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THE DECISION PROCESS IN HURRICANE FORECASTING

SOUTHERN REGION HEADQUARTERS
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ABSTRACT

Despite the progress made in understanding the structure and energetics of hurricanes, numerical models for predicting the movement and development of hurricanes remain a frail source of guidance to the hurricane forecaster for three reasons. First, an error in direction of movement as small as 8-10 degrees---nominally an acceptable one in a 24-hour forecast for extra tropical storm centers---can yield disastrous results in hurricane warnings if followed literally. Second, the performance of most hurricane prediction models depends significantly upon the initial direction of movement of the center, which in turn depends upon an exact knowledge of the current center position and the position 6 and 12 hours earlier. The average positioning error is more than 20 nm, and often leads to initial direction errors of 15-20 degrees. Finally, the forecaster remains hard put to identify and diagnose the frailties of numerical prediction models for individual forecasts. All too often this has led to near abandonment of the guidance materials and the application of empirical and individual experience factors in decision making.

The main thrust of development programs at the National Hurricane Center described here is to provide objective diagnostic methods for evaluating the numerical prediction results by analyzing the dynamical character and tendencies of the vortex environment and of the vortex itself.

The procedures and decision ladders for each phase of the forecast are described, including the positioning of the center, the development of a disturbance, growth of a vortex, and movement of the center.

2. THE DECISION PROCESS IN HURRICANE FORECASTING

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INTRODUCTION

For decades hurricane forecasting has remained a product of subjective reasoning which varies with each forecaster's personal exposure to the hurricane problem, the "rules of thumb" he has developed, and the intuitive and analogue skills he has acquired (Dunn and Miller, 1964). In recent years, however, several factors have led to a review and to some changes in prediction procedures and decision making processes.

First, the Hurricane Warning Services are rapidly losing by attrition and retirement the more experienced and individually successful forecasters--a loss which cannot be replaced with a new generation of similarly trained empiricists. In this age of central data processing and numerical prediction models, the young forecaster faces an entirely different exposure to weather prediction and warning problems. He must be concerned with error analysis of the machine products and with the identification of circulation and weather patterns of smaller scale than that which is resolved by machine models.

The second (and happier) factor is that the knowledge gained in the 15 years since the establishment of the National Hurricane Research Project, especially that gained from research flights into hurricanes, is influencing prediction procedures. Much has been learned, not only about the structure of the hurricane vortex but also about the characteristics of the circulating environment which influence its movement and development (Riehl and Palmén, 1957; Malkus and Riehl, 1969; Miller, 1962 and 1964; Hawkins and Rubsam, 1968).

While progress in modeling the development and especially the movement of hurricanes has been slow, the knowledge gained from the research flights together with present day opportunities for high-speed data processing have opened the door for development of diagnostic procedures and computations by which a prediction result can be obtained and optimized by successive approximation. The decision ladder by which this is accomplished supplies a systematic means of formalizing prediction experience which in turn can be used to develop more effective prediction models.

As part of a policy for centralizing data processing and prognoses in the National Weather Service, the responsibility for forecasts of Atlantic hurricanes and for supervising the preparation of advisories and warnings at hurricane warning offices has been assigned to the National Hurricane Center at Miami. The purpose of this paper is to describe the procedures and decision-making processes presently in use at this Center, most of which draw upon automated analyses and computation programs.

The sophisticated analysis and prediction models (Shuman and Hovermale, 1968), which have met with such success in temperate latitudes, are less effective and dependable south of the 30th parallel. One of the principal reasons is that the computations are based upon a data grid of too large a mesh to describe, much less predict, the scale of motions in most tropical disturbances. Secondly, the prediction of development if not the movement of tropical disturbances depends, it is now believed,*in a subtle way upon the interaction of meso-convective scales of motion with those of the larger synoptic scale (Kuo,1965; Ooyama, 1967; Rosenthal, 1970; and Miller, 1969). As yet no way has been found to effectively parameterize this interaction.

A number of numerical models have been developed for predicting hurricane movement, some purely dynamical, others drawing upon statistical screening techniques (Miller and Chase, 1966; Miller, Hill, and Chase, 1968). The main difficulty with these models is that of diagnosing the errors of individual predictions in order to flag those which are unreliable. In the tropics the best predictions by most numerical models tend to occur when persistence is also a good predictor. Models are most likely to fail when a critical but uncertain change in track is impending. For these reasons the emphasis at the National Hurricane Center is presently being placed on the development of diagnostic procedures and tools, first to identify the frailties of each numerical prediction and second to enable the heuristic reasoning of the forecaster to be applied systematically to a decision ladder from which an effective forecast judgment can be reached with minimum subjectivity.

PREDICTION ERRORS AND THEIR CONSEQUENCES

The long-term average error for 24-hour predictions of hurricane movement is 129 nautical miles. This figure is for all hurricanes regardless of distance from the coastline. The error is smaller when the storm approaches the coast and is monitored more extensively. The average landfall error for a 24-hour prediction is of the order of 100 nautical miles.

To understand these errors they must be reviewed in terms of their component parts. These are the displacement error and the initial positioning error. The positioning error is defined as the distance from the point identified by the forecaster as the vortex center at the time he made his forecast to the actual location of the center at that time based upon a post-analysis determination of the best track.

During the 1969 hurricane season, the mean positioning error for all storms (4 forecasts per day) was 27 nautical miles. In 1970 it was 18 nautical miles. In 1969 the positioning error in each of 5 storms was more than 30 nm and in one 40 nm. In 1970 two storms had errors in excess of 30 nm. However, in both years several storms had positioning errors less than 10 nm.

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*GARP Joint Organizing Committee Report No. 4, First Tropical Experiment (TROMEX)

The positioning error is due in part to faulty judgment by the forecaster in evaluating conflicting information on center location; however, it appears mainly to be due to basic errors in positioning the center by reconnaissance aircraft. A significant part of the aircraft "fix" error is probably due to navigation errors, but at times can be attributed to the difficulty in identifying the exact center once an eye penetration has been made. Navigation errors can now be virtually eliminated by the installation of Omega or other precision navigation equipment. However, the error in identifying the meteorological center can be reduced only by increasing the level of experience of pilots and weather observers.

The immediate outlook for reducing the displacement error by directly improving dynamical prediction models is not favorable, first because this will call for a three dimensional model which effectively parameterises the interaction between meso-convective and synoptic scale circulations, and second because of the initial data problem in applying such a model in real time. Reduction in the displacement error for the next 5-8 years will probably come, in the writer's opinion, from the astute application of the diagnostic procedures mentioned earlier.

