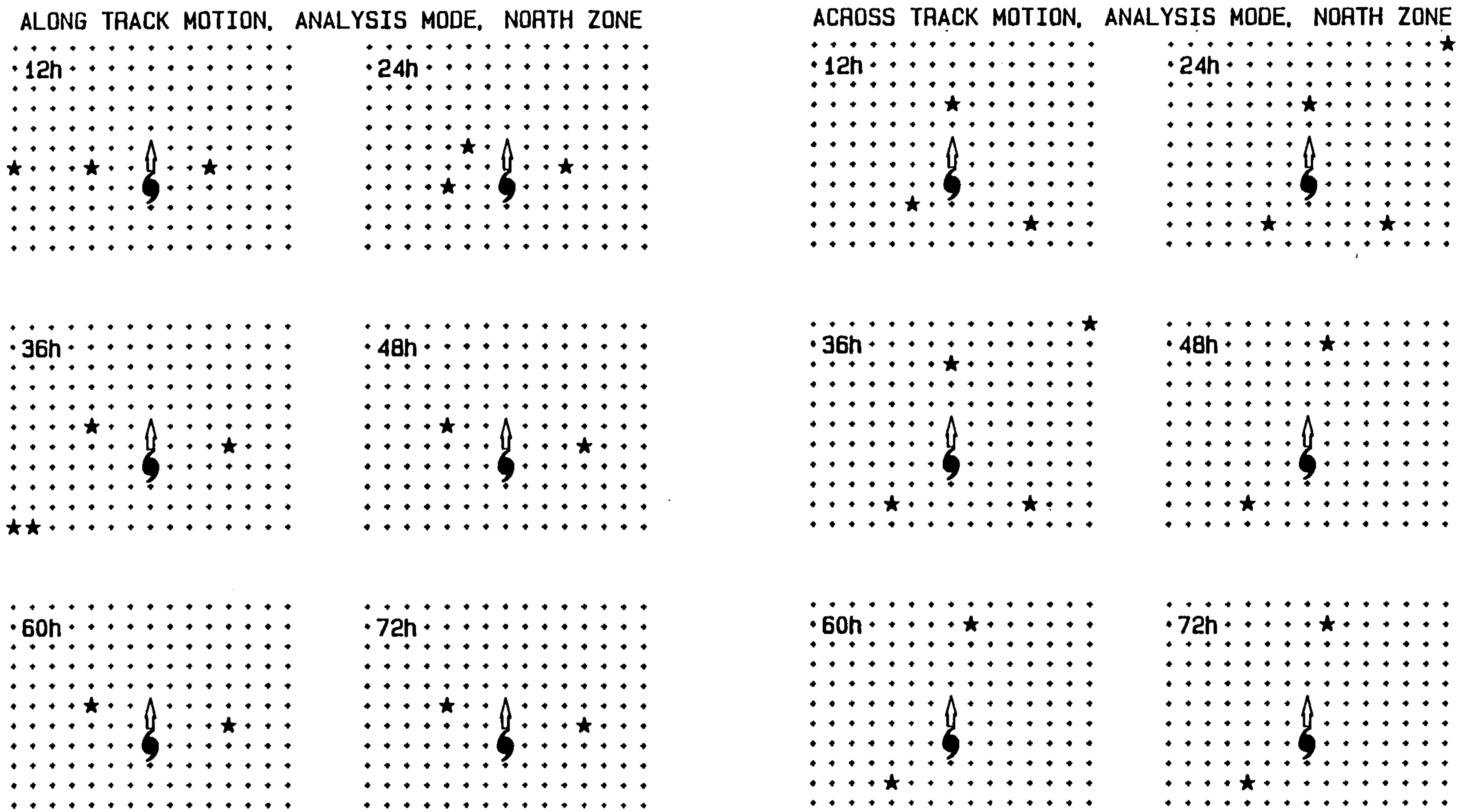

Fig. 12. Similar to Fig. 11 except for North-zone.

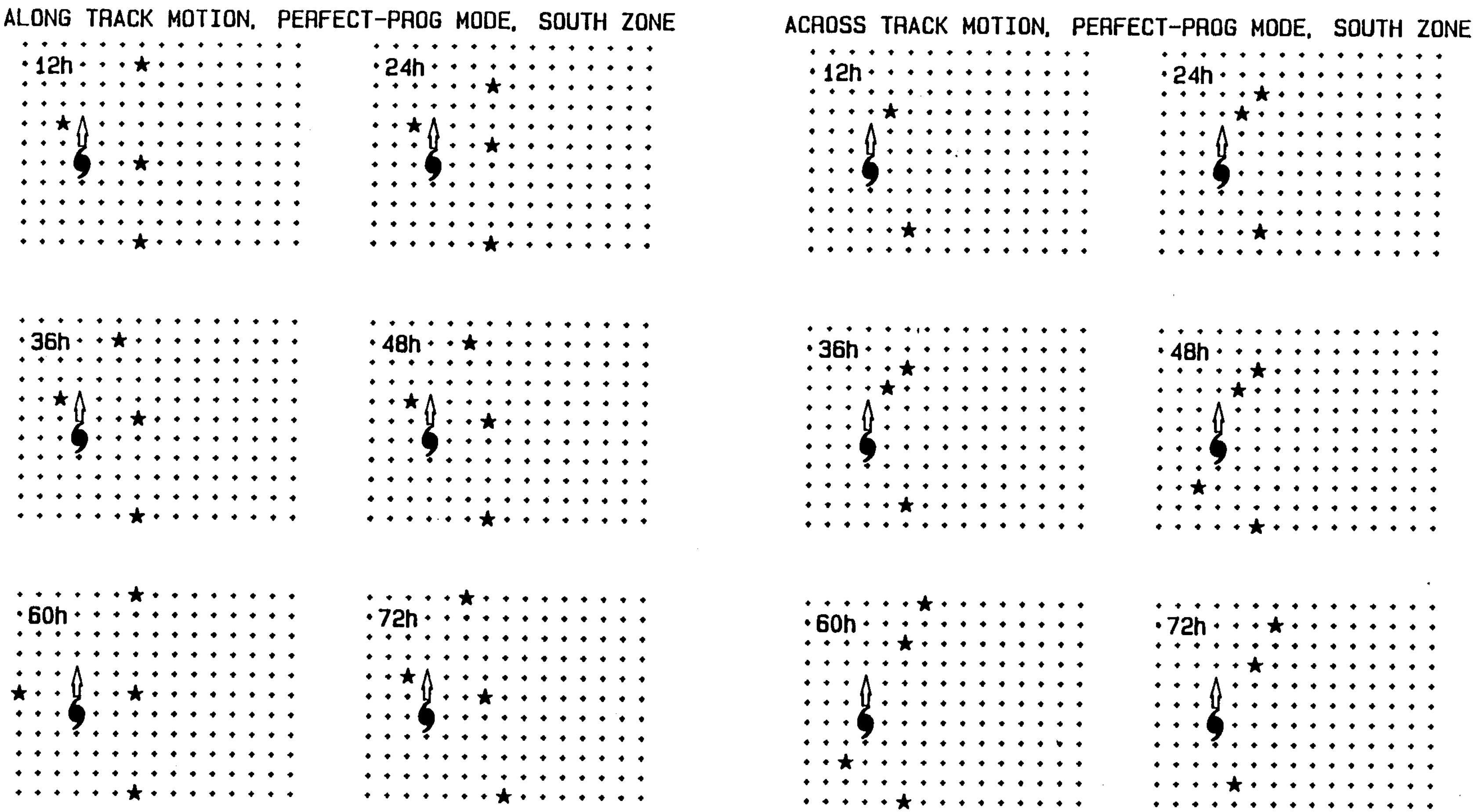

Fig. 13. Predictor location (starred gridpoints) for "perfect-prog" mode (Model 3) over South-zone.

