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A GUIDE TO ATLANTIC AND EASTERN PACIFIC MODELS FOR THE PREDICTION OF TROPICAL CYCLONE MOTION

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ABSTRACT. A number of prediction models, both statistical and dynamical, are used as objective guidance preparatory to the issuance of tropical cyclone advisories for the Atlantic and the Eastern Pacific areas. This study presents a brief description of these models and places each in its proper historical and operational perspective. A homogeneous sample of operational forecasts is used to compare the performance of the various models with the performance of the CLIPER (CLImatology and PERsistence) model, the latter being considered a kind of "base-line" skill model.

1. INTRODUCTION AND PURPOSE

Responsibility for preparation, coordination and issuance[1] of tropical cyclone advisories for the Atlantic tropical cyclone basin rests with the National Hurricane Center (NHC), Coral Gables, FL. Similar responsibility for the Eastern North Pacific is assigned the Eastern Pacific Hurricane Center (EPHC), located at the Weather Service Forecast Office, San Francisco, CA. Preparatory to the issuance of these advisories, a number of models which provide statistical and numerical guidance on the forecast track, generally through 72h, are routinely activated and made available to the NHC or EPHC hurricane forecaster. Each of these models has been described in various professional meteorological journals or NOAA Technical Memoranda. However, a collective description which serves to place each model in its proper historical and operational perspective has not been available. Hopefully, the present study will satisfy this need. Based on some recent verification statistics, the study will also cite temporal and spatial performance characteristics of the various models and the "official" forecast, the latter referring to the specific final forecast released by the appropriate Center after having access to at least some guidance.

Necessarily, the treatment will merely highlight the salient features of each of the 10 models in the National Weather Service (NWS) inventory. In all cases, however, reference to a more thorough treatment of each model and other applicable background material will be provided.

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[1] Advisories for storms located with an area of responsibility assigned to Weather Service Forecast Office, San Juan, PR, are issued by that office after coordination with the National Hurricane Center.

Table 1. Classification of and nomenclature for Atlantic and Eastern N. Pacific models for the prediction of tropical cyclone motion. SANBAR and MFM models are applicable to either ocean through grid relocation.

CLASSIFICATION	NOMENCLATURE	
	ATLANTIC	E. PACIFIC
I. Statistical models		
A. Analog	HURRAN	EPANLG
B. Regression equation		
1. Excluding synoptic data	CLIPER	EPCLPR
2. Including synoptic data	NHC67/NHC72	EPHC77
Statistical-dynamical model	NHC73	
Numerical models		
A. Barotropic	SANBAR	SANBAR
B. Baroclinic	MFM	MFM

2. BACKGROUND

Objective models for the prediction of tropical cyclone motion have been in continuous use at NHC for a number of years, the earliest of these generally considered to be the "Riehl-Haggard" (Riehl *et al.*, 1956) and the "Miller-Moore" (Miller and Moore, 1960) methods. These were relatively simple statistical models which were based on a single-level geopotential height analysis around the storm area. By comparison, today's models are considerably more complex and may require objective analyses for a number of levels for a number of environmental parameters over a major portion of the Hemisphere as well as over the equatorial portions of the Southern Hemisphere. For a historical treatment of the transitional years, the reader is referred to Staff, NHC (1979). Background on the more recent development of prediction models for the Eastern Pacific can be found in Neumann and Leftwich (1977).

3. TYPES OF PREDICTION MODELS

In the broadest sense, models for the prediction of tropical cyclone motion are classed as being either statistical or dynamical. An intermediate class of model, referred to as "statistical-dynamical" is also recognized. These latter models incorporate numerically forecast data into a statistical prediction framework. A finer synthesis of the various types of models is afforded by Table 1. Each of the models listed in the table will be treated separately. Operational versions of these models in tropical cyclone basins other than the Atlantic or Eastern Pacific are cited by Hope and Neumann (1977).

A. Analog Models

Analog models are founded on the principle that "families" of storm tracks exist, tend to be repetitive, and to be associated with likewise repetitive synoptic patterns. For any given storm, identification of a family allows inference to be made about the future behavior of the storm.

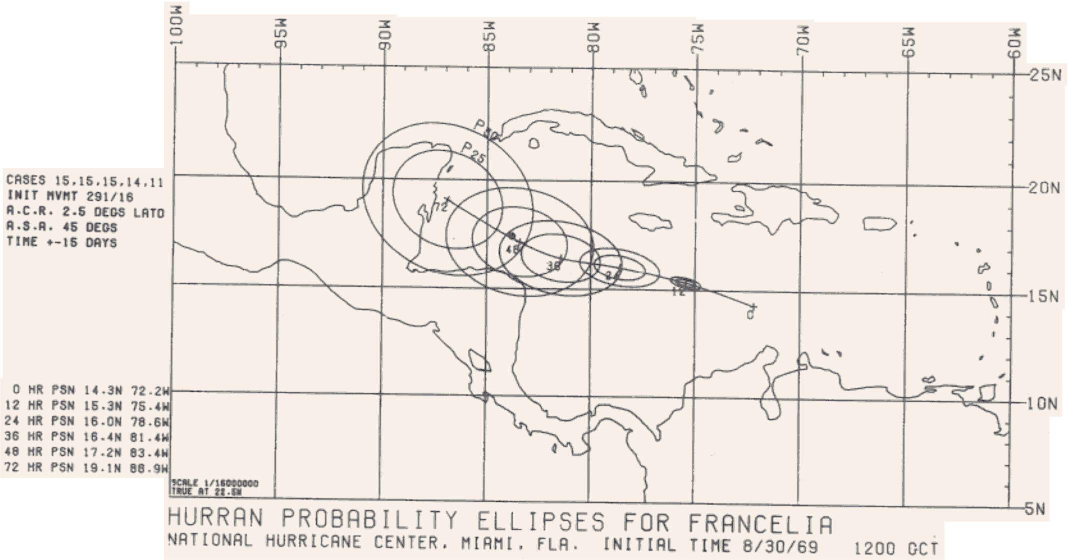

Fig. 1. Example of analog forecast on hurricane Francelia, initially located 14.2N, 72.2W on 8 August, 1969. Elliptical envelopes give 25 and 50% confidence limits on forecast track. Legend in upper-left refers to initial analog acceptance criteria.

In the Atlantic analog model, HURRAN (HURRicane ANalogs), a current storm is associated with a parent storm track by a computer algorithm which scans all historical storms back to the year 1886[2]. These latter storms have recently been documented by Neumann *et al.* (1978) and transferred to magnetic tape by Jarvinen and Caso (1978). Analog candidates are selected by considering such criteria as storms 1) occurring within 15 days, 2) passing within 2 1/2 degrees of latitude, 3) moving within 22 1/2 degrees in direction, 4) moving within 5 knots in speed[3] of a current storm. Selected storms are then translated to a common origin and rotated to a common heading. After further processing, clusters of analog storm positions after 12, 24, 36, 48 and 72h are next fitted to a bivariate normal distribution and the locus of the centroids of these distributions are taken as the most likely forecast track. Elliptical probability ellipses depict less likely tracks. A typical analog forecast as it might be presented to the hurricane forecaster is illustrated in Figure 1. HURRAN became operational at NHC for the 1969 season. Its derivation is described by Hope and Neumann (1970) while an error analysis is provided by Neumann and Hope (1972).

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[2] Through the year 1978, a total of 773 such storms are recorded.

[3] These criteria can be modified to force the selection of additional or fewer analogs.

The Eastern Pacific analog model EPANLG (Eastern Pacific ANaLoG) was adapted for NWS use from the U.S. Navy (Jarrell *et al.*, 1975) analog model for that area. The adaptation is described by Neumann and Leftwich (1977).

As pointed out by Hope and Neumann (1977), analog models are the only operational model common to all tropical cyclone basins. Their popularity, in spite of relatively poor performance in terms of vector error on more northerly storms (see section 5), is partially due to the presentation of the forecasts in terms of probability ellipses. These provide a large amount of diagnostic information with a minimum amount of computer resources and cost. Their utility is discussed by Simpson (1971) and by Neumann and Leftwich (1977).

B. Regression Equation Models Which Exclude Synoptic Data

The two models in this category are CLIPER (CLImatology and PERsistence) for the Atlantic and EPCLPR (Eastern Pacific CLiPeR) for the Eastern Pacific. The former, as originally conceived, was intended as a backup for HURRAN when that model failed to produce a forecast because of insufficient analog candidates. However, as will be shown later in this study, both CLIPER and EPCLPR consistently (and somewhat suprisingly) outperform their analog counterparts when this performance is measured in terms of mean vector error.

The models in this class derive their predictability from exactly the same type of information considered by the purely analog models except that they accomplish this by least squares fitting to continuous polynomial functions as distinguished from the discrete analog process. This has the advantage of always providing a forecast, even under anomalous situations. Another major advantage of this class model is its utter simplicity compared to the analog class models. In the latter, the historical storm file must be scanned each time the program is run. whereas in the CLIPER-class models, the storm file is processed only during the initial formulation of the regression equations.