No weather prediction is ever made by a forecaster in which the consequence of error in the movement or the development of a pressure system is so appalling as in hurricane forecasting. Consider, for example, Figure 1. Here a prediction error of 10 degrees in direction of motion shifts the scene of greatest action and danger along a coastline by 75-100 miles. The predicted landfall would require the evacuation of all exposed beaches in the Clearwater-Sarasota sector, with only precautions for gale winds and no evacuation for the Naples-Venice sector. However, with the observed track, water levels in the Clearwater-Sarasota sector would be below normal with winds less than gale force while the Naples-Venice area would receive the worst the hurricane had to offer.

Moreover, the price of preparing for a severe hurricane is high and there is an economic constraint on the extent to which warnings can be extended to insure against the frailties of the forecast. In the greater Miami area for example it is estimated that a minimum of $2,000,000 is spent on a programmed basis when hurricane warnings are issued.

Hurricane Celia, which devastated the Corpus Christi area in August 1970, illustrates another kind of prediction frailty. Celia reached the coast while in the process of extreme development in which the central pressure fell about 40 mb in less than 15 hours. This was an unforeseen event which transformed this small cyclone from a run-of-the-mill hurricane to one of the most damaging storms of history.* Fortunately, the community had responded promptly and effectively to the hurricane warnings and was as prepared for a severe hurricane as for a moderate one. These prediction frailties emphasize the need for systematic decision procedures which, in the face of inexact computations and uncertain developments, will identify the course of least regret in decision making.

*Property losses in Celia, $454 million, were exceeded only by Camille, 1969; Betsy, 1965; Diane, 1955; and Carol, 1954.

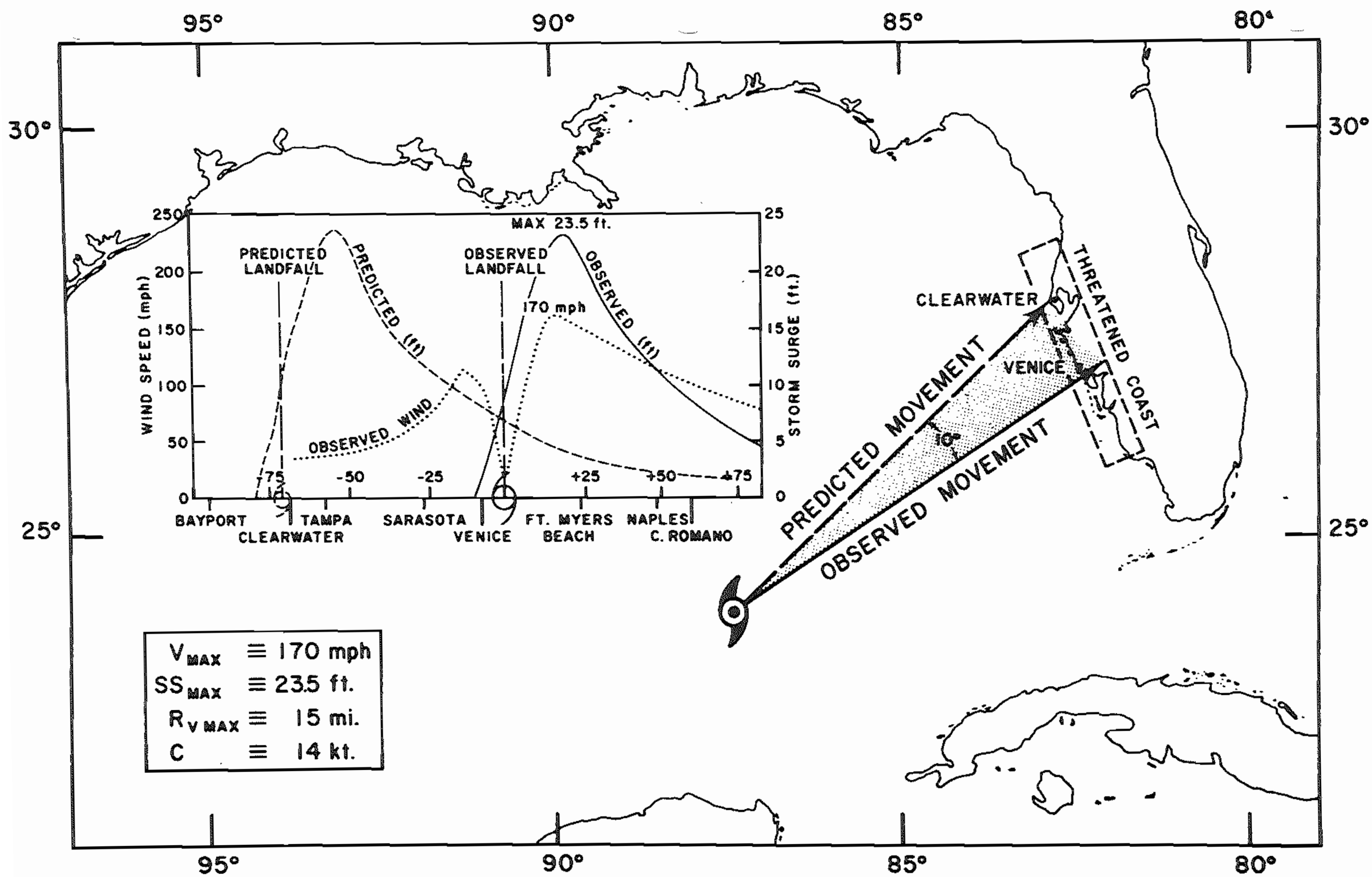

Figure 1. The Consequences of a 10° Error in Predicting the Track of a Hurricane. Warnings based upon wind and storm surge, if issued explicitly for the predicted landfall, would involve serious consequences for the coastal residents. In one instance protective measures and evacuations would have been made unnecessary, while in the adjacent coastal region residents who would have been in dire need of warning and evacuation would not have realized the full scope of the hazard they faced.

ELEMENTS OF THE HURRICANE FORECAST

Hurricane warning decisions necessarily involve a hierarchy of diagnostic and prognostic problems. This begins with the analysis of the circulation environment upon which the vortex feeds both for its growth and its movement. Second is the problem of locating and tracking the vortex center. The forecaster must then assess the stability of the vortex and its potential for further development. He must be able to determine the instantaneous steering and the trends in this steering as a first yardstick for judging the applicability of the numerical prediction results. Finally, as the center approaches a coastline he must have a procedure for identifying the most probable point of landfall. For planning purposes and to permit the military services and some Government agencies to initiate the more time consuming preparedness measures, an extended projection of the storm track for periods up to 72 hours must be prepared. At least 36 hours in advance the forecaster must identify the coastal sector where a hurricane watch must be posted so all concerned can prepare for fast action should specific warning measures become necessary. Then, while the storm is still 12 to 18 hours from its landfall, a decision must be reached as to the precise area of the coast which will require hurricane,storm, and gale warnings, and the point of maximum storm surge together with its height and the profile of water levels to either side of the landfall point must be determined. Areas must be identified where excessive rains and flash floods will occur, and warnings of tornadoes issued where these may accompany the hurricane as it approaches the coast.