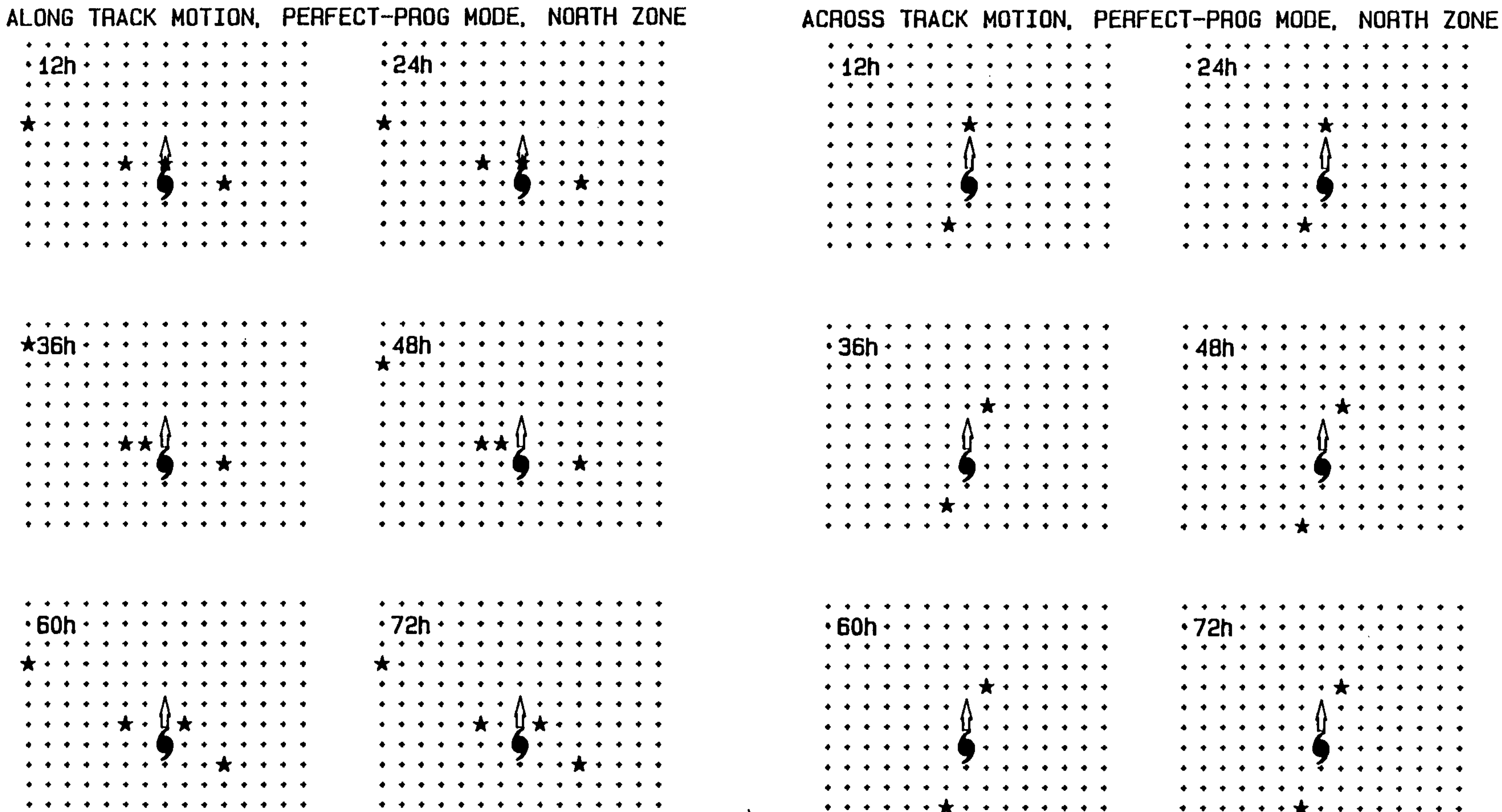

Fig. 14. Similar to Fig. 13 except for North-zone.

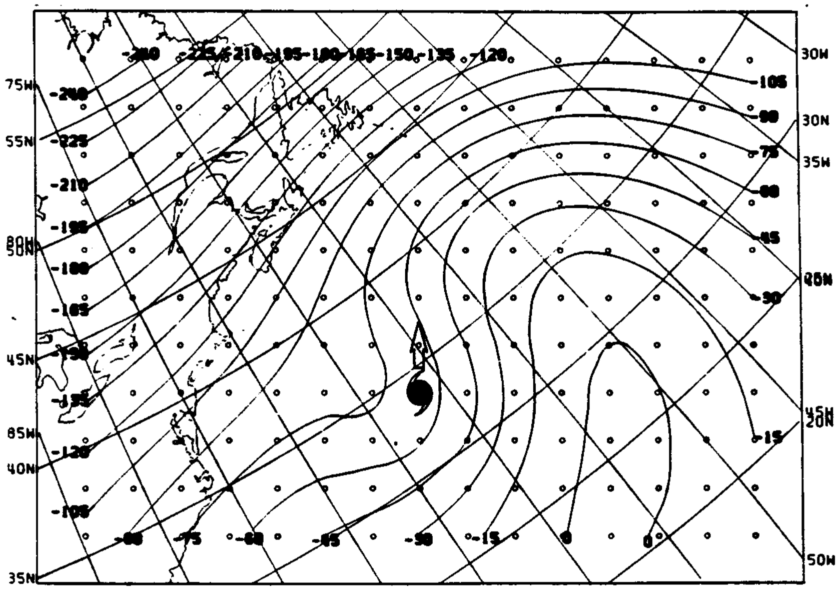

Fig. 15. Composite geopotential height field for North-zone storms. Storm is positioned at average location and is moving towards the average (vector) heading of the 733 cases comprising dependent data set for this zone. Deep-Layer-Mean contours are labled in departure (meters) from mean September deep-layer-mean height of 6060.5 meters. (see Section 3.1)