CLIPER incorporates eight first-order predictors. These are: 1) current storm latitude, 2) current storm longitude, 3) current storm u-component of motion, 4) 12h old u-component of motion, 5) current storm v-component of motion, 6) 12h old v-component of motion, 7) day number, 8) maximum sustained windspeed. These same predictors, less number 8, are used in EPCLPR. Additional predictors in CLIPER-class models include products and cross-products of the first-order terms.

Output from CLIPER-class models can be presented to the forecaster in the form of probability ellipses similar to those provided by HURRAN-class models as illustrated in Figure 1. Although this option has not been incorporated in the Atlantic or Eastern Pacific version, it has been incorporated into another version of the CLIPER-class model developed for the North Indian Ocean (Neumann and Mandal, 1978). Thus, in many respects, these models are similar to analog models and, indeed, they have been referred to as *simulated analog models* although this nomenclature is not entirely justified. The derivation of the original

CLIPER model for the Atlantic area is described by Neumann (1972). A comparison of the performance and other attributes of these models is given by Neumann (1977). A version for the South Indian Ocean is described by Neumann and Randrianarison (1976).

C. Regression Equation Models Which Include Synoptic Data

This class of model includes NHC67 and NHC72 for the Atlantic and EPHC77 for the Eastern Pacific. The rationale dates back to earlier models developed for NHC by the National Hurricane and Experimental Meteorology Laboratory (NHEML, formerly NHRP and NHRL) such as the NHC64 (Miller and Chase, 1966) model. These, in turn, relate back to still earlier work performed by the Travelers Weather Research Center under contract to NHRP and NHRL such as Miller (1958) and Veigas (1962)

The basic difference between these and the models discussed in the previous sub-section is the additional use of current and 24h- old upper-level geopotential height data in the prediction algorithm. Heights or combinations of heights are systematically selected by stepwise screening methods as being significantly correlated with future zonal and meridional tropical cyclone motion. The heights are represented on the storm-centered, 8 x 15 grid system which translates with the storm. Such a grid is illustrated in Figure 2. The most important geopotential heights selected in this process represent height differences across the storm - east/west differences for meridional motion and north/south differences for zonal motion. These are referred to as "steering" predictors.

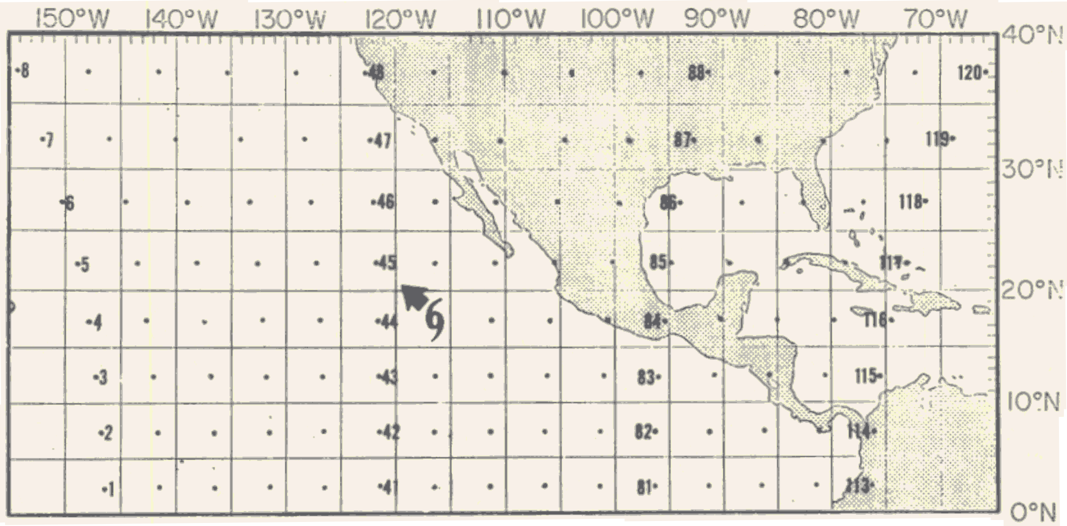


Fig. 2. Mercator map version of grid system typically used by statistical models which incorporate synoptic data. Grid is relocatable and storm is always positioned at grid-point 52 (row 4, column 7). Grid spacing is 300n.mi. (556km.). In this example, storm has been positioned at the average location of Eastern Pacific tropical cyclones.

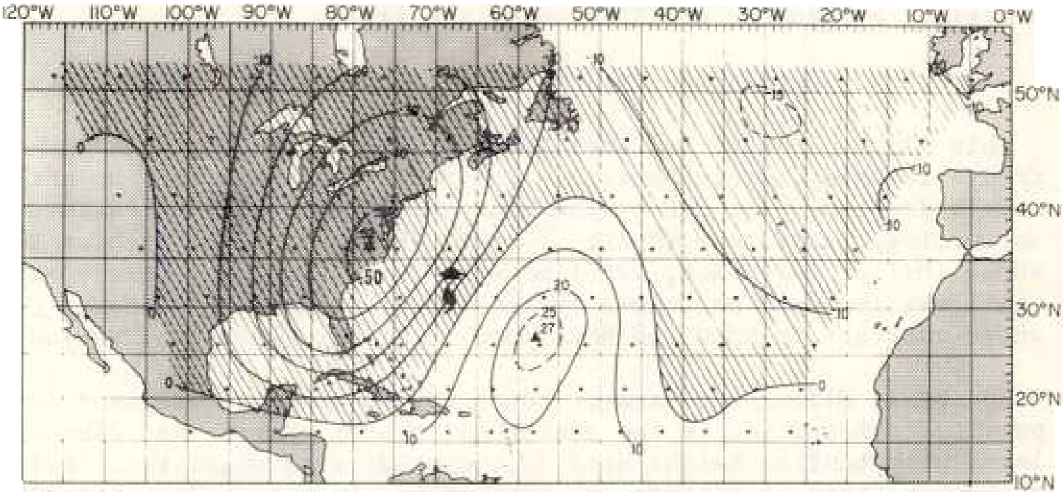


Fig. 3. Zero-order correlation coefficient field between 12h tropical cyclone motion and a deep-layer-mean geopotential height field (see Eq. 1). Stipling shows areas of negative correlation with northward storm motion considered positive. Grid-point having maximum correlation (0.50) is number 37 (row 5, column 5). These data were derived from 994 12h forecast situations, 1965 - 1977. The storm itself, located at grid-point number 52, has been positioned at its average location over the 13-year period.

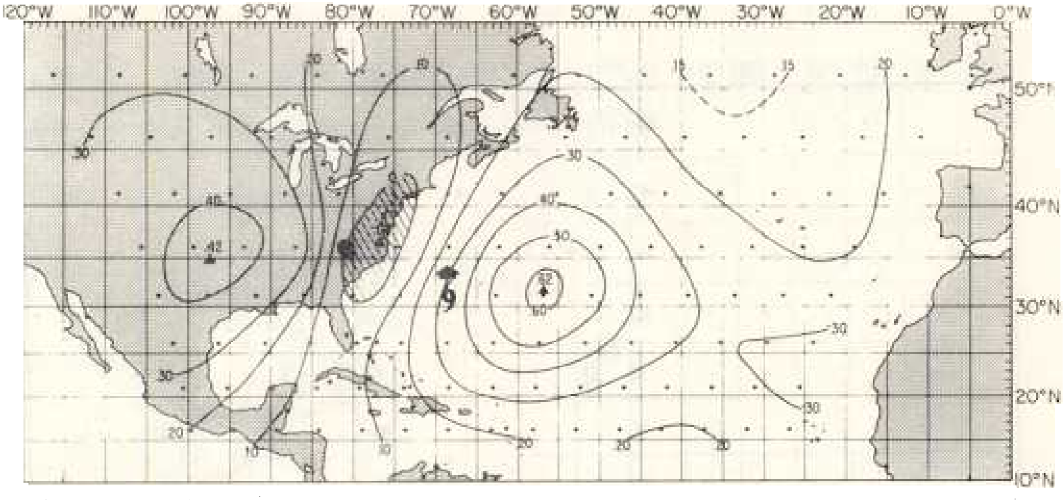


***Fig. 4.** Similar to Figure 3 except that isopleths depict first-order partial correlation coefficient field given that predictor number 37 (marked with darkened circle) has already been selected.*

For meridional motion, the selection of significant predictors (grid-points) proceeds as illustrated in Figures 3 and 4. Figure 3 shows the correlation coefficient field between current geopotential heights and future 12h meridional displacement of the tropical cyclone center. The grid point showing the maximum correlation (row 5, column 5) is automatically selected by a stepwise screening regression program as the best single predictor. However, given that this predictor is already selected, Figure 4 shows the completely new (first-order partial) correlation field which emerges. Here, grid point number 68 (row 4, column 9) is automatically selected.