The following sections will outline the procedures and the decision processes used by the forecaster in carrying out these tasks.

PROCEDURES AND DECISION PROCESSES

Analysis of Circulation in the Hurricane Environment. One of the principal difficulties with tropical prediction models is that of initial data and of the analyses from which they are derived. In low latitudes the gradients of geopotential are so weak that small computational errors or local temperature biases due to convection cause large errors in the implied circulation at any single level of analysis. For exactness one necessarily must derive the geopotential gradients from the observed wind field, or employ a system which describes the circulation in terms of the observed winds, computing vorticities and divergences directly from interpolated winds. At the National Hurricane Center the latter alternative is used but in a particularized sense. Instead of analyzing a succession of layers in the low, middle, and upper troposphere, analyses are made of computed deep layer mean winds, one for the lower troposphere, 1000-600 mb, another for the upper troposphere, 600-200 mb. The mean winds are analyzed using a system first developed by Eddy (1967) and subsequently applied in the tropics by Sanders (1968). This system, basically a "least squares" interpolation procedure, utilizes a multiple regression analysis and requires the insertion of manufactured wind components for specified grid points in areas where observations are not regularly available. Figures 2 and 3 are examples of the lower and upper tropospheric mean circulation.

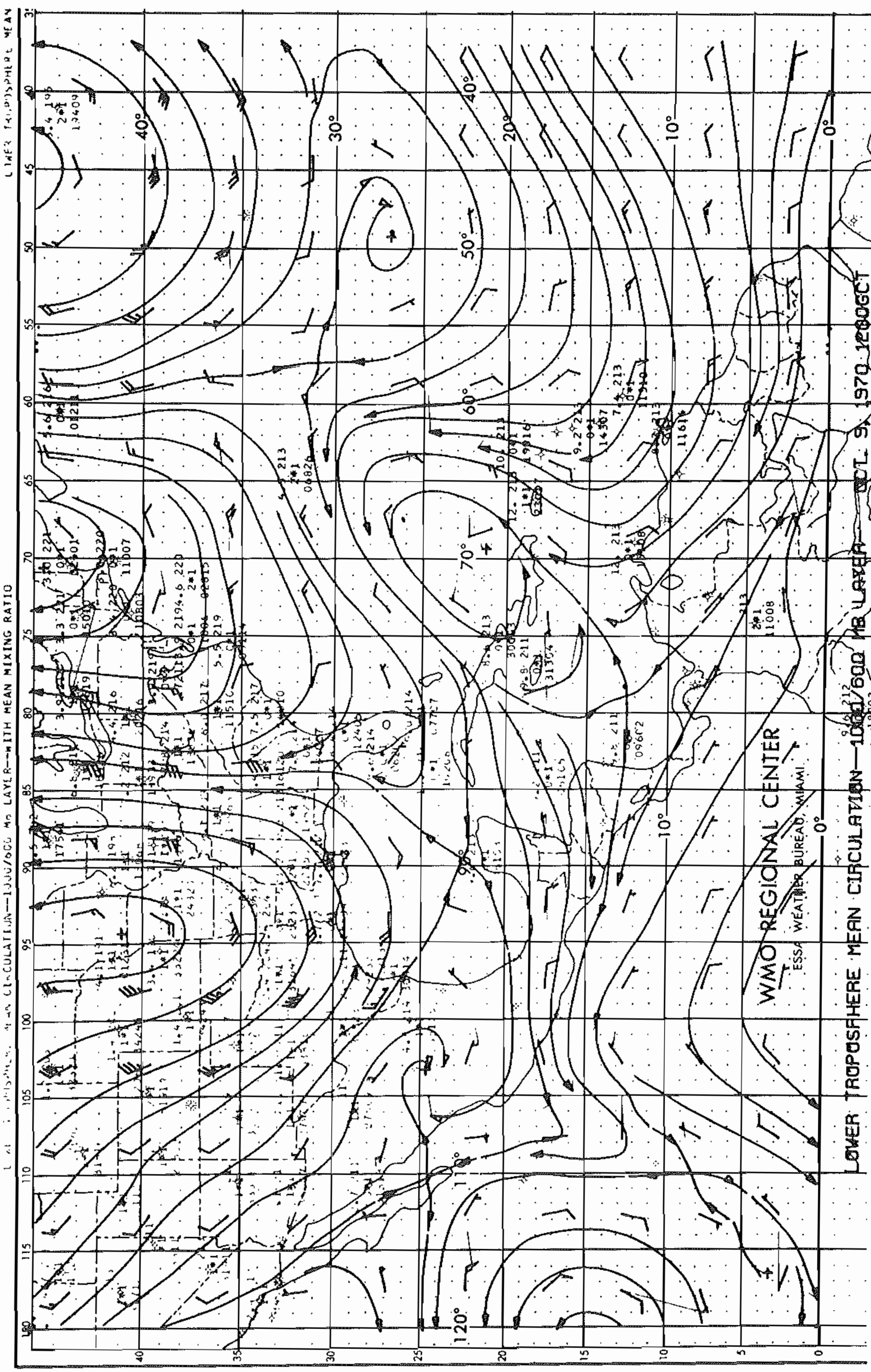
LOWER TROPOSPHERE MEAN CIRCULATION—1000/600 MB LAYER—OCT. 9, 1970 1200GCT
WMO REGIONAL CENTER
ESSA WEATHER BUREAU, MIAMI

Figure 2.