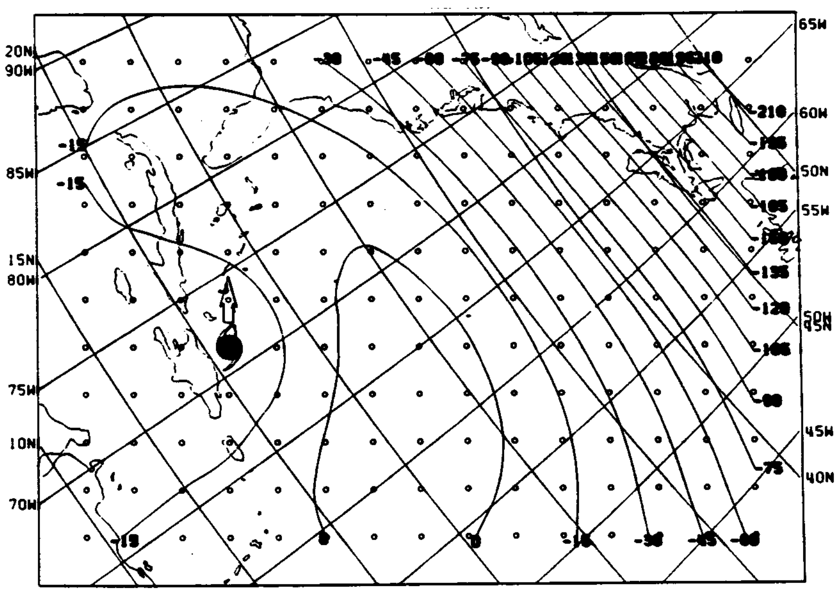

Fig. 16. Same as Fig. 15 except for 317 cases comprising dependent data set for South-zone.

4.8 COMPOSITED GEOPOTENTIAL HEIGHT FIELDS

The geopotential height fields composited with respect to storm motions are shown for the North- and South-zones, respectively in Figs. 15 and 16. In Fig. 15, the pattern suggests that the storm is crossing contours to the left. This is consistent with compositing studies of other authors such as George and Gray (1976), Brand et al. (1981) and Dong and Neumann (1986)

In Fig 16, not much can be said in regard to storm motion in relation to the orientation of the contours. The pattern suggests however, that a reasonably strong ridge is needed to keep a storm in the easterlies.

4.9 SUMMARY OF NHC83 PERFORMANCE ON DEVELOPMENTAL DATA

As discussed in Section 4.1.2.1 and as illustrated in Fig. 4, NHC83 consists of 5 sub-systems which have been referred to as Models 1 through 5. In summary: Models 1, 2 and 3, respectively, are derived from predictors based on CLIPER-type variables, on current deep-layer-mean geopotential heights and on numerically forecast deep-layer-mean geopotential heights with actual analysis being substituted for the latter in the developmental mode; Model 4 is based on a combination of Models 1 and 2 while the final Model 5 is based on a combination of Models 1, 2 and 3. In combining models, the predictions from each of the three Models 1, 2 and 3, in terms of along and across track displacements, are used as developmental data (predictors) for further development of Models 4 and 5 in accordance with Eq. (2).

In this Section, performance of each of these five models, based on developmental data, will be described. Since Model 3 was completely and Model 5 was partially based on actual analyses substituted for numerical prognoses, these would be expected to perform very well in the developmental mode and, indeed, this was the case.

4.9.1 Predictands

Tables 3 and 4 present statistical data for the mean and standard deviation of the predictands, that is, the observed tropical cyclone displacements for the South- and North-zones, respectively. The initial across track mean displacements are small compared to the initial along track displacements, particularly in the North-zone. This is a consequence of aligning the grid with the initial motion of the storm as defined by current and -12 h positions. The initial (instantaneous) across track motion is therefore forced to be zero.

Also included in Tables 3 and 4 are the average initial location and motion of the storms within each of the two zones. These had been depicted earlier in Figs 2 and 3. Changes in average initial position and motion throughout the 72 h forecast period occur in the South-zone because faster storms tend to continue in the same zone. In the North-zone, the faster moving storms tend to become extratropical and be dropped from further consideration in the model.

Table 3. Mean and standard deviation (nmi) of along and across track tropical cyclone displacements (predictands) for specified forecast interval in South Zone. Also given are average location, vector motion of storms (as defined by storm positions at -6h and +6h) and sample size.

	12h	24h	36h	48h	60h	72h
Mean along track displacement..............	110.9	209.4	295.7	368.3	431.7	483.5
Standard deviation of along track displacement.........	48.7	88.6	128.6	171.7	217.0	266.2
Mean across track displacement..............	7.3	26.1	57.3	96.6	153.3	227.0
Standard deviation of across track displacement.........	31.3	73.7	126.0	184.0	248.2	321.4
Average storm location.......	21.1N 71.3W	21.2N 71.1W	21.2N 70.9W	21.1N 70.2W	21.1N 69.4W	21.0N 68.7W
Vector motion (degs/kts).....	303.4/9.0	304.4/9.0	304.9/9.1	304.8/9.2	305.4/9.3	306.3/9.4
Sample size..................	317	295	276	259	241	220

Table 4. Mean and standard deviation (nmi) of along and across track tropical cyclone displacements (predictands) for specified forecast interval in North Zone. Also given are average location, vector motion of storms (as defined by storm positions at -6h and +6h) and sample size.

	12h	24h	36h	48h	60h	72h
Mean along track displacement	142.0	253.7	331.7	389.7	427.7	444.6
Standard deviation of along track displacement.........	101.2	191.4	269.3	334.7	404.8	450.0
Mean across track displacement..............	10.0	28.5	49.1	80.9	108.2	147.9
Standard deviation of across track displacement.........	51.4	125.2	204.6	278.3	355.5	406.0
Average storm location.......	33.8N 61.6W	33.4N 61.2W	33.0N 61.1W	32.6N 61.1W	32.4N 60.9W	32.2N 61.1W
Vector motion (degs/kts).....	035.6/9.2	034.6/8.1	033.8/7.2	033.4/6.7	032.2/6.3	030.5/5.9
Sample size..................	733	614	507	412	333	269

4.9.2 Reductions of Variance

It can be noted that standard deviations (S_y) of predictands in the two zones are quite different, being considerably higher in the North. Reduction of variance (R^2), is given by the relationship,

$$R^2 = 1 - S_e{}^2/S_y{}^2 \qquad (3)$$

where R is the multiple correlation coefficient and S_e, the standard error, refers to the standard deviation of the errors (residuals) which are measured about the regression hyperplane. Thus, reduction of variance and multiple correlation coefficient are not absolute quantities and must be considered in the context of Eq. (3). In general, the higher values of along track R^2 in Tables 5, 6 and 7 indicate higher standard deviations of along track motion rather than greater skill in predicting this component of motion.

Tables 5 and 6, respectively, give the variance reduction attained by Model 2 (based on predictors derived from initial analysis only) and Model 3 (based on predictors derived from "perfect-prog" fields only). Reductions from the latter are always higher. The increase or decrease of

Table 5. Developmental data [Model 2 (analysis mode)] reduction of variance ($0 \le R^2 \le 1$) of tropical cyclone motion for specified forecast interval and for specified zone and component of motion. Sample size for respective zone is same as that given in Tables 3 and 4.