Although not illustrated here, similar rationale applies to the selection of zonal-motion predictors and it can be shown that predictor number 54 (row 6, column 7) is initially selected followed by number 50 (row 2, column 7). These two predictors (and the two meridional motion predictors) are obviously working in pairs and represent the storm's response (steering) to the height configuration. For the longer range forecasts through 72h, additional predictors at greater distances from the storm center are selected. Statistical pitfalls one encounters in this selection process are discussed by Neumann *et al.* (1977).

Although NHC67, NHC72 and EPHC77 use similar methodology in the selection of synoptic predictors, there are important differences. These differences relate largely to the types of predictors and the method of stratification. The NHC67 and NHC72 models select synoptic predictors in the form of geopotential heights or height functions (gradients, thicknesses, 24h changes) from 1000, 700 and 500mbs. However, later studies, notably Neumann *et al.* (1977) and Takeuchi (1976) suggest that such a large number of predictors lead to problems in determining statistical significance of the resulting regression equations. Typically, too many predictors are retained. Accordingly, the more recent EPHC77 considers predictors from one level only, namely, 500mbs.

The models also differ in regard to the treatment of predictors derived from climatology and persistence. The NHC67 model was developed before the introduction of the CLIPER model, the latter making optimum use of climatology and persistence. Many of the important (often non-linear) predictors used by CLIPER only implicity enter the NHC67 model. However, output from CLIPER explicitly enters the NHC72 and EPHC77 prediction scheme.

A strategic stratification, providing it does not seriously curtail sample size, conceptually improves on the performance of a statistical model. Therefore, NHC67, NHC72 and EPHC77 use this concept. NHC67 is stratified according to whether the storm's initial position is within the easterlies or westerlies with a constant boundary between the two currents being taken as 30N. An additional NHC67 stratification allows for separate prediction equations depending on whether storms initially within the northern zone are moving "slow" or "fast".

The stratification of the NHC72 model is completely different and is based on the initial direction of motion of the current storm. The scheme is described in Figure 5. EPHC77 stratification is patterned after NHC72.

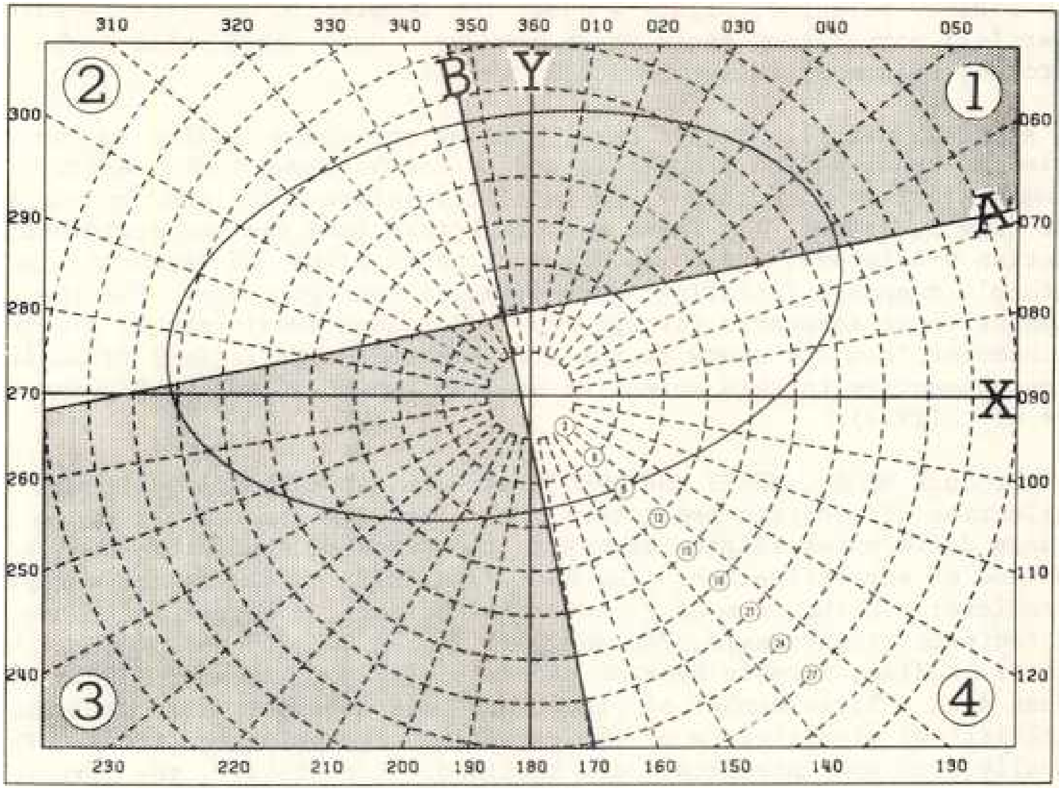


Fig. 5. Stratification scheme applicable to the NHC72 model. Separate prediction equations are used depending on whether the storm initial motion vector falls in sectors 1, 2, 3 or 4. Appropriate weighting functions apply to "borderline" vectors. The vector average initial motion vector is towards 340/06 knots. The elliptical envelop centered at this point contains 99% of the developmental motion vectors. Storms located in the deep tropics (<18N) and those over the Western Caribbean or the Gulf of Mexico (=>81.5W and =<31.5N) are treated by a separate stratification.

D. Statistical-dynamical Models

In the early 1970's, a large number of Atlantic storms with anomalous motion characteristics highlighted the inherent inability of the purely "classical" models typified by NHC67 and NHC72 to forecast such motion with acceptable accuracy. This gave impetus to the development of another echelon of model, referred to as *statistical-dynamical*. The application of statistical-dynamical concepts to hurricane prediction was first investigated by Veigas (1966) under contract to the former National Hurricane Research Laboratory (NHRL, now NHEML). However, Veigas' attempts were not particularly successful due, presumably, to the questionable quality of the tropical barotropic prognoses available at that time. A much greater degree of success was achieved by Neumann and Lawrence (1975) with the statistical-dynamical NHC73 model which incorporates more recent numerical prognoses. Predictors entering the NHC73 model include: 1) the output from the CLIPER model, 2) current 1000, 700 and 500mb. analyses and 3) 24, 36 and 48h geopotential height prognoses from the NMC primitive equation model (Shuman and Hovermale, 1968). These height fields are represented on the same grid system depicted in Figure 2 and as used by the NHC67 and NHC72 models. Predictor selection and methodology in formulating the NHC73 prediction algorithm is considerably more complex than for the other statistical models in use at NHC and involves modification of the "perfect-prog" and model output statistics (MOS) concept described by Klein and Glahn (1974).

An expanded areal stratification system addresses the problem of having varying degrees of data quality across the tropical Atlantic, that over the easternmost sections being little better than climatology. The basin is subdivided into 52 zones. Fifty of these form a rectangular 5x10 (4 degrees of latitude x 6 degrees of longitude) grid across the bulk of the basin and extending from 45W to 99W and from 18N to 34N. An elliptical scan was used to select overlapping sets of developmental data, each set being centered on and applicable to a given point. Additional stratification zones include storms initially located south of the grid (south of 18N) and north of the grid (north of 34N). Forecasts are not provided for storms initially located east of 45W longitude. An illustration of the grid plus further information on NHC73 can be found in Neumann and Lawrence (1973, 1975).

E. Barotropic Models

The SANBAR (SANders BARotropic) model, as originally developed by Sanders and Burpee (1968) and later discussed by Sanders *et al.* (1975, 1977), has been in continuous use at NHC for a number of years. Also, the model has recently been introduced as objective guidance over the Eastern Pacific. Much of the original work on the model was supported by the former National Hurricane Research Laboratory (now NHEML) although most of the operational aspects of the model such as programming, initial analyses and operational implementation was accomplished at NHC.