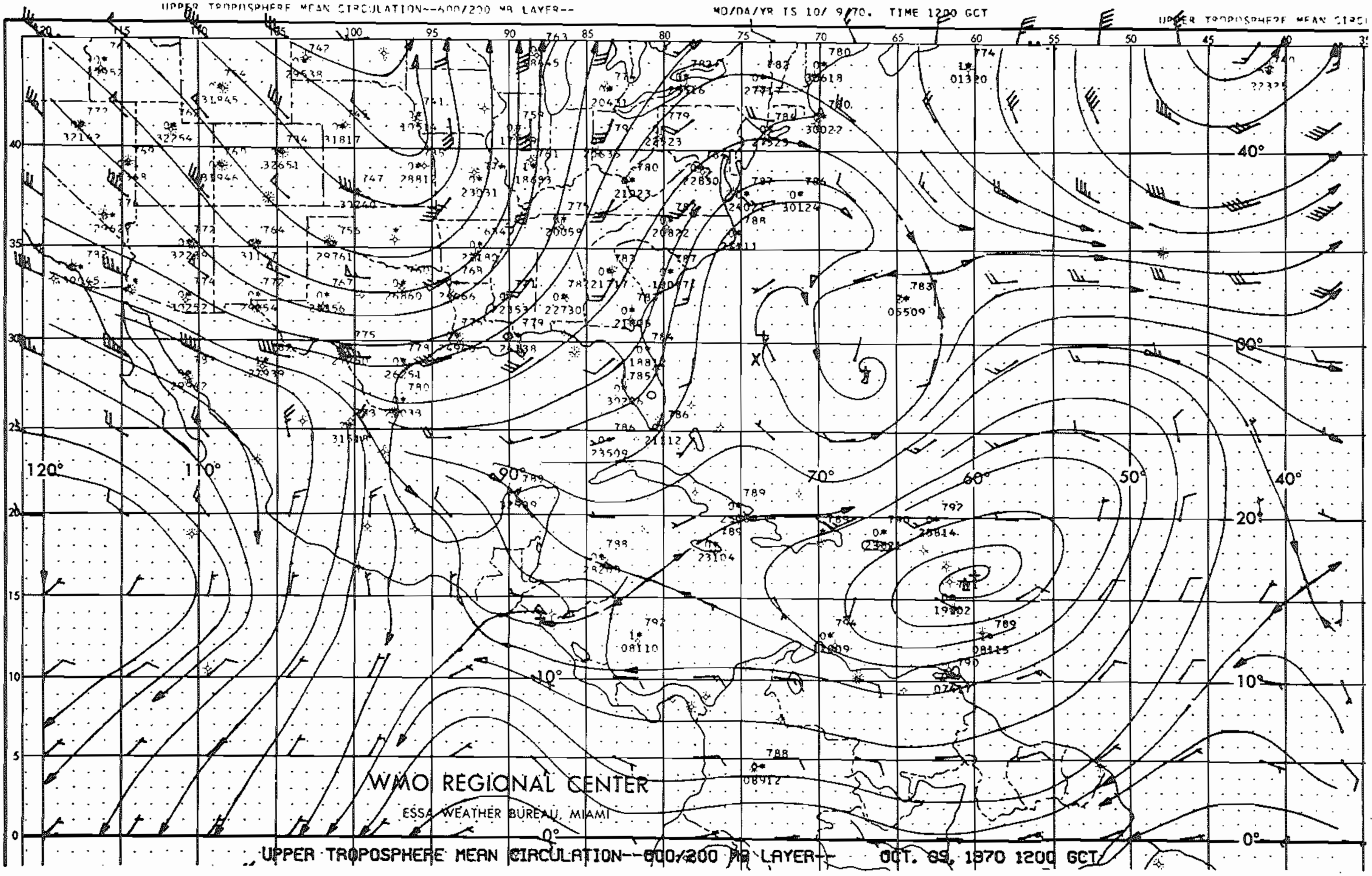
UPPER TROPOSPHERE MEAN CIRCULATION--600/200 MB LAYER--
MO/DA/YR IS 10/ 9/70. TIME 1200 GCT
WMO REGIONAL CENTER
ESSA WEATHER BUREAU, MIAMI
UPPER TROPOSPHERE MEAN CIRCULATION--600/200 MB LAYER-- OCT. 09, 1970 1200 GCT

Figure 3.

A number of advantages stem from the use of these charts as a primary basis for heuristic reasoning and for computations. First, while the circulation reflected on individual pressure surfaces frequently involves transitory aberrations difficult to distinguish from the conservative properties, experience shows that in the layer mean wind analyses the transitories are subdued or damped while the conservative properties are retained. Secondly, the mean layer circulation presents a more conservative and graphic field of vorticity, especially in the lower troposphere. The generation of vorticity by redistribution of the potential energy stored from latent heat sources may be distributed variously through the lower and middle troposphere. In tropical disturbances, vorticity is reflected mainly in the form of horizontal shear in the lower two kilometers, while in the 2-5 km layer it tends to be more frequently expressed in terms of curvature. It is well known* that this is the kinematic result of a decrease in strength of the basic current with height which changes the geometry of the disturbed circulation. The analyst thus can be led to conclude erroneously that a disturbance reaches its greatest development in a relatively shallow layer in the middle troposphere, while the vorticity is actually distributed uniformly throughout a much deeper layer.

A tropical wave during its migration across the Atlantic often encounters significant variations in the vertical profile of the basic current which causes large changes in amplitude of the wave at any one pressure surface without change in vorticity of the system. In these cases the layer mean circulation chart is a more conservative and effective instrument for representing the changes in development of a disturbance.

From the two layer mean wind analyses,whose streamlines and grid point winds are machine products, two other charts are derived. The subtraction of grid point winds in the lower troposphere from those in the upper troposphere provides a field of tropospheric mean wind shear which is analyzed by the streamline technique used in the first two charts. Figure 4 is an example of such an analysis. A printout of winds at grid points has been found to be more generally useful to the forecaster than an isotach analysis. The fourth chart, derived from the grid point subtraction of the mean geopotential in the lower layer from that in the upper layer, leads to tropospheric mean temperature values for which analyses are made of deviations from normal. The march of the seasons is assessed from the ten-day averages of these anomalies together with the daily trends.

The basic analysis package is completed with lower and upper boundary layer charts. The lower boundary known as the TOE chart (Top-of-the-Ekman layer), uses wind sounding data at 2000' augmented by ship winds and low-level winds derived from ATS III satellite movie loops. This

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* e g, see LaSeur, N.E.: On the Structure of Tropical Disturbances and Hurricanes, NATO Symposium, London, July 1966.