	12h	24h	36h	48h	60h	72h
South Zone along track variance reduction.........	0.401	0.479	0.479	0.456	0.432	0.400
South Zone across track variance reduction.........	0.148	0.169	0.202	0.245	0.268	0.269
North Zone along track variance reduction.........	0.766	0.653	0.579	0.432	0.419	0.377
North Zone across track variance reduction.........	0.368	0.444	0.461	0.370	0.345	0.328

Table 6. Developmental data [Model 3 (perfect-prog mode)] reduction of variance ($0 \le R^2 \le 1$) of tropical cyclone motion for specified forecast interval and for specified zone and component of motion. Sample size for respective zone is same as that given in Tables 3 and 4.

	12h	24h	36h	48h	60h	72h
South Zone along track variance reduction.........	0.425	0.506	0.578	0.642	0.707	0.785
South Zone across track variance reduction.........	0.198	0.339	0.456	0.575	0.659	0.740
North Zone along track variance reduction.........	0.821	0.850	0.845	0.852	0.863	0.854
North Zone across track variance reduction.........	0.462	0.643	0.728	0.778	0.797	0.785

Table 7. Developmental data reduction of variance ($0 \le R^2 \le 1$) obtained by combining Models 1, 2 and and 3 into a single model (Model 5...see Fig. 4). Sample sizes for specified zones are slightly less than those given in Tables 3 and 4 due to reasons specified in text, page 31. being available.

	12h	24h	36h	48h	60h	72h
South Zone along track variance reduction.........	0.869	0.801	0.753	0.734	0.757	0.814
South Zone across track variance reduction.........	0.774	0.605	0.588	0.632	0.691	0.759
Sample size (South zone).....	307	286	269	252	235	215
North Zone along track variance reduction.........	0.929	0.916	0.887	0.889	0.882	0.869
North Zone across track variance reduction.........	0.815	0.764	0.785	0.805	0.817	0.803
Sample size (North zone).....	721	605	500	406	329	266

variance reduction with time is dependent on a number of factors, including the relationship given by Eq. (3), and the relatively small standard deviations of initial across track components as given in Tables 3 and 4.

Table 7 gives the variance reduction attained by the final Model 5. These are artificially high, being based partially on best-track CLIPER predictors and observed, rather than forecast, geopotential heights. It is to be noted that the sample sizes are slightly less than those given earlier. This reduction is due to unavailability of CLIPER forecasts for some of the cases and the elimination of a few cases where the initial analysis was apparently incorrect in regard to contour orientation and storm motion over the next 12 h. This was determined from a residual analysis of forecast storm displacements.

4.9.3 Minimum Attainable Forecast Error from Statistical Models

Forecast errors for the developmental data set are given in Tables 8, 9 and 10 where forecast error is defined as the great-circle distance between the observed (best-track) storm position and the forecast storm position. Smaller errors in the South-zone is typical of all statistical prediction models of this type and does not necessarily imply greater skill in this zone. Also included in these tables is the percentage improvement of the final Model 5 forecast errors over Model 1 (CLIPER) errors. The Model 5 errors given in Tables 8, 9 and 10, are based on <u>absolutely ideal</u> initial conditions and can only be approached but never attained. These errors can be thought of as an absolute minimum insofar as statistical models are concerned for the given basin.

5.0 OPERATIONAL IMPLEMENTATION OF NHC83

The model was first tested operationally for the 1983 Atlantic Hurricane season but, because of the scarcity of storms for that year, the operational test was continued through the 1984 season. These tests indicated that the model was performing very well and it has been run in a more or less fully operational mode beginning with the 1985 season. There have been no changes to the structure of the model over the period. However, there have been changes in the numerical model which drives NHC83. This will be discussed in Section 5.4.

5.1 <u>AVAILABILITY OF MODEL (GRAPHICAL OUTPUT)</u>

Unlike other NHC models which make use of numerical guidance, NHC83 output is made available to the forecaster in time to meet all advisory deadlines. This is accomplished by making optimum use of numerical products including the Global Data Assimilation System (GDAS) "first guess" fields and the 0000GMT once per day MRF run to 240 h. The NMC products currently used by NHC83 are shown in Table 11. The 0000Z "early" run and both of the "regular" runs require numerical products beyond the period currently being provided by the Aviation Run. Current practice at the NHC is to extrapolate the 72 h field as constant in time whenever this occurs. Tests indicate that this does not have a negative effect on NHC83 performance probably because of decreasing forecast accuracy of the numerical model with time.

Output is made available to the forecaster in both digital and graphical format. he graphical depiction is in the form of 7 charts, one for the "initial nalysis" and one each for the projections, at 12-hourly intervals, 12 hrough 72 h. The charts provide contours of deep-layer-mean geopotent al height with a contour interval chosen to adequately represent the steering" pattern. Also portrayed are the forecast tropical cyclone tra k and past storm positions at -12 and -24 h.

Table 8. ›evelopmental (dependent data) forecast errors (nmi) on South Zone storms for Model 1 (CLIPER), 'odel 2 (analysis mode) and Model 3 (perfect-prog mode). Also shown are forecast errors from comb ed Models 4 and combined Model 5 (see Fig. 4). Sample size is identical to that given in Table 7 f South zone.

	12h	24h	36h	48h	60h	72h
CLIPER (M el 1) errors.	21.0	60.6	113.8	176.1	240.0	313.1
Analysis de (Model 2) errors.	39.8	79.4	127.1	177.1	233.7	298.1
Perfect-p g (Model 3) errors	39.5	74.4	108.3	135.7	163.2	181.3
Model 4 (dels 1 and 2 combine errors...........	19.8	55.4	102.4	156.6	212.6	280.7
Model 5 (dels 1, 2 and 3 combine errors (NHC83)...	19.3	50.3	86.9	121.7	152.7	171.5
Percentag improvement of Model 5 ver Model 1.......	8.1	17.0	23.6	30.9	36.4	45.2

Table 9. ›evelopmental (dependent data) forecast errors (nmi) on North Zone storms for Model 1 (CLIPER), 'odel 2 (analysis mode) and Model 3 (perfect-prog mode). Also shown are forecast errors from comb ed Models 4 and combined Model 5 (see Fig. 4). Sample size is identical to that given in Table 7 f North zone.

	12h	24h	36h	48h	60h	72h
CLIPER (M el 1) errors.	31.8	102.5	184.1	265.8	352.5	434.2
Analysis de (Model 2) errors.	54.4	125.1	199.8	293.7	367.9	425.0
Perfect-p g (Model 3) errors	49.0	90.5	131.2	159.9	193.5	226.0
Model 4 (dels 1 and 2 combine errors...........	29.2	92.9	171.0	255.6	333.6	392.1
Model 5 (dels 1, 2, and 3 combine errors (NHC83)...	27.9	68.4	112.5	142.2	180.3	212.7
Percentag improvement of Model 5 ver Model 1	12.3	33.3	38.9	46.5	48.9	51.0

Table 10. Developmental (dependent data) forecast errors (nmi) on North and South zone storms combined r Model 1 (CLIPER), Model 2 (analysis mode) and Model 3 (perfect-prog mode). Also shown are error from combined Models 4 and combined Model 5 (see Fig. 4).