The character of the model was formed by the belief that momentum advection is the primary physical mechanism for motion of intense tropical vortices. Loosely speaking, the assertion is that the storm is "steered" by the larger-scale current in which it is embedded. Accordingly, input is a deep-layer (1000 to 100 mb.) u- and v-field analysis over the grid domain of the model. These grids, one designed for the Atlantic

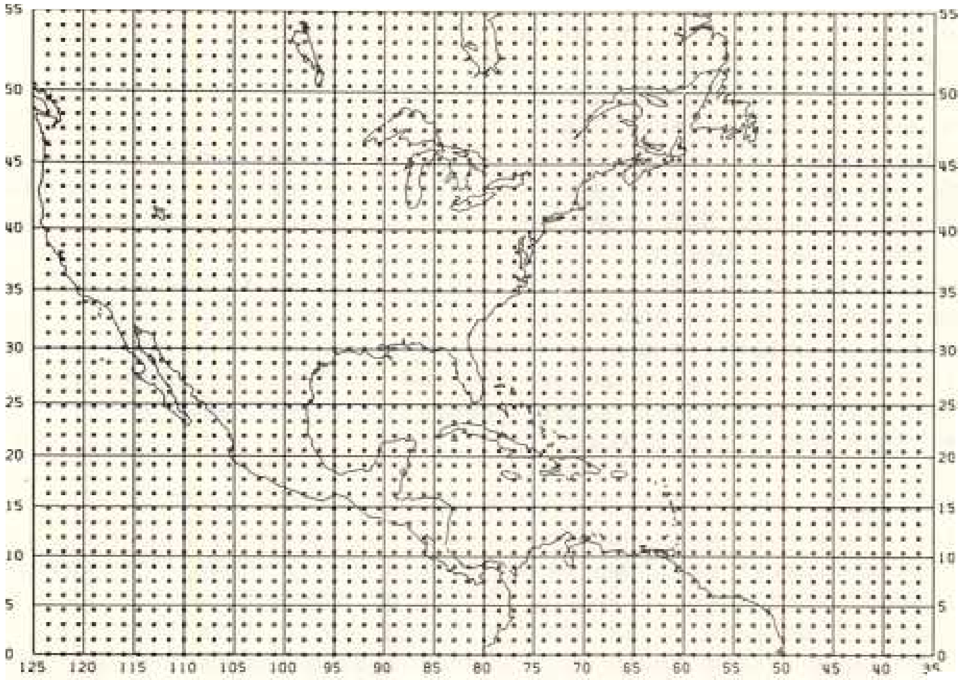


Fig. 6. SANBAR 45x59 grid system for Atlantic area storms Grid spacing is 90 n. mi. (167km.)

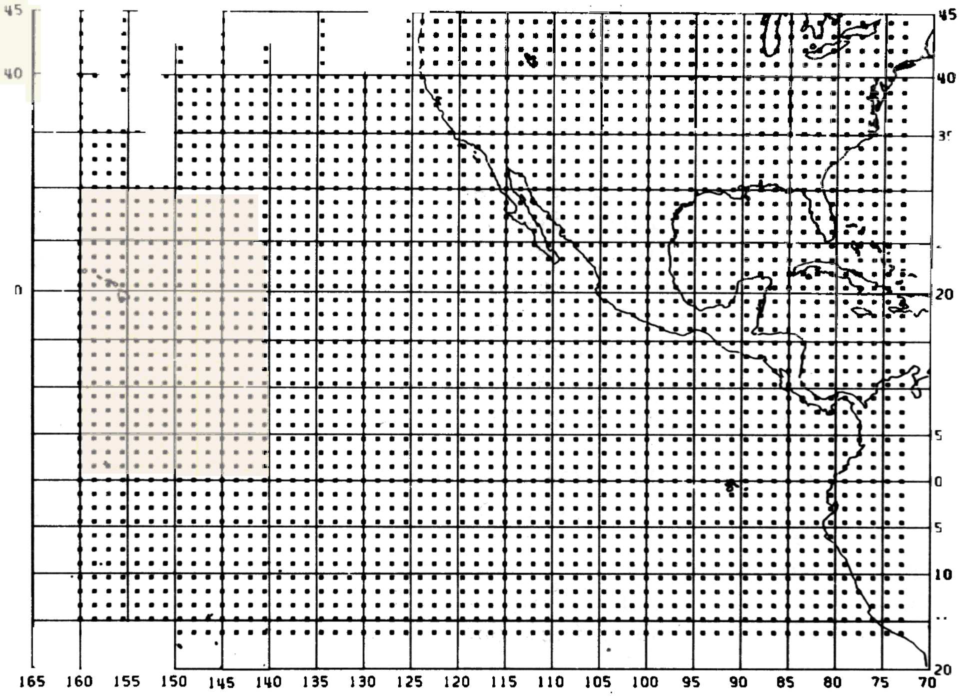


Fig. 7. Similar to Fig. 6 except for Eastern Pacific storms.

area and the other for the East Pacific are illustrated, respectively in Figures 6 and 7. The extension of the Pacific grid south of the equator was accomplished to accommodate the more southerly latitudes of Eastern Pacific tropical cyclones compared to those in the Atlantic.

Methods of obtaining the deep-layer wind analysis vary depending on availability of data. For the Atlantic grid, deep-layer pressure weighted u- and v-components are computed for all available rawinsonde stations according to the relationship,

$$W_m = (75W_1 + 150W_2 + 175W_3 + 150W_4 + 100W_5 + 75W_6 + 50W_7 + 50W_8 + 50W_9 + 25W_{10})/900 \qquad (1)$$

where W_m refers to the weighted u- or v-components and the subscripts 1 through 10 refer, respectively, to the levels 1000, 850, 700, 500, 400, 300, 250, 200, 150 and 100 mb. Suitable adjustments are made to (1) to allow for missing levels. For oceanic areas where observations are scarce, the deep-layer u- and v-components are estimated at 44 strategically located "bogus" points by statistical regression equations relating the deep-layer component to the components at the lower (cumulus) levels and the upper (cirrus) levels. Having the components at the irregularly spaced rawinsonde stations and bogus points, the Eddy (1967) analysis scheme is used to obtain u- and v-components at the grid-points themselves.

For the Pacific SANBAR initial snalysis, regression equations as given by Adams and Sanders (1975) are used directly to estimate the gridpoint values of the deep-layer u- and v-components. The cirrus and cumulus level winds needed by the regression equations are obtained (for both the Atlantic and Pacific grids) from analyses of these fields prepared by NHC.

In both the Atlantic and Pacific versions of SANBAR, a technique described by Pike (1972), is used to modify the wind field near the storm to better conform to the initial storm motion vector. Having obtained the u- and v-fields, relaxation techniques are used to obtain the initial stream function field. The latter quantity is then forecast in 30-minute time steps using the barotropic vorticity equation. A storm center may be identified by a local minimum stream function and maximum vorticity.

Continued studies by Sanders and the Hurricane Center have indicated the need for improved analysis techniques for initializing SANBAR. It is considered likely that improvements will be incorporated in future versions of the model.

F. Baroclinic Models

In the early 1970's, a series of storms with anomalous motion characteristics led to the development of the statistical-dynamical NHC73 model which, conceptually, could better respond to anomalies. These same storms gave impetus to the development of the baroclinic Movable Fine Mesh (MFM) model at the National Meteorological Center. The MFM (Hovermale and Livezey, 1977) was first operationally tested on Atlantic tropical cyclones during the 1975 season and has been considered more or less fully operational beginning in 1976. However, the model is still being fine-tuned and occasional changes will be made. Although actually developed by the National Meteorological Center (NMC), the MFM can be considered as the fruition of earlier theoretical work, much of which was accomplished by or through the National Hurricane and Experimental Meteorology Laboratory (NHEML).

The physics of the model is generally the same as that of the other Primitive Equation (PE) models now in operation. However, one of its unique characteristics in comparison to the other operational PE models is the ability of the grid to follow storms as they move during a forecast. Another major difference between MFM and other operational PE models is that the MFM is of finer resolution both in the horizontal and vertical. In the vertical, it is a ten-layer model, and in the horizontal, the grid spacing can be varied but a 60-km. spacing is currently used, this spacing being more or less consistent with current operational and initialization constraints. Using the 60km. grid requires about 120 minutes of computer time for a 48h forecast. Because of the fine grid, it was necessary to make the total areal coverage much smaller than the existing operational models. Therefore, the MFM grid domain is approximately 3000 x 3000km. (50 x 50 grid array).

Since it has been impractical from both observational and computational standpoints to initialize the model with the detailed structure of the actual hurricane vortex, a model storm, derived from an axisymmetrical vortex which is qualitatively similar to the hurricane, has been used. This two-dimensional analog has been empirically formulated so that, when it is added to the initial steering current (out to about 1000km.), a balanced, stable initial field is produced and this forms the initial conditions for the numerical integration. More realistic vortex initialization procedures will gradually be incorporated into the MFM model.

4. Some Operational Considerations

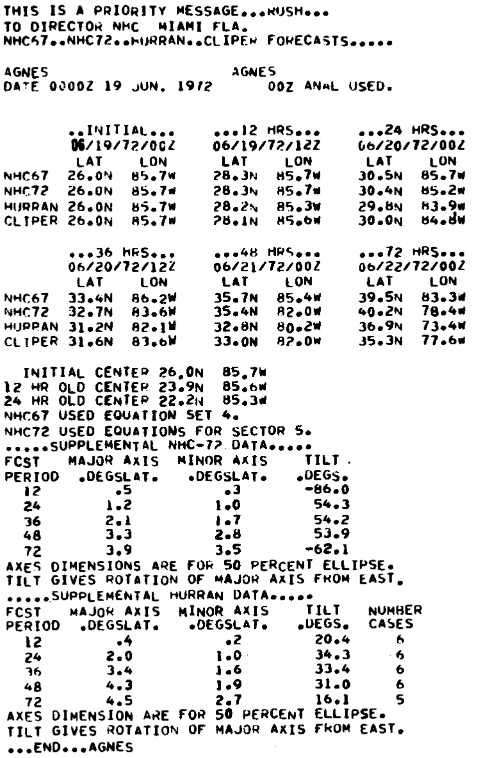
Over the Atlantic tropical cyclone basin, schedule tropical cyclone release times are 0400, 1000, 1600 and 2200GMT. Eastern Pacific advisories are issued one-hour earlier at 0300, 0900, 1500 and 2100 GMT. Every effort is made to provide objective guidance at least 1 1/2 hours prior to these schedule release times. This allows for coordination and actual preparation of the advisory. However, for a number of reasons, all related to operational constraints, attainment of this goal, particularly for the Eastern Pacific, is not always possible.