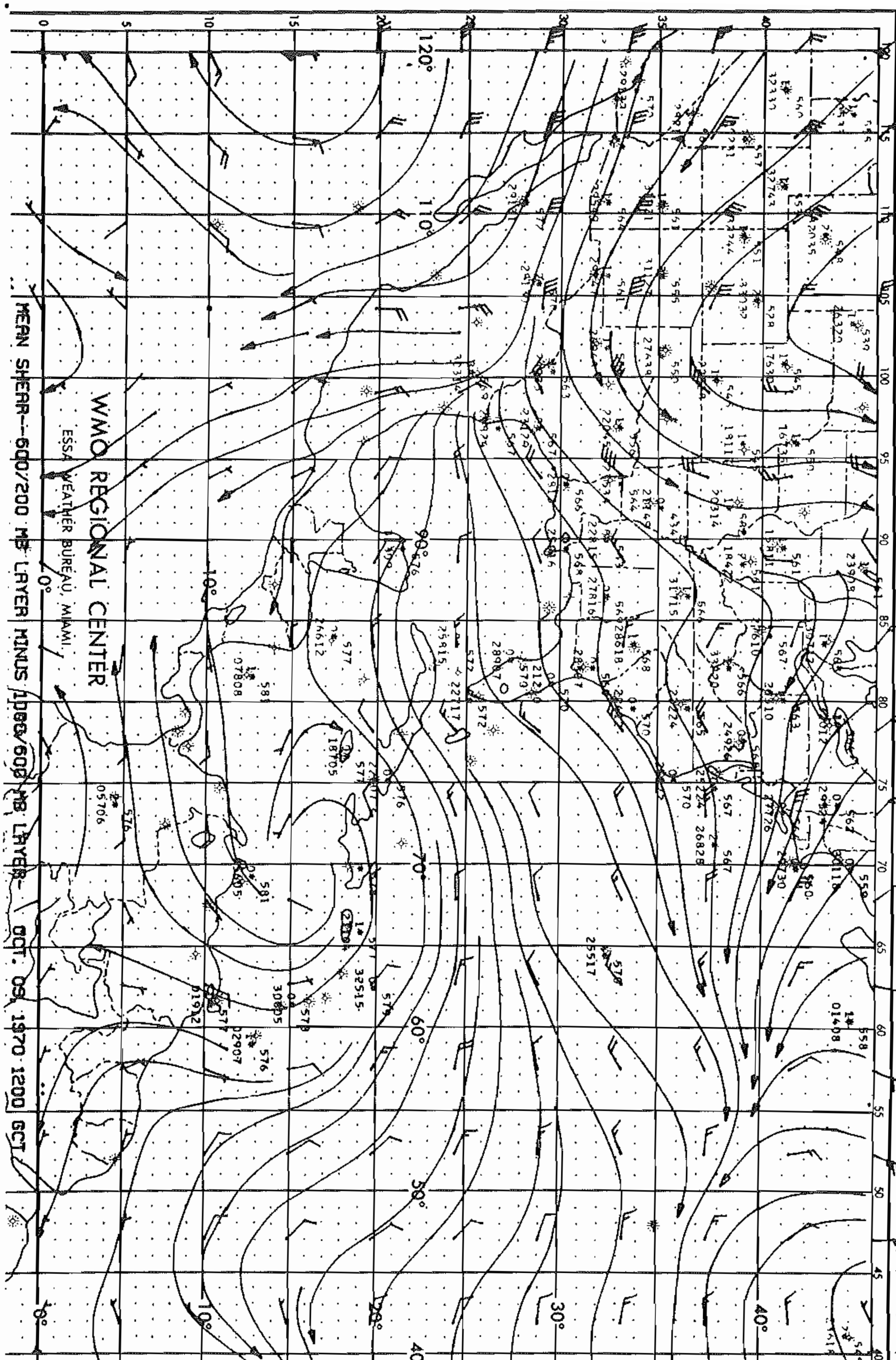

WMO REGIONAL CENTER
ESSA WEATHER BUREAU, MIAMI.
MEAN SHEAR--600/200 MB LAYER MINUS 1000/600 MB LAYER- OCT. 05, 1970 1200 GCT
MO/DA/YR IS 10/ 5/70. TIME 1200 GCT

Figure 4.

is essentially a kinematic chart for identifying and tracking disturbances in the trade winds and the equatorial trough, and shear lines which intrude from higher latitudes. Other than its kinematic tracking functions, this chart is the means of examining the interaction between the circulations of the equatorial trough and the trade winds, the migration of the asymptote of intertropical confluence (ITC), and for identifying the mechanisms which generate the convection in the equatorial trough (ITCZ) (Simpson et al, 1968). Experience thus far suggests that the ITCZ convection frequently does not align itself with the ITC but rather with a boundary layer convergence mechanism such as that described by Charney and Eliassen (1967) as conditional instability of the second kind (CISK). The principal convection from satellite cloud mosaics is transferred onto the TOE chart in order to identify where possible the convergence mechanism involved and to relate it to the synoptic scale circulation dynamics.

The upper boundary is considered to be the 200 mb surface. In summer the most interesting feature of circulation at this level is the semi-permanent trough or shear line which extends from north of the Azores southwestward into the Caribbean Sea. During winter an equatorial jet stream apparently emanating from the upper Amazon Valley, extends northwestward into the Southern Caribbean, thence eastward into the tropical Atlantic. Large interhemispheric exchanges and eddy transports across the equatorial trough are present the year around at this level in the vicinity of the Americas.

The surface chart is constructed only for a small regional area, and as a supplemental, rather than a primary tool of analysis and prediction. During hurricane exigencies this chart is extended to include the environment of the hurricane wherever it may exist. Other supplemental tools, products of machine processing, are spinoffs from the data bed required for the mean layer circulation analyses. These include a meridional and a zonal vertical cross-section, 10 tephigrams, and a number of computational sub-routines.

Tracking Disturbances and Tropical Cyclone Vortices. In the course of a hurricane season an average of more than 100 trade wind disturbances are tracked across the Atlantic by means of the analysis system described earlier. This task, of course, is largely dependent upon the cloud motion analyses from ATS III satellite pictures received and analyzed at NHC. While a majority of these disturbances, which have become known as hurricane seedlings, emanate from the African continent, some are generated at the ITC, and others from cold lows (see e.g. Simpson et al, 1969, and Frank, 1970). The progressive evolution and development of these disturbances and the nature of their dynamics remain obscure. While this paper does not propose to discuss the structure or origin of these seedlings, it is interesting to note here that only about 1 in 5 acquire an identifiable pressure center, and only 1 in 10 develops into a tropical storm or hurricane in the Atlantic. On the average about one out of every 5 disturbances which cross Central America is associated with cyclogenesis in the Eastern Pacific.

The geosynchronous satellite provides the most effective overall surveillance of the tropical cyclone environment during all stages of development. While there is still much subjectivity in estimating the maximum sustained wind speeds in tropical cyclone vortices using satellite cloud pictures alone, and the precise location of the center is generally less dependable than by radar or by aircraft penetration, the satellite indeed serves as the best first approximation of the translation vector of the storm center, and for evaluating the short term growth and development of the vortex. This is because geocentric satellite pictures can be received as frequently as one each 11 minutes and composed into a time-lapse movie loop from which the movement of an eye center can be measured, and both wind speeds and mass transports in the lower boundary and the out-flow layers can be estimated.

The Need for Exactness in Tracking the Vortex Cannot be Over Emphasized. The reason is that nearly all methods of predicting hurricane movement lean heavily upon the direction and speed of motion for the preceding 6 to 12 hours. In some instances an error of as little as 10-15 degrees in computed direction of vortex motion, based upon the position 12 hours ago and the present location, can produce variations in the predicted displacement of 75-100 miles in 24 hours and 400 miles in 72 hours. Figure 5 shows two computations for hurricane Celia based upon 0000GCT data in which a difference in positioning of the center led in the first case to a direction of motion 10° to the left of that in the second computation. In this case the two computations imply a need for quite different warning requirements. However, the forecaster frequently finds he must reach a judgment on the location of a center and present direction of motion in terms of highly conflicting information.