	12h	24h	36h	48h	60h	72h
CLIPER (M el 1) errors.	28.6	89.1	159.5	231.5	305.6	380.0
Analysis de (Model 2) errors.	50.1	110.4	174.4	249.0	312.0	368.3
Perfect-p g (Model 3) errors	46.2	85.3	123.2	150.6	180.9	206.0
Model 4 (dels 1 and 2 combine errors...........	26.4	80.9	147.0	217.7	283.2	342.3
Model 5 (dels 1, 2 and 3 combine errors (NHC83)...	25.2	62.6	103.5	134.3	168.8	194.3
Percentag improvement of Model 5 ver Model 1	11.9	29.7	35.1	42.0	44.8	48.9
Sample si	1028	891	769	658	564	481

Table 11. NHC83 run schedule. All numerical forecasts are based on output from the NMC Medium Range Forecast (MRF) model but with different Optimum Interpolation Initial Analysis data cutoff times. Symbols * and #, respectively, indicate that NHC83 needs numerical forecast through 84h and 78h but product is only available through 72h. GDAS refers to Global Data Assimilation System; F00 and F06, respectively, refer to model initialized analysis and model 6h forecast. Forecaster availability times are approximate. (Schedule as of 6/1/88)

NHC83 RUN DESCRIPTION	SCHEDULE ADVISORY RELEASE	TIME OF INITIAL CONDITIONS	TIME NHC83 OUTPUT AVAILABLE TO FORECASTER	INITIAL ANALYSIS USED BY NHC83	NUMERICAL MODEL USED BY NHC83
0000Z "Early"	0400Z	0000Z	0130Z	GDAS "First Guess" for 00Z	12Z AvRun to 72h*
0000Z "Late"	0400Z	0000Z	0545Z	F00 FROM 00Z AvRun	00Z AvRun to 72h
0600Z "Regular"	1000Z	0600Z	0730Z	F06 FROM 00Z AvRun	00Z AvRun to 72h#
1200Z "Early"	1600Z	1200Z	1330Z	GDAS "First Guess" for 12Z	240h 00Z MRF run to 84h
1200Z "late"	1600Z	1200Z	1745Z	F00 FROM 12Z AvRun	12Z AvRun to 72h
1800Z "Regular"	2200Z	1800Z	1930Z	F06 FROM 12Z AvRun	12Z AvRun to 72h#

5.2 OPERATIONAL VERIFICATION STATISTICS

5.2.1 Homogeneous Comparisons for 0000 and 1200GMT, 1983-1987

Figure 17 shows the operational performance of NHC83 for the five-year period 1983-1987 relative only to the operational performance of the CLIPER model (Neumann and Pelissier, 1981a). This homogeneous sample of forecasts from both models shows the comparison for each of the seven projections, 12 through 72 h. Consistent with the practice at the National Hurricane Center for a number of years, errors in initial storm positioning are taken into account in these and other verification data to be presented. This is a simple adjustment of forecast positions based on the spatial differences between initial operational positions and best-track positions. The small effect of these differences on verification statistics is discussed by Neumann and Pelissier (1981b). In any case, this would have little effect, if any, on Figs. 17, 18 and 19 since these involve ratios rather than actual values of forecast errors.

Figure 17 contains two sets of data, one "without 1987 bias correction" and another "with 1987 bias correction". The meaning of these two sets of data will be discussed later. The main point from the figure is that the NHC83 model improves substantially over climatology and persistence with maximum improvement occurring at the 48-hour projection. Whether there is any temporal significance to this maximum relative to numerical models which have fed into NHC83 has not been determined. The data presented in Fig. 17 and elsewhere in Section 5.0 are for the 0000 and 1200GMT "late" runs of NHC83 only, the term "late" having been defined in Table 11.

Figure 18 is a homogeneous comparison between NHC83 and some of the other models[8] in use at the National Hurricane Center (Neumann and Pelissier, 1981a). The exceptional performance of NHC83 is clearly indicated.

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[8] Fig. 18 does not include comparison with the analog HURRAN model, the barotropic SANBAR model nor the baroclinic MFM model since the requirement for homogeneity would have severely restricted the sample size. It also does not include the NHC67 model since verification of that model was discontinued after the 1986 season.

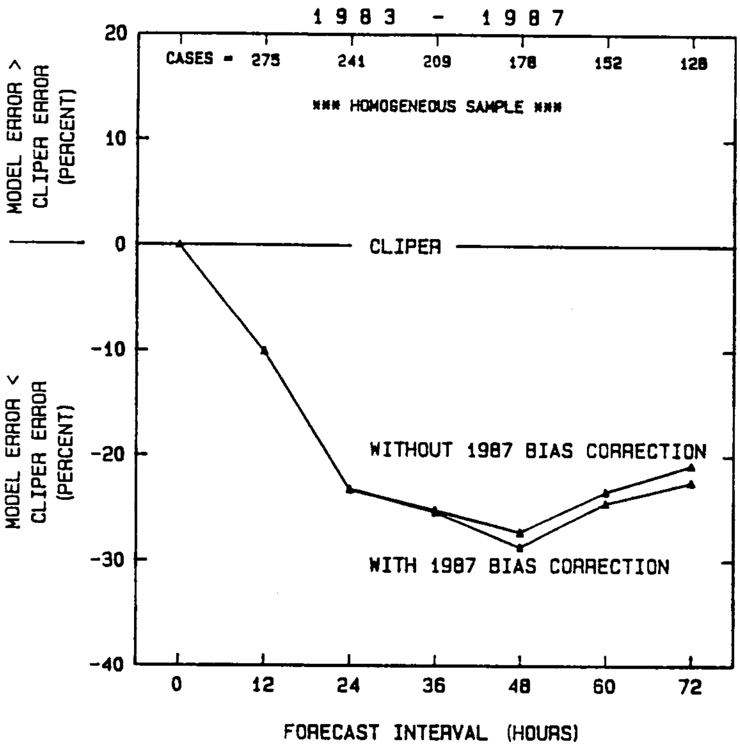

Fig. 17. Operational performance of NHC83, 1983-1987, relative to operational performance of homogeneous sample of CLIPER forecasts. For a discussion of the "bias correction", see Section 5.3. Sample includes 0000 and 1200GMT forecasts only.

Finally, Fig. 19 presents a similar comparison between the baroclinic MFM model and NHC83. For the years prior to 1987, the performance of these two models (except at 24 h and earlier where NHC83 excelled), was comparable. However, the MFM performed relatively poorly for the 1987 season.

NHC83 performance from one year to the next was very consistent over the five-year period. This is demonstrated in Table 12 which presents forecast errors (corrected for initial positioning error) for four of the NHC models as shown along with the "Official Forecast". Also included in Table 12 is the average forecast errors over the five-year period. These latter data were graphically depicted in Fig. 18.

5.2.2 Forecasts at 0600 and 1800GMT

Verification data presented in Figs. 17 through 20 are for forecasts made for the 0400 and 1600GMT tropical cyclone advisories (based on 0000 and 1200GMT initial data). However, NHC83 forecasts are also available for the 1000 and 2200GMT advisories which are based, respectively, on 0600 and 1800GMT initial data. This is accomplished by using numerical forecasts for +6 h as the initial conditions, +18 h as the 12 h forecast, etc. (see Table 11). Although formal verification of 0600 and 1800GMT forecasts is not available for the full five-year period, informal studies for some of the years, as documented in National Hurricane Center Progress Reports, indicate that the performance for these time periods is comparable to that obtained for the 0000 and 1200GMT "late" runs.