There are two major problems. Models of type II and III (see Table 1) are based at least partially on objective analyses available only for the 0000 and 1200GMT synoptic hours. Thus, these models can be activated only twice per day. Also, these same models require a more complete initial analysis than the purely statistical models of type I such that, for example, delivery of the guidance for the 0400 and 1600 GMT advisories (which are based respectively, on 0000 and 1200GMT analyses) cannot be accomplished until after advisory release. The models so affected (SANBAR, NHC73, MFM) do, however, provide guidance for the 1000GMT and 2200GMT advisories but with an effective six-hour loss in forecast lead time. The nominal lag time in delivery of the final product to the forecaster is shown in Table 2. For convenience, CLIPER, HURRAN, NHC67 and NHC72 and their Eastern Pacific counterparts are collectively made available to the forecaster at 2 + 15. However, delivery of CLIPER and HURRAN (EPCLPR, EPANLG) at the times indicated in Table 2 could be accomplished.

Table 2. Nominal delay time (hours and minutes after 0000GMT) in receipt of guidance for Atlantic 0400GMT (0300GMT for Eastern Pacific) tropical cyclone advisory.

Guidance	Delay
CLIPER/EPCLPR	1 + 15
HURRAN/EPANLG	1 + 30
NHC67/NHC72/EPHC77	2 + 15
SANBAR	4 + 10
NHC73	5 + 30
MFM	7 + 30

Actual delivery of guidance output to the user is typically accomplished through the NWS KCRT system with a teletype message as backup. A sample message on the results of the NHC statistical guidance package for an Atlantic 0400GMT advisory as illustrated in Figure 8. All computations are done on the NOAA computer complex located in Suitland, MD through a computer terminal located at the National Hurricane Center. A smiliar message is prepared for Eastern Pacific statistical guidance. Plotting of the Atlantic probability ellipses from the parameters given in the lower half of the message is accomplished on a small computer system located at the National Hurricane Center. Similar plotting capability is not yet available to EPHC.



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THIS IS A PRIORITY MESSAGE...RUSH...
TO DIRECTOR NHC  MIAMI FLA.
NHC67..NHC72..HURRAN..CLIPER FORECASTS.....

AGNES                          AGNES
DATE 0000Z 19 JUN. 1972        00Z ANAL USED.

         ..INITIAL...      ...12 HRS...      ...24 HRS...
         06/19/72/00Z      06/19/72/12Z      06/20/72/00Z
          LAT    LON        LAT    LON        LAT    LON
NHC67   26.0N  85.7W      28.3N  85.7W      30.5N  85.7W
NHC72   26.0N  85.7W      28.3N  85.7W      30.4N  85.2W
HURRAN  26.0N  85.7W      28.2N  85.3W      29.8N  83.9W
CLIPER  26.0N  85.7W      28.1N  85.6W      30.0N  84.8W

         ...36 HRS...      ...48 HRS...      ...72 HRS...
         06/20/72/12Z      06/21/72/00Z      06/22/72/00Z
          LAT    LON        LAT    LON        LAT    LON
NHC67   33.4N  86.2W      35.7N  85.4W      39.5N  83.3W
NHC72   32.7N  83.6W      35.4N  82.0W      40.2N  78.4W
HURRAN  31.2N  82.1W      32.8N  80.2W      36.9N  73.4W
CLIPER  31.6N  83.6W      33.0N  82.0W      35.3N  77.6W