A vortex center can be located with reasonable accuracy by land-based radar when the eye is small, circular, and the eye wall is closed. Not infrequently, however, the eye wall is not completely closed, or when closed is elliptical or irregularly shaped; and this shape varies from hour to hour. In such instances radar tracking may imply irregular movements of the vortex. The positioning of a vortex center by aircraft radar may suffer additionally by navigation errors, first in positioning the aircraft geographically, and through certain other biases less well understood. For example, experience shows that as an aircraft approaches a hurricane center and views it from a distance of 150 miles or more, the ranging tends to be distorted to imply that the center position is closer to the aircraft by as much as 10-20%.

The most satisfactory positioning of the vortex center is by aircraft penetration. The center is identified during a penetration as the point of lowest pressure whenever the eye is sufficiently small that a definite point of the minimum pressure can be located, otherwise by the point of zero wind speed. Of course, for the moving storm system these two positions cannot coincide. And in the case of tropical storms lacking an eye wall, or a hurricane with a very large diameter eye, there are frequently two or more circulation centers or

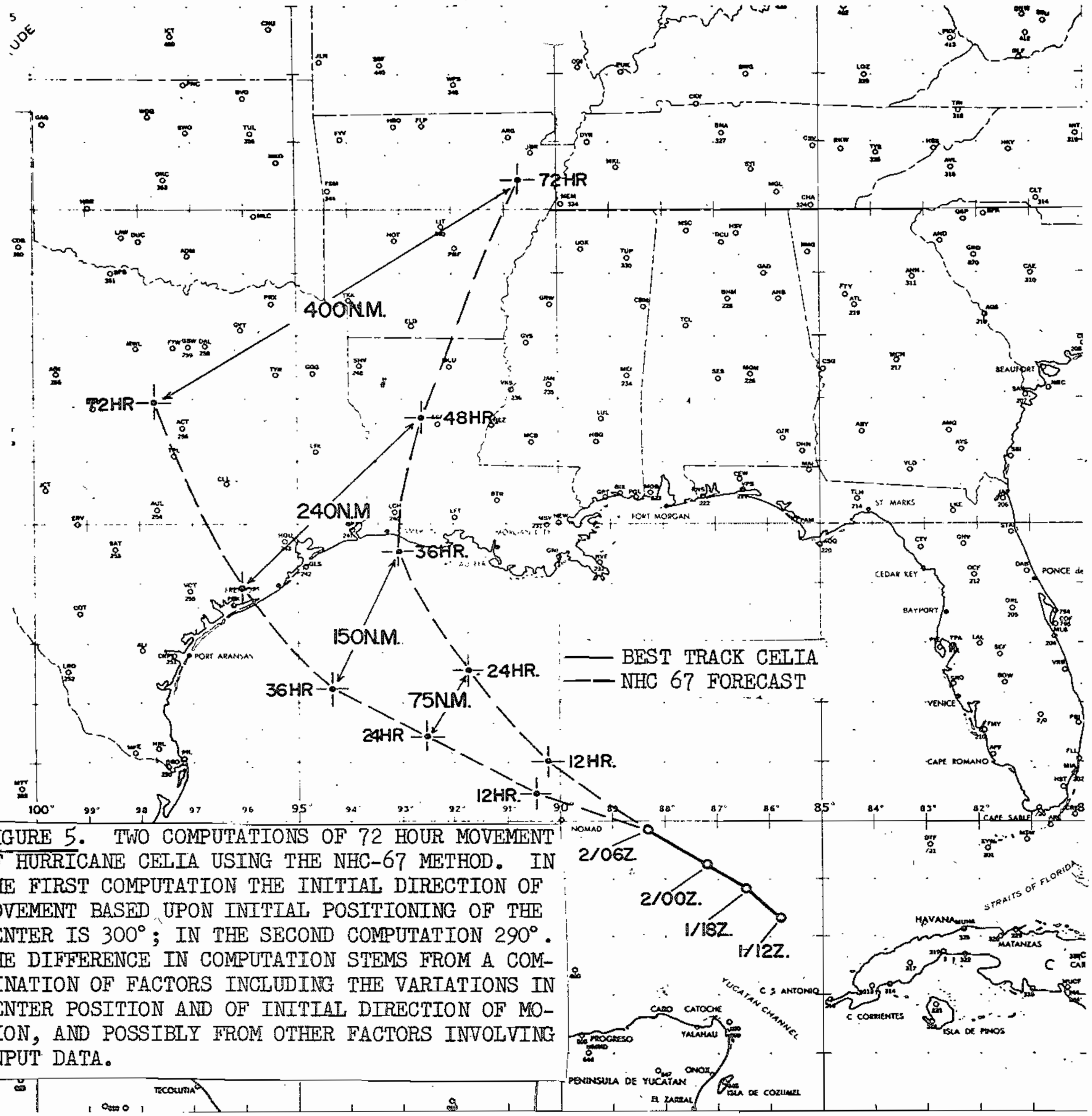


FIGURE 5. TWO COMPUTATIONS OF 72 HOUR MOVEMENT OF HURRICANE CELIA USING THE NHC-67 METHOD. IN THE FIRST COMPUTATION THE INITIAL DIRECTION OF MOVEMENT BASED UPON INITIAL POSITIONING OF THE CENTER IS 300°; IN THE SECOND COMPUTATION 290°. THE DIFFERENCE IN COMPUTATION STEMS FROM A COMBINATION OF FACTORS INCLUDING THE VARIATIONS IN CENTER POSITION AND OF INITIAL DIRECTION OF MOTION, AND POSSIBLY FROM OTHER FACTORS INVOLVING INPUT DATA.

points of zero wind speed. Probably the most conservative identification of the vortex center is the geometric center of the ring of maximum winds surrounding the eye. This ring apparently tends to remain circular and its center to move in a nearly straight line, even though the geometric center of the cloud wall surrounding the eye may become distorted and appear to follow an irregular path. Since the radius of maximum winds is seldom less than 12-15 miles, the location of the point of maximum wind in each of the four quadrants of the storm as a means of identifying the dynamical center of the vortex is a more tedious and difficult process than the location of a single pressure minimum or circulation singularity. During the 1970 hurricane season, hurricane reconnaissance aircraft for the first time flew special tracks radially across each of the four quadrants of the vortex providing the first opportunity to identify the vortex center in terms of the ring of the maximum winds. For effective real time application of this technique, machine processing of digitally recorded data from the radial profiles will be required. This remains several years away.

In summary, the accuracy with which the center can be located by aircraft penetration is limited at present by two sources of errors, one navigation, the other that of locating the point of minimum pressure or the circulation singularity. The latter can be reduced substantially by adequate training and experience, although in the past the rotation of air crews in and out of hurricane reconnaissance duty has limited the amount of experience that could be acquired. Navigation errors can be virtually eliminated by the installation of modern equipment such as the Omega system, although few reconnaissance aircraft are so equipped at the present time.