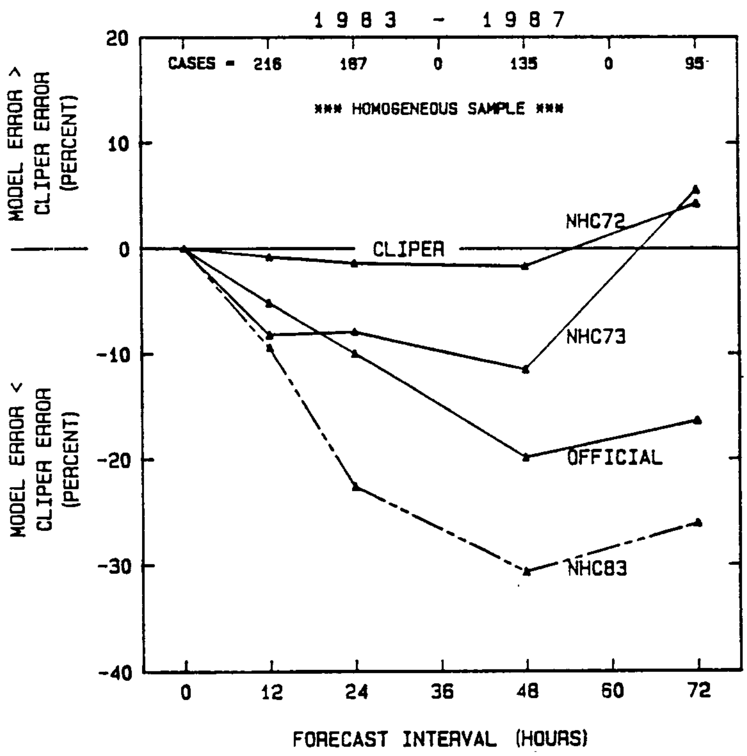

Fig. 18. Operational performance of specified model and of the "Official Forecasts", 1983-1987, relative to operational performance of homogeneous sample of CLIPER forecasts. Sample includes 0000 and 1200GMT forecasts only.

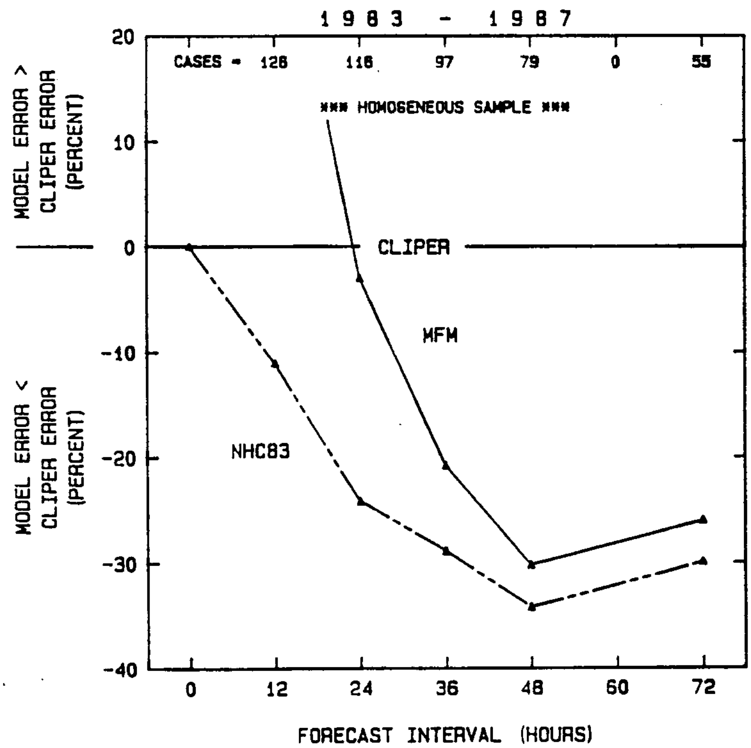

Fig. 19. Same as Fig. 18 except for NHC83 and MFM models.

AVERAGE FORECAST ERRORS (NMi) FOR EACH YEAR, 1983-1987

***** HOMOGENEOUS SAMPLE *****

		NHC83	CLIPER	NHC72	OFFICIAL	NHC73	SAMPLE SIZE
	12H	26*	30	32	39	32	08
1983	24H	49*	63	67	81	90	05
	48H	166	140*	149	223	213	03
	72H	374*	441	666	397	417	02
		NHC83	CLIPER	NHC72	OFFICIAL	NHC73	SAMPLE SIZE
	12H	48*	53	50	53	50	65
1984	24H	96*	119	104	116	119	57
	48H	217*	260	252	224	243	47
	72H	324*	332	422	341	419	37
		NHC83	CLIPER	NHC72	OFFICIAL	NHC73	SAMPLE SIZE
	12H	48*	53	57	48*	50	75
1985	24H	88*	117	128	100	107	66
	48H	168*	271	290	222	242	44
	72H	288*	399	367	333	466	26
		NHC83	CLIPER	NHC72	OFFICIAL	NHC73	SAMPLE SIZE
	12H	43	47	42*	44	43	35
1986	24H	88*	109	95	101	99	29
	48H	173*	241	210	230	228	17
	72H	294*	377	405	387	429	11
		NHC83	CLIPER	NHC72	OFFICIAL	NHC73	SAMPLE SIZE
	12H	47	52	51	47	41*	33
1987	24H	103*	140	147	114	109	30
	48H	222*	391	365	233	293	24
	72H	313*	638	556	365	466	19
		NHC83	CLIPER	NHC72	OFFICIAL	NHC73	SAMPLE SIZE
1983	12H	46.2*	51.0	50.6	48.4	46.8	216
THRU	24H	91.8*	118.6	117.0	106.8	109.3	187
1987	48H	195.2*	281.8	276.9	225.7	249.0	135
	72H	309.5*	419.0	436.9	350.1	442.4	95

Table 12. Average forecast errors (operational) of specified model for each year, 1983 - 1987, and over entire five-year period. Asterisk (*) adjacent to error identifies minimum for that period. Graphical depiction of 1983-1987 errors are shown in Fig. 18.

5.3 EFFECTS OF "PERFECT" AND "IMPERFECT" INPUT DATA

The significance of "perfect" versus "imperfect" initial data to the performance of the NHC83 model is discussed in this Section. Reference here is to both CLIPER input variables and the numerically forecast geopotential height data. What is the effect on the NHC83 model of uncertainties in specifying these input data? This question was addressed by rerunning the five-years of operational data on best-track CLIPER data and by substituting "perfect" analysis for the "imperfect" numerical forecast fields. The test was conducted in the following manner:

(1) Operational Errors from the CLIPER model alone were determined. These are given by data set 1 in Table 13.

(2) The percentage improvement of the 1983-1987 operational NHC83 errors over the homogeneous set of operational CLIPER errors runs was determined. This is given as data set 2 in Table 13. These data had been previously depicted graphically as the lower "curve" of Fig. 17.