  INITIAL CENTER 26.0N  85.7W
12 HR OLD CENTER 23.9N  85.6W
24 HR OLD CENTER 22.2N  85.3W
NHC67 USED EQUATION SET 4.
NHC72 USED EQUATIONS FOR SECTOR 5.
.....SUPPLEMENTAL NHC-72 DATA.....
FCST   MAJOR AXIS  MINOR AXIS   TILT
PERIOD  .DEGSLAT.   .DEGSLAT.   .DEGS.
  12        .5          .3      -86.0
  24       1.2         1.0       54.3
  36       2.1         1.7       54.2
  48       3.3         2.8       53.9
  72       3.9         3.5      -62.1
AXES DIMENSIONS ARE FOR 50 PERCENT ELLIPSE.
TILT GIVES ROTATION OF MAJOR AXIS FROM EAST.
.....SUPPLEMENTAL HURRAN DATA.....
FCST   MAJOR AXIS  MINOR AXIS   TILT   NUMBER
PERIOD  .DEGSLAT.   .DEGSLAT.   .DEGS.  CASES
  12        .4          .2       20.4     6
  24       2.0         1.0       34.3     6
  36       3.4         1.6       33.4     6
  48       4.3         1.9       31.0     6
  72       4.5         2.7       16.1     5
AXES DIMENSION ARE FOR 50 PERCENT ELLIPSE.
TILT GIVES ROTATION OF MAJOR AXIS FROM EAST.
...END...AGNES
```

Fig. 8. Sample KCRT message on Atlantic statistical guidance.

Except for the MFM, all objective guidance (including Eastern Pacific guidance) is activated by or through NHC. The MFM is activated by NMC (at the request of NHC or EPHC) whenever tropical cyclones threaten populated land areas. A facsimile chart of the MFM 1000mb analyses at four forecast intervals through 48h is routinely transmitted by NMC following all MFM runs.

*Table **3**. Mean vector error (n.mi.) on homogeneous sample of Atlantic tropical cyclone forecasts over 6-year period 1973 - 1978.*

STORMS INCLUDED	MODEL	FORECAST PERIOD			
		12-hr	24-hr	48-hr	72-hr
A. All storms	CLIPER	55.9	125.0	276.3	380.9
	NHC67	55.9	119.2	293.3	428.5
	NHC72	54.7	120.2	269.3	393.0
	NHC73	54.1	119.8	244.5	366.7
	SANBAR	59.5	120.8	256.4	389.2
	OFFICIAL	54.4	116.5	266.4	399.6
	Sample size	*261*	*232*	*161*	*109*
B All storms >24.5N	CLIPER	63.9	149.1	334.8	434.9
	NHC67	61.2	133.3	352.2	517.5
	NHC72	61.5	137.7	307.3	407.9
	NHC73	60.1	137.6	282.1	364.0
	SANBAR	66.0	140.3	307.2	455.4
	OFFICIAL	60.8	137.6	319.4	
	Sample size	*159*	*137*	*91*	
All storms =<24.5N	CLIPER	43.4	90.2	200.3	325.9
	NHC67	47.8	98.9	216.8	337.8
	NHC72	44.0	95.0	219.9	377.8
	NHC73	44.7	94.2	195.6	369.3
	SANBAR	49.3	92.8	190.3	321.7
	OFFICIAL	44.3	86.1	197.5	363.5
	Sample size	*102*	*95*	*70*	*54*

*Table **4**. Mean vector error (n.mi.) on homogeneous sample of Atlantic tropical cyclone forecasts over 6-year period 1973 - 1978.*

STORMS INCLUDED	MODEL	FORECAST PERIOD			
		12-hr	24-hr	48-hr	72-hr
A. All storms	HURRAN	58.7	134.6	301.3	402.3
	CLIPER	57.2	125.1	271.3	366.2
	Sample size	*362*	*316*	*224*	*153*
B. All storms >24.5N	HURRAN	77.3	186.5	455.2	544.6
	CLIPER	72.1	167.3	392.4	477.9
	Sample size	*173*	*137*	*76*	
. All storms =<24.5N	HURRAN	41.6	94.8	222.3	346.7
	CLIPER	43.5	92.8	209.1	323.2
	Sample size	*189*	*179*	*148*	*110*

*Table **5**. Mean vector error (n.mi.) on homogeneous sample of Atlantic tropical cyclone forecasts over 3-year period 1976 - 1978.*

STORMS INCLUDED	MODEL	FORECAST PERIOD			
		12-hr	24-hr	48-hr	72-hr
All storms >24.5N	CLIPER	40.7	111.8	361.9	-----
	NHC67	38.1	84.0	270.6	-----
	NHC72	38.8	109.5	317.5	-----
	NHC73	37.6	97.9	264.7	-----
	SANBAR	42.7	105.1	319.0	-----
	MFM	54.1	108.3	264.2	-----
	OFFICIAL	42.3	107.7	303.6	-----
	Sample size	*24*	*20*	*15*	*0*

5. VERIFICATION

Verification of all official forecasts and objective models is routinely accomplished at NHC for Atlantic storms and at the NWS Western Region Headquarters for all Eastern Pacific storms. For meaningful comparisons on the performance of two or more models, these verifications must be limited to homogeneous samples of forecasts; that is, sets of forecasts on the same forecast situation given the same operational conditions. This requirement for homogeneity introduces a number of problems including: 1) some models (see section 4) are activated only twice per day, 2) the analog model does not run under anomalous initial conditions, 3) the initial operational implementation of the various models ranges from the year 1967 for the NHC67 model to 1976 for the MFM model, 4) the MFM has been run only on storms threatening populated land areas, and 5) "Official" forecasts are not available for the 36h projection.

To avoid a drastic reduction in sample size, some compromise must be effected. Since the analog and MFM models are principally responsible for heterogeneities in the sample, the compromise must logically involve these models. Accordingly, verification summaries were prepared three ways. These are shown in Tables 3, 4 and 5. Table 3 is a homogeneous comparison between all models and the official forecast over the 6-year period 1973 - 1978 but omitting HURRAN and MFM; Table 4 compares HURRAN and CLIPER over the same period while Table 5 compares all models including MFM but excluding HURRAN for a very abbreviated sample during the years 1976 - 1978. The Atlantic tropical cyclones occurring over the 6-year period 1973 - 1978 are shown in Figure 9. Tables 3 and 4 are further subdivided into three parts; part A includes the entire storm sample, part B includes only those storms initially located poleward of 24.5N (northerly storms) while part C includes only those storms initially located at and equatorward of 24.5N (southerly storms). It can be noted from Figure 9 that the "southerly" storms were essentially moving with a substantial westerly component whereas the "northerly" storms had either recurved or were in the process of doing so. Since all of the small sample of MFM forecasts were in the "northerly" category, the additional stratification was not applicable to Table 5.

A. Mean Vector Error

The quantity *mean vector error* (E) used in Tables 3, 4 and 5 represents the difference between the forecast (Y_f, X_f) latitude and longitude of a storm and the observed (Y_o, X_o) best-track[4] position. Across the earth's surface, this (great-circle) distance is given by,

$$E = 60 \cos^{-1}[\sin Y_o \sin Y_f + \cos Y_o \cos Y_f \cos(X_o - X_f)]. \qquad (2)$$

It usually turns out that the final best-track location of the

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[4] The accepted storm track after a post-analysis

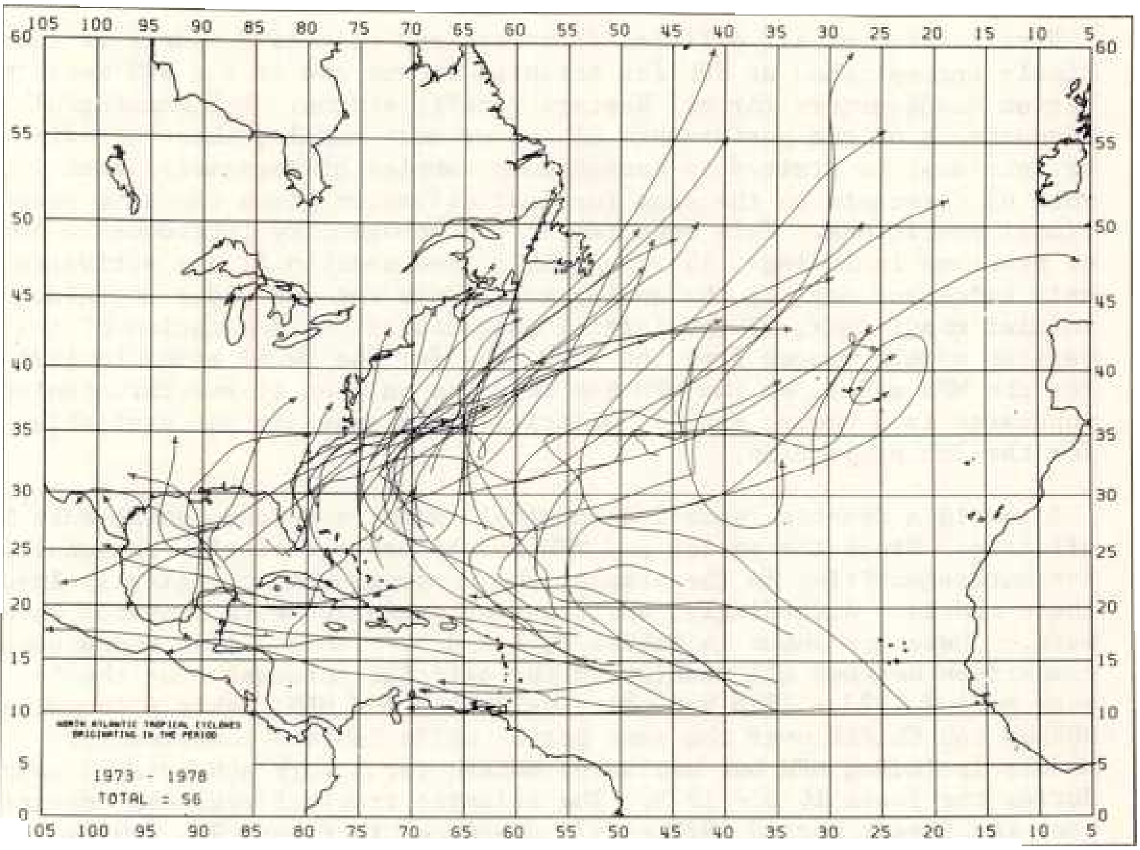

Fig. 9. The 56 Atlantic tropical cyclones, 1973 - 1978

initial storm position differs slightly (an average of 15-20 n.mi.) from the assumed operational initial position. For consistency, this difference, which is referred to as *initial positioning error*[5] is removed from either (Y_f,X_f) or (Y_o,X_o) before application of Eq. (2).

Examination of the data given in Tables 3 or 4 discloses what appears to be a disparity in the ability to forecast northern and southern storms in that the errors associated with the latter are approximately 25 to 40% less than for the northern storms. However, southern storms are known to be "easier" to predict in that they typically move slower and the tracks are more persistent. Thus, it is not transparent from the data given in the tables whether the "skill" of any particular model is better on southerly storms or northerly storms. Similarly, it is not clear whether a given model exhibits greater "skill" in one forecast period over another. This is one of the shortcomings in unqualified use of the quantity *mean vector error*.

B. A Measurement of Skill

To offset the problem mentioned in the previous paragraph, the CLIPER