In evaluating conflicting information on the location of the vortex, the forecaster must condition his thinking to the thesis that the best information is that which places the vortex closest to the predicted track, unless there are changes occurring in the ambient circulation which could account for larger departures from the predicted track.

Thus the task of tracking begins with the process of "dead reckoning". The first guess location is that obtained from the latest prediction. This predicted track is then compared with the direction and speed of movement of the center observed on the current ATS-III satellite movie loop. If the satellite's apparent movement does not confirm the dead reckoning position, the degree to which the tentative center location is displaced from the dead reckoning position will depend first upon an assessment of gridding errors, the probable error of identifying the eye position in satellite photographs, and finally upon whether the deviations from a dead reckoning track are supported by the changes observed or suspected in the ambient circulation. Where additional information is available from land-based radar, these reports nominally are weighted more heavily than the satellite information, providing there is a clearly identifiable eye which is closed and of relatively small diameter. Heaviest weight ordinarily is given the aircraft center position obtained by an eye penetration. If the aircraft "center fix" differs substantially from the predicted position, the forecaster will finally place the center along the line which connects the adjusted dead reckoning position and the aircraft observed position, the exact position depending upon the extent to which the deviation of the aircraft position from the predicted track is supported by changes in the ambient circulation, and whether this is supported by the motion implied by satellite.

The decision ladder for the location of the center used by the forecaster is shown in Figure 6. Figure 7 is an example of successive center fixes by aircraft and satellite for Hurricane Felice, September 1970.

Development Potential of the Vortex. Having decided upon a location for the center the next task is to assess the destructive potential of the system and the opportunities for growth and development of the vortex.

It is not unusual for a reconnaissance aircraft to penetrate a pressure center and find very little wind until it moves radially outward 50-100 miles to the vicinity of a spiral rainband where speeds of 50-60 knots may be measured electronically in the boundary layer. The question then arises whether this is a transitory release of kinetic energy or a conservative trend which could transform a weak tropical storm into a full hurricane in a matter of less than 6 hours, as in Camille in 1969. On the other hand a tropical cyclone observed to have maximum winds in excess of 100 knots early in the day may, 6 hours later, be only of moderate hurricane intensity. The deepening hurricane often tends towards dynamic instability in which the vortex expands and loses strength as rapidly as it gained it.

The decision ladders for assessing the development potential of seedlings and of named storms are presented in Figures 8 and 9. Consider first the seedling. The development of any disturbance depends upon a means of causing surface pressures to fall. In the tropics this depends mainly upon the storage of latent heat in a deep tropospheric column. The controlling factor is the vertical wind shear. Experience indicates that within a radius of 4 degrees latitude, the vertical shear must not exceed about 15 kt if the disturbance is to grow.

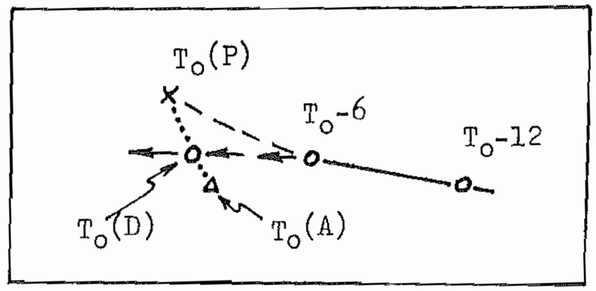
The next step concerns the shear vorticity in the boundary layer. Along the radial which represents the pressure ascendancy, the relative vorticity due to shear must be positive in the area approximately 2-6 degrees latitude from the center if growth of circulation in the disturbance is to be conserved.

In the outflow layer the advection of relative vorticity must be negative to organize and enhance the divergent outflow of cumulonimbus clusters.

DECISION LADDER
for
POSITIONING THE HURRICANE CENTER

LEGEND:

- T_o-12 Center position 12 hours ago
- T_o(P) Current position from predicted track
- T_o(Pa) Current position adjusted from predicted track
- T_o(R) Current position from land based radar
- T_o(A) Current aircraft center fix
- T_o(D) Decision on current center position