(3) NHC83 was rerun for all of the 1983-1987 forecast situations using CLIPER input data determined from the best-track. The percentage improvement of these errors over operational CLIPER errors (data set 1) was determined. These errors are given as data set 3 in Table 13.

(4) NHC83 was rerun for all of the 1983-1987 forecast situations using operational CLIPER input but with observed deep-layer-mean fields computed from the NMC initial analysis rather than from the forecast fields. These errors and the percentage improvement over operational CLIPER are given as data set 4 in Table 13.

(5) Finally, steps (3) and (4) were combined. That is, the 1983-1987 NHC83 forecasts were rerun using best-track rather than operational CLIPER and using analyses rather than numerical height field forecasts. Results are given as data set 5 in Table 13.

The results of the test are more or less as would be expected. Substantial improvements in the performance of the NHC83 model occurred as the quality of the input CLIPER variables improved and as the quality of the numerical prognoses improved. Although not explicitly included in the test, further improvements could also be expected as the quality of the initial analysis itself improved. Examination of some of the larger NHC83 forecast error situations, even after step (5) was accomplished, disclosed some analysis deficiencies which undoubtedly had a negative effect on the performance of the NHC83 model. Notable among these was frequent mis-positioning the tropical cyclone vortex in the initial analysis (see Section 6.2).

The results of the test in step (5), above, are somewhat equivalent to running the model on dependent data, this having been discussed earlier in Section 4.9.3 with specific forecast errors from the dependent data mode having been given in Table 10.

Table 13. Results of test to determine effect of "perfect" and "imperfect" data on the performance of the NHC83 model. Errors are in nautical miles and period of record is 1983-1987.

		12h	24h	36h	48h	60h	72h
1	Operational (OPNL) CLIPER errors...	53.6	121.8	199.5	273.9	340.2	390.7
2	Errors from regular NHC83 OPNL runs........................	48.2	93.6	148.6	195.3	256.9	302.7
	Improvement over OPNL CLIPER.......	10.1%	23.2%	25.5%	28.7%	24.5%	22.5%
3	Reruns with best-track CLIPER and numerical forecasts..........	22.8	65.8	121.6	172.0	241.9	297.8
	Improvement over OPNL CLIPER.......	57.5%	44.0%	39.0%	37.2%	28.9%	23.8%
4	Reruns with OPNL CLIPER and analyses.....................	48.1	91.6	140.1	172.2	221.0	251.7
	Improvement over OPNL CLIPER.......	10.3%	24.8%	29.8%	37.1%	35.0%	35.6%
5	Reruns with best-track CLIPER and analyses.....................	22.4	62.7	112.6	148.8	205.3	240.2
	Improvement over OPNL CLIPER.......	58.2%	48.5%	43.6%	45.7%	39.7%	38.5%
	Sample size......................	275	241	209	178	152	128

5.4 EFFECTS OF NUMERICAL MODEL BIASES

Use of the "perfect-prog" concept in developing the NHC83 model made it vulnerable to biases in the numerical model which drives NHC83 (see Section 4.1.1). For the 1983 through 1986 seasons, the NHC83 model was activated from the operational ("Aviation-Run) NMC 12-layer version of the spectral model and virtually no biases in the forecasts of geopotential height were observed. However, for the 1987 hurricane season, the 18-layer MRF (Medium-Range Forecast) model replaced the older spectral model in the operational "Aviation-Run". The MRF has a cold bias which leads to an erosion of the geopotential height field (and an appropriate bias in the wind field) with time. This bias has been discussed by a number of authors including Saha and Alpert (1988), Epstein (1988), Schemm and Livesey (1988) and White (1988).

Some bias characteristics of the older 12-layer vs. the newer 18-layer model are depicted in Fig. 20. The figure shows the average geopotential height biases of the 18-layer MRF model for the summers of 1985, 1986 and 1987. Also shown are average biases for the 12-layer spectral model for the 1985 season. These biases represent the average from all NMC grid points from the equator to 35N and from 0W westward to 180W, the general domain of Atlantic and Eastern Pacific tropical cyclones. A very slight positive bias of the 12-layer model compared to the large negative biases of the 18-layer model are clearly shown on Fig. 20.

The geographical pattern of the bias is shown in Fig. 21. The 72 h average biases within the Atlantic subtropical ridge line exceed 40 meters in the negative sense. This is approximately two standard deviations from the mean observed geopotential height. The NHC83 model interprets this height "fall" as a real synoptic scale feature.

The bias had a detrimental effect on NHC83 performance for the 1987 season and a temporary "fix-up" which forces the MRF average forecast hemispheric geopotential heights to conform to the initial hemispheric average for each forecast cycle has been incorporated into the model. The NHC83 forecasts for the 1987 season were rerun with this simple bias correction scheme in place and the improvement (reduction of errors) for the 1987 season was about 6% for the 72 h projection with smaller improvements for the other projections. The effect of the 1987 bias correction on the entire sample of NHC83 forecasts over the five-year period was shown in Fig. 17 to be quite small.

The effect of the MRF biases is greatest in the South-zone where the forecast is heavily dependent on the strength of the sub-tropical ridge line [typically located poleward from the storm (see Section 4.6.3)]. Indeed, the improvement noted on 1987 NHC83 forecast verification, after accounting for the bias, is about 13% for the 60 and 72 h projection if only South-zone storms are considered.

It is anticipated that more refined bias correction procedures of the type described by Saha and Alpert (1988) will be incorporated into the NHC83 model. Their procedure is to keep a "running" 30-day average bias correction for each grid point and to apply this correction on the 31st day.

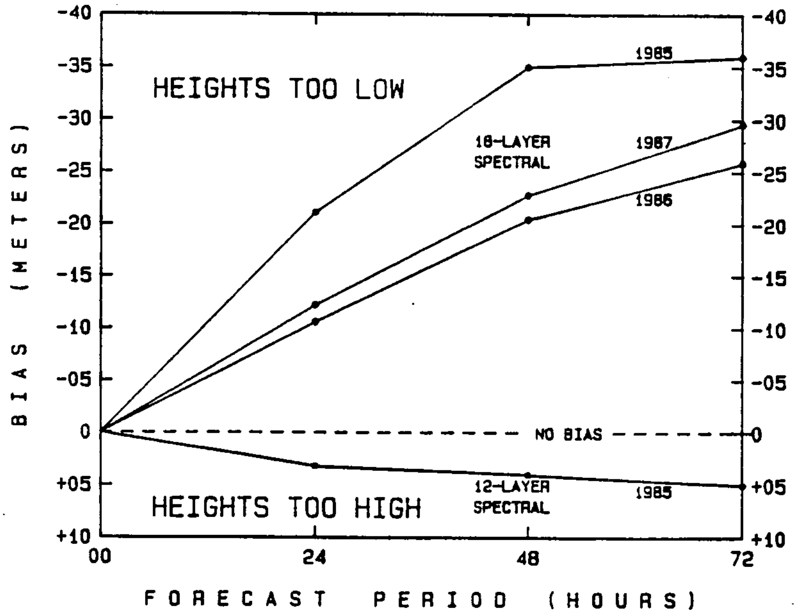

Fig. 20. Bias (forecast - observed) in forecasts of 500 mb geopotential height for specified model, for specified forecast period and for specified year. Includes forecasts made at 0000GMT for months July, August and September. Geopotential heights have been averaged for all NMC grid points over area from 0W westward to 180W and from equator to 35N.