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[5] The impact of initial positioning error on tropical cyclone prediction is discussed by Neumann (1975a and 1975b).

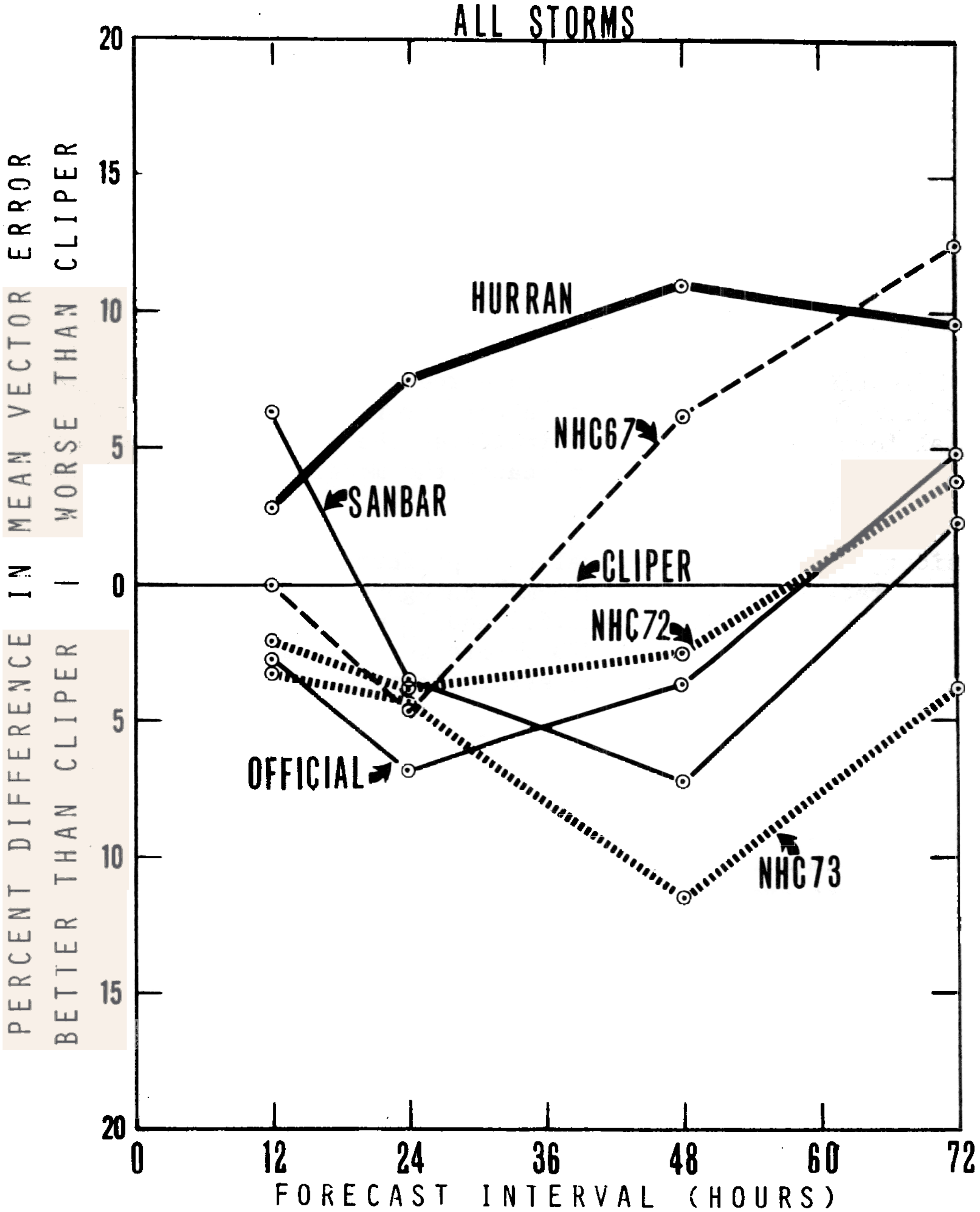

Fig. 10. Performance (percentage improvement or deterioration in mean vector error) of specified prediction system relative to the CLIPER model. Sample is homogeneous and includes all storms over the six-year period 1973 - 1978. Ratings are based on comparisons made at 12, 24, 48 and 72h. Ratings for 36 and 60h are based on linear extrapolation.

model can be used as a kind of equalizer or "no-skill" model which provides a convenient benchmark upon which to judge the skills of the other models. The term *no-skills* is somewhat relative in that it can be argued that the CLIPER does, indeed, show some skill and the forecaster does not have the ability to optimize the linear and non-linear combinations of climatology and persistence as is done by that model. Nevertheless, the model does present a rational frame of reference which provides at least some normalization.

To further effect meaningful temporal and spatial comparisons between the different models, it is convenient to express differences between CLIPER mean vector error and the mean vector error of another model in terms of percentage improvement or deterioration over CLIPER Figures 10, 11 and 12 were prepared in this manner with the relative standings of each model being computed from,

$$P = 100(E_c - E_m)/E_c \tag{3}$$

where P is the relative standing in percent, E_c is the CLIPER mean vector error and E_m is the mean vector error of the model (or the official forecast). Positive P indicates the model performed better than CLIPER while negative P indicates the model performed inferior to CLIPER for that time period.

Consider, for example, the relative performance of NHC73 and CLIPER for the 48h forecast in the "all-storms" category given in Table 3A. According to Eq. (3), with $E_c = 276.3$ and $E_m = 244.5$, P computes to +11.5% indicating that the NHC73 errors were 11.5% less than those of CLIPER for that time period and stratification.

C. Overall Performance of Various Models

Figure 10 is a plot of the data contained in Table 3A after having been normalized to the CLIPER model according to Eq. (3). The best overall performance has been shown by the statistical-dynamical NHC73 model and worst overall performance by the HURRAN model. The failure of NHC73 to effect even better performance beyond 48h is probably related to the fact that the model does not use any PE forecast data beyond 48h. These results confirm that the use of statistical-dynamical concepts in the prediction of tropical cyclone motion is sound and insofar as statistical modeling is concerned, continued research should be geared towards this approach to tropical cyclone forecasting.

The poor overall performance of the analog HURRAN model is somewhat surprising since this class of model has given relatively better performance over other tropical cyclone basins. This suggests that the model should be restructured to incorporate some of the improvements in analog prediction as accomplished for the U.S. Navy for these other basins.

Apart from the performance of HURRAN and NHC73, there is a host of other diagnostic information offered by Fig. 10. Maximum improvement

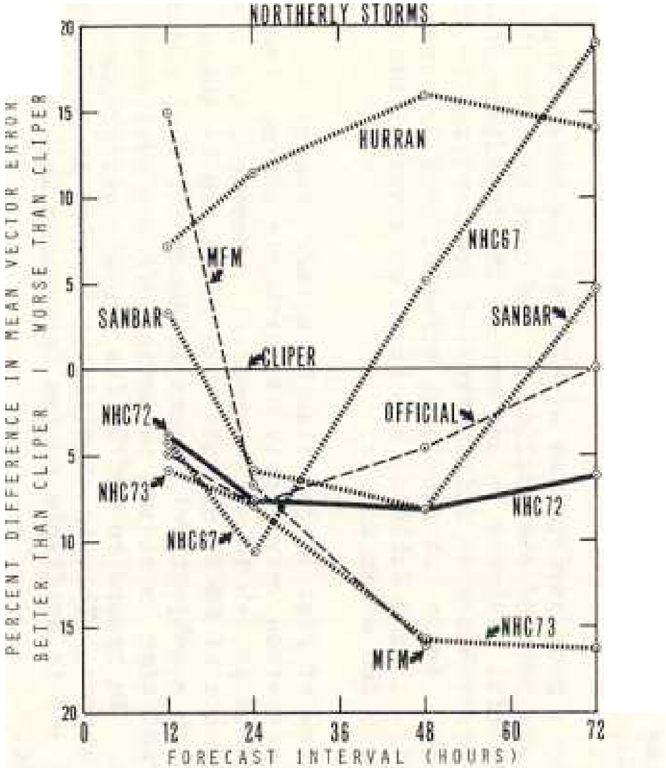

Fig. 11. Similar to Figure 10 except based only on storms initially located >24.5N. MFM results are not based on a homogeneous sample, see text.

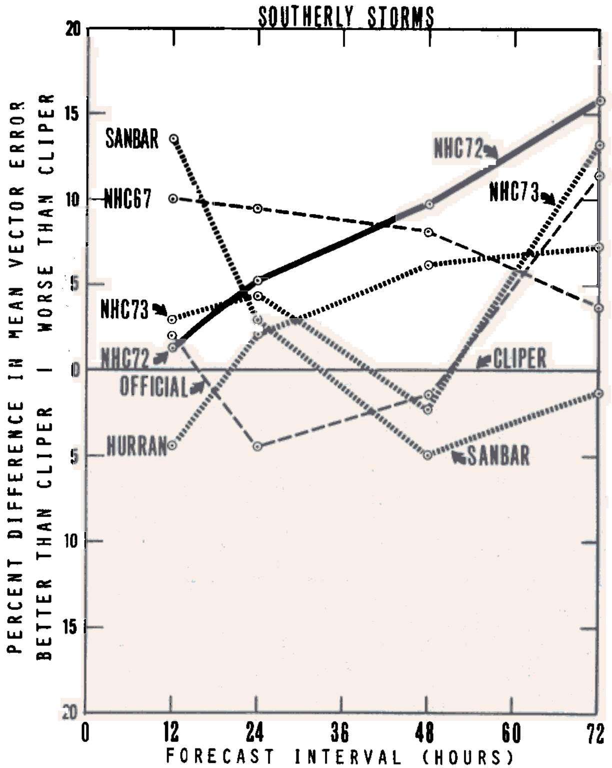

Fig. 12. Similar to Figure 10 except based only on storms initially located =<24.5N.

of the "official-forecast" over CLIPER (as well as over the other models) is seen to occur at the 24h forecast period. However, at 72h, the official forecasts are seen to be somewhat inferior to the CLIPER forecasts. Indeed, CLIPER tends to outperform all models except NHC73 at 72-hours.

It is interesting to note that the best relative performance of the SANBAR model, along with NHC73, is at the 48h forecast period. The relatively poor performance of SANBAR at 12 and 24 hours reflects the effect of uncertainties in the initial analysis in the vicinity of the storm itself. Statistical models NHC67, NHC72 and NHC73 have similar problems with synoptic data near the storm but circumvent the problem by making judicious use of the rather abundant information on current and past storm motion as supplied by satellite and aircraft. A Pike (1972) modification of the SANBAR initial analysis by adjustment of the initial wind field to conform to current storm motion, appears to be relatively ineffective in significantly improving SANBAR forecasts for the short-range projections. It is likely, however, that without the Pike modification, SANBAR performance, particularly at 12h, would have been inferior to that shown on Fig. 10.

D. Performance on "Northerly Storms"

Whereas Fig. 10 addressed the entire storm sample, Fig. 11 deals only with those storms initially located north of 24.5N, the performance of which was summarized in Tables 3B, 4B and 5. The actual positioning of MFM on Fig. 11 was not based directly on Eq. (3) but rather on its overall relative performance. Its 48h positioning resulted from the consideration that it slightly (see Table 5) outperformed the NHC73 model at that time period. MFM is currently not run beyond 48h. The 24h positioning was based on the fact that MFM performance was about average when compared to the other models for that time period. Its position at the 12h projection was notably inferior and this led to its relatively poor standing on Fig. 11.

The relatively poor performance of MFM for the short range forecast reflects (as was pointed out earlier in the case of SANBAR) uncertainties in initial analysis in and around the immediate storm area. Forthcoming improvements in initialization are expected to improve on MFM performance. Again, it should be stressed that MFM results, as depicted in Fig. 11 and Table 5, are based on a very limited sample when compared to the other models.

Other features of Fig. 11 can also be noted. Except for the HURRAN model, which performed very poorly on northerly storms, the clustering of all the models at 24h is quite apparent. However, the somewhat better performance of NHC67 at this time frame can be noted. This tends to confirm a subjectively noted tendency for that model to excel in the 24h prediction on storms recurving off the east coast of the United States. In regard to NHC72, its overall performance is good on northerly storms. This is significant because it is "early-guidance" (see Table 2) and is available to the forecaster well before the NHC73 and MFM models.

E. Performance on "Southerly" Storms

The principal difference between the depiction for southerly storms (Fig. 12) when compared to northerly storms (Fig. 11) is a general upward shift of the ratings into the "worse than CLIPER" category. However, the SANBAR model emerges as being the best performer (in terms of mean vector error) at the 48 and 72h forecast periods while the official forecast is noticeably superior at 24h and the analog model, HURRAN, at 12h. Since MFM forecasts were limited to "northerly" storms, it is not included in Fig. 12.