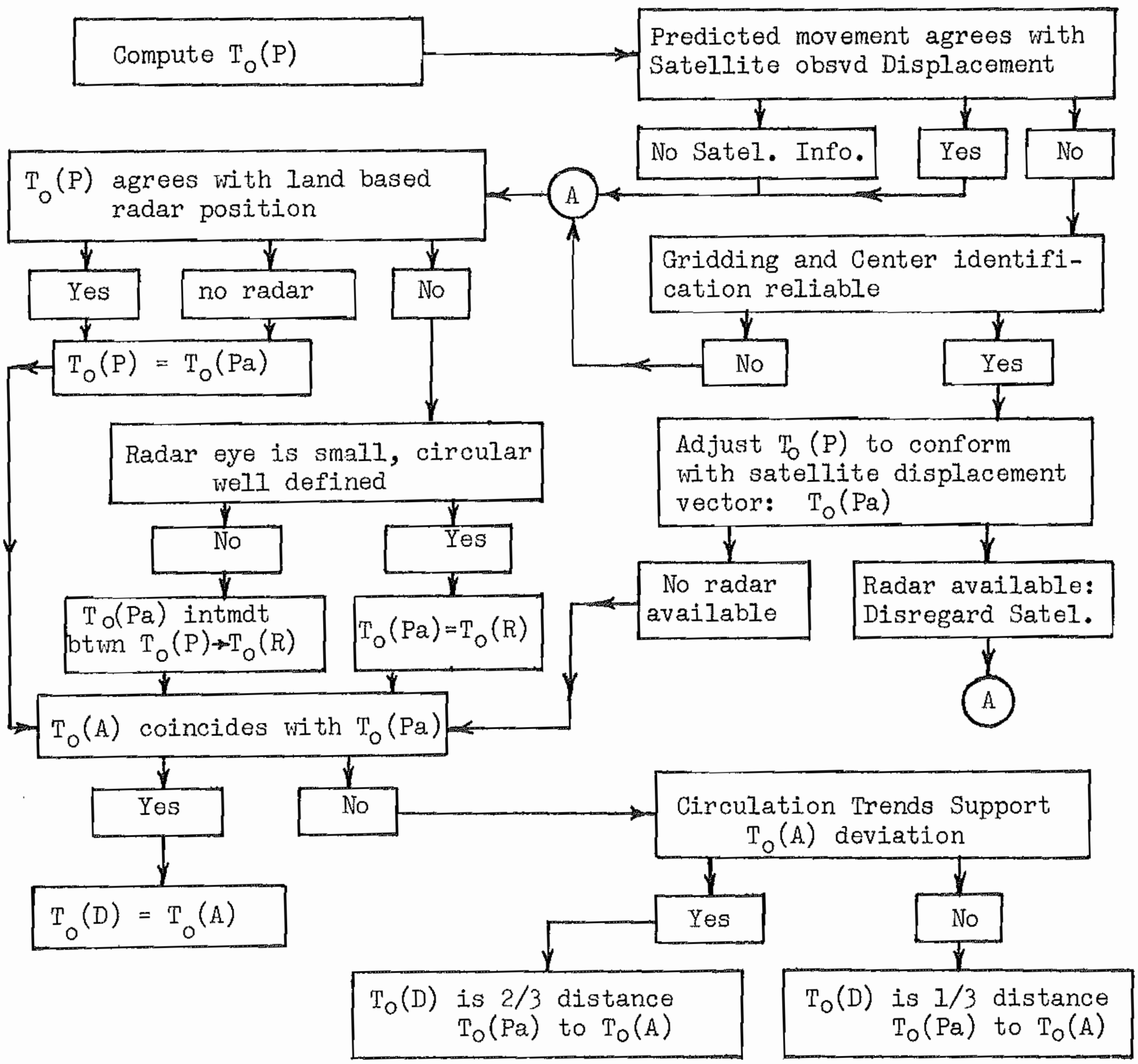


Figure 6

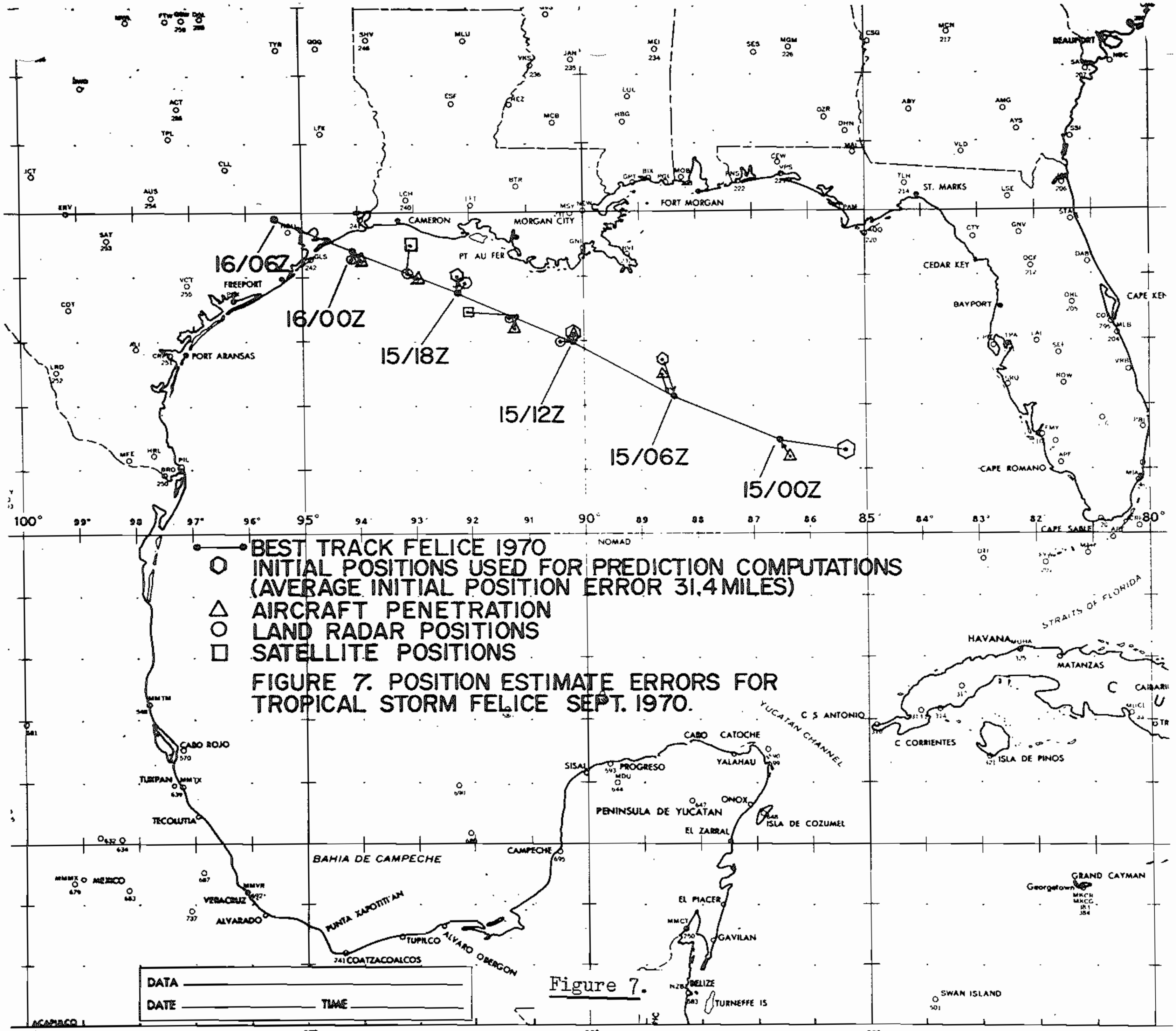

BEST TRACK FELICE 1970
INITIAL POSITIONS USED FOR PREDICTION COMPUTATIONS (AVERAGE INITIAL POSITION ERROR 31.4 MILES)
AIRCRAFT PENETRATION
LAND RADAR POSITIONS
SATELLITE POSITIONS
FIGURE 7. POSITION ESTIMATE ERRORS FOR TROPICAL STORM FELICE SEPT. 1970.
16/06Z
16/00Z
15/18Z
15/12Z
15/06Z
15/00Z
100°
95°
90°
85°
80°
CAMERON
MORGAN CITY
FORT MORGAN
PT AU FER
ST. MARKS
CEDAR KEY
BAYPORT
CAPE ROMANO
CAPE SABLE
CAPE KEN
BEAUFORT
FREEPORT
PORT ARANSAS
STRAITS OF FLORIDA
HAVANA
MATANZAS
C CORRIENTES
ISLA DE PINOS
C S ANTONIO
YUCATAN CHANNEL
CABO CATOCHE
YALAHAU
ISLA DE COZUMEL
PENINSULA DE YUCATAN
EL ZARRAL
PROGRESO
SISAL
CAMPECHE
EL PIACER
GAVILAN
BELIZE
TURNEFFE IS
GRAND CAYMAN
Georgetown
SWAN ISLAND
BAHIA DE CAMPECHE
PUNTA XAPOTITLAN
COATZACOALCOS
TUPILCO
ALVARO OBREGON
ALVARADO
VERACRUZ
TECOLUTLA
TUXPAN
CABO ROJO
MEXICO
ACAPULCO
NOMAD
DATA
DATE
TIME

Figure 7.

SEEDLING DEVELOPMENT POTENTIAL (24-hour)

DECISION LADDER