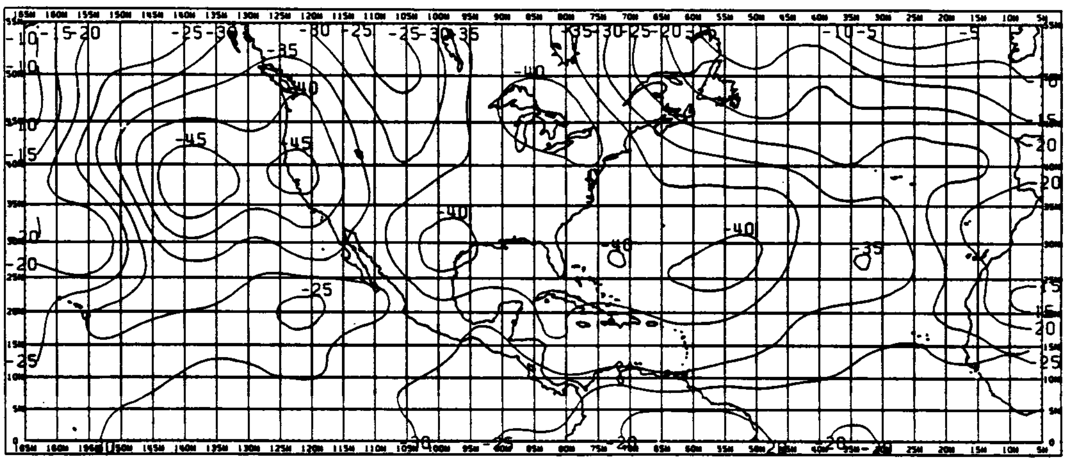

Fig. 21. Bias (forecast - observed) in the MRF model 72h forecasts of 500 mb geopotential height for main portion (July, August and September) of the 1987 hurricane season. Spatial average of contoured field south of 35N is -29.6 meters. Maximum bias over the Atlantic (25N - 30N) is near the average position of the subtropical ridge line. Sample includes forecasts made at 0000GMT only. Contour interval is 5 meters and all values are negative over domain of the analysis.

6.0 POSSIBLE IMPROVEMENTS TO THE MODEL

The excellent performance of the NHC83 model (see footnote 2) suggests that the use of numerical guidance in a statistical prediction framework has considerable merit in tropical cyclone prediction. Nevertheless, there are weaknesses both in the NHC83 model itself and the numerical models which provide input to NHC83. These need to be addressed in future updates or complete revisions to the model. Some of these recommended improvements are discussed in this Section.

6.1 STATISTICAL IMPROVEMENTS

6.1.1 Use of Winds Instead of Heights.

Experiments by Pike (1987a) suggest that deep-layer-mean winds might more profitably be used as statistical predictors of tropical cyclone motion than heights. In the original development of NHC83, the use of winds over heights was preferred and considered but a sufficiently long sample of such winds was not available. Additionally, the use of winds would reduce, but not entirely eliminate, the bias problem currently being experienced by the NHC83 model.

6.1.2 Modification of Rotated Grid System

The grid-rotation system used in NHC83 adds a considerable amount of presumably justified complexity to the model. Since NHC83 contains a number of innovations, it has not been determined whether the rotated system is, in part, responsible for the good performance of the model. It is, indeed, possible that the grid rotation system is working in the negative sense; additional research is needed to determine this.

Pike (1987b) demonstrated that a grid rotation system based on the non-correlated axes of a bivariate normal distribution fitted to observed storm motion at the different projections might be used in developing the model. This system is not only simpler to use than current NHC83 methodology but, in Pike's experiments, gave lesser forecast error on dependent data.

6.1.3 Re-evaluating regression constants in Model 5

As shown schematically in Fig. 4, the final NHC83 model is a weighted combination of Models 1, 2 and 3. The weighting was necessarily based on developmental data. Accordingly it is almost a certainty that both Model 1 (based on best-track CLIPER forecasts) and Model 3 (based on actual "perfect" analyses rather than imperfect numerical prognoses) are overweighted. This could be corrected by re-evaluating the weighting functions based on operational forecasts for Model 1 and Model 3 rather than developmental forecasts, i.e., a type of simulated Model Output Statistics (Neumann and Lawrence, 1975).

6.1.4 Adjustment to the "Forecast Recycle Option"

The practice of recycling through the prediction algorithm to compensate for initial motion vector errors was discussed in Section 4.1.2.2. Currently, 2 iterations are used for all forecasts. Experiments suggest, however, that the number of iterations should be set as a function of the given forecast situation.

6.2 NUMERICAL IMPROVEMENTS

One of the advantages of the "perfect-prog" approach is that improvements in the numerical side of the model are passed on to the statistical side.

Graphical output from the NHC83 model (not illustrated in this Technical Memorandum) can be used to evaluate both the numerical product and the NHC83 forecast. Inconsistencies become immediately apparent. Although a review of the numerical input to NHC83 over the past five years is still underway, preliminary results disclose three problem areas with the numerical guidance in addition to the bias problem already discussed in Section 5.4.

6.2.1 Initial Analysis Problems

If one assumes that a tropical cyclone moves in accordance with the deep-layer-mean flow, there are several instances when the operational analyses used by NHC83 (see Table 11) seemed to contradict this assumption. However, brief visual inspections of the analyses in these instances suggests that the analysis "steering" pattern was incorrect in vicinity of the storm. This further suggests that storm motion could be used to enhance the analyses in these situations which typically occur over otherwise data-void areas.

6.2.2 Incorrect Progression of Synoptic Features

NHC83 forecasts are explicitly related to synoptic scale "steering" patterns given by the numerical package. Several of the large NHC83 forecast errors over remote regions of the Atlantic have been traced to incorrect predictions or movement of long and short waves in the westerlies. Re-running of these forecasts in the "perfect-prog" mode; that is, by substituting actual analysis for the numerical product, often brings a dramatic reduction in forecast error.

6.2.3 Incorrect Positioning of Tropical Cyclone Center

The NHC83 prediction system is such that the storm circulation should not be included in the analysis. However, if a vortex is present, the assumption is made that the position is correct. Misplacement of the vortex by the objective analysis scheme typically occurs when an isolated upper-air reporting station such as Bermuda in the Atlantic or Socorro Island in the Eastern Pacific comes under the influence of the small scale storm circulation. Here, the analysis treats the observation in the larger scale synoptic sense. Often, the problem is compounded by juxtaposition of the tropical cyclone with cold-core circulations.

This appears to be the major problem encountered by the NHC83 model at the present time. Even a small misplacing of the vortex has a profoundly detrimental effect on NHC83 performance. Research here should focus on: (1) forcing the vortex into the correct position or (2) removing the vortex without removing important synoptic scale information. The latter might be accomplished by selective spectral filtering in the area around the storm (DeMaria, 1987, 1988).

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