Perhaps the most significant aspect of Fig. 12 is that NHC72 for all time periods and NHC73 at all but 48h, are distinctly inferior to CLIPER in spite of the fact that CLIPER is one of the explicit components in these models. Thus, one must conclude that the inclusion of synoptic data (both analyses and prognoses) in these models has actually *degraded* CLIPER forecasts. This accentuates the pitfalls of using synoptic data as a source of statistical predictive skill in the tropics.

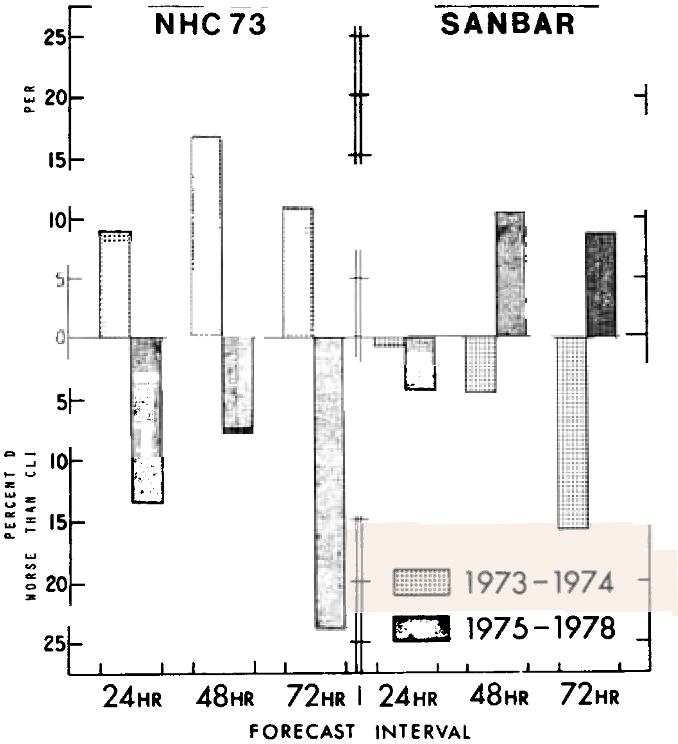

Fig. 13. Performance (percentage improvement or deterioration in mean vector error) of NHC73 and SANBAR models relative to the CLIPER model both before (1973 - 1974) and after (1975 - 1978) use of the NMC spectral analysis package by the NHC73 model. Sample is homogeneous and includes only those storms initially located =< 24.5N.

Poor performance of NHC73 on southerly storms compared to its performance on northerly storms was studied in greater detail. If performance is examined on a year-to-year basis, it can be shown that a discontinuous deterioration in NHC73 performance began in 1975. This coincides with the initial use by this model (as well as by the other statistical models) of the NMC global spectral analysis package. Fig. 13 illustrates this deterioration in NHC73 over the tropics rather strikingly. This figure is somewhat similar to Fig. 12 except that the storm sample is further subdivided into two time periods: one period for the years 1973 and 1974, during which the model was run from a Cressman (1959) scan analysis and the other period for the later years beginning in 1975 when the spectral analysis (Flattery, 1970) was used by the model. For the earlier years, it is seen that NHC73 significantly improved over CLIPER while for the later spectral analysis years, Fig. 13 shows a substantial NHC73 deterioration over CLIPER. With the same temporal stratification, it can be noted that SANBAR forecasts, essentially independent of NMC analysis changes, showed significant improvement over CLIPER forecasts.

Poor performance of NHC73 in the tropics following introduction of the new analysis method is not too surprising when one considers that the original NHC73 model (as well as the other models) were developed from a data set consisting of pre-1971 Cressman scan or of hand-analyzed charts. It appears likely that the use of analyses and prognoses with different (not necessarily better or worse) statistical characteristics over the data-poor areas at 500 mb. contributed to the decline of the model in the tropics. Data dissimilarities of this type, that is, between developmental and operational data, typically lead to ill-defined regression coefficients, intercepts and weighting functions and are a recognized pitfall of statistical prediction. Steps are being taken to correct this deficiency and tune the models to current and proposed analyses and prognoses. For additional information on this topic, the reader is referred to Leftwich *et al.* (1977).

6. Performance of Eastern Pacific Models

Verification statistics presented in Section 5 have pertained to the Atlantic tropical cyclone basin. Because the period of record is so short, a meaningful comparison between the performance of EPANLG, EPCLPR, EPHC77, SANBAR and MFM cannot be made at this time. If one considers only the statistical models, two years of records are available and it appears that EPCLPR provides for the best overall performance and this is about on a par with the official forecasts provided by the Eastern Pacific Hurricane Center. For storms which remain in the easterlies, the performance of EPCLPR and EPANLG is very similar and both appear to perform somewhat better than EPHC77. For recurving storms, both EPCLPR and EPHC77 appeared to have performed better than EPANLG but the period of record is very short.

Conceptually, the SANBAR model would be expected to perform quite well on Eastern Pacific storms since approximately 80% of these storms remain in the easterlies and SANBAR performs quite well on this type of storm in the Atlantic. However, the poor observational network over the Eastern Pacific does not allow for a satisfactory deep-layer wind analysis as required by SANBAR. Thus, to date, the performance of SANBAR over this basin has been irregular. Post-season studies have showed good performance with reasonable initial analyses and poor performance with unreasonable initial analyses. However, in an operational framework, there is currently no practical method of assessing the reasonableness of the initial analysis.

As in the Atlantic, MFM forecasts are only available for storms threatening populated areas. This would include only the few storms recurving into Mexico or the Southwestern United States or those threatening the Hawaiian Islands. Thus, it will take a period of years to obtain a large enough homogeneous sample of MFM forecasts.

7. SUMMARY

This study has briefly described each of the operational models currently being used at the National Hurricane Center and the Eastern Pacific Hurricane Center as guidance on the prediction of tropical cyclone motion. Verification statistics, adopted from mean vector errors, were presented for all the models over the Atlantic basin. However, a similar presentation for the Eastern Pacific will have to await the availability of a longer period of record.

Even though the verification statistics presented here are reasonably objective and one could decide on this basis which models are "superior", the real value of a model must be based on a number of additional factors including landfall error, orthogonal error components, utility, economy, timeliness, consistency, availability, performance on difficult or critical forecast situations, etc. Mean vector errors do not reflect these factors. For example, a model with a consistent bias to the left or right of track, fast or slow, is more valuable than one in which the error is random even though both may have the same vector error. Overall evaluation will therefore need be based on a number of factors which may even involve trade-offs in some areas.

The models included in the NHC prediction inventory each excels in its own unique temporal or spatial area. The only reason NHC67 is retained, for example, is its ability (as demonstrated in Fig. 11) to excel on 24h forecasts of those "northerly" storms. Similarly, the HURRAN model would be discontinued except that it handles the short range forecasts of "southerly" storms quite well. Also, its ability to provide additional diagnostic information in the form of probability ellipses is another asset. The CLIPER model does not perform well on "northerly" storms. However, its simplicity, economy, timeliness and accuracy on storms embedded in the easterlies is well established. The MFM, the most expensive model to run, can certainly be justified in that it appears to excel in forecasting changes in hurricane path, a definite asset in connection with the posting of hurricane watches and warnings. Also, the chances of effecting continued improvements in MFM are high compared to the purely statistical models.

Unique advantages of the other models can also be cited. Thus, all of the models serve a useful purpose and will be retained in the NWS/NHC prediction inventory until such time that a given model's usefulness can no longer be demonstrated. The ultimate goal would be to consolidate the better features of each model into an "all-purpose" model. Currently this is being both subjectively and objectively accomplished by the hurricane forecaster.

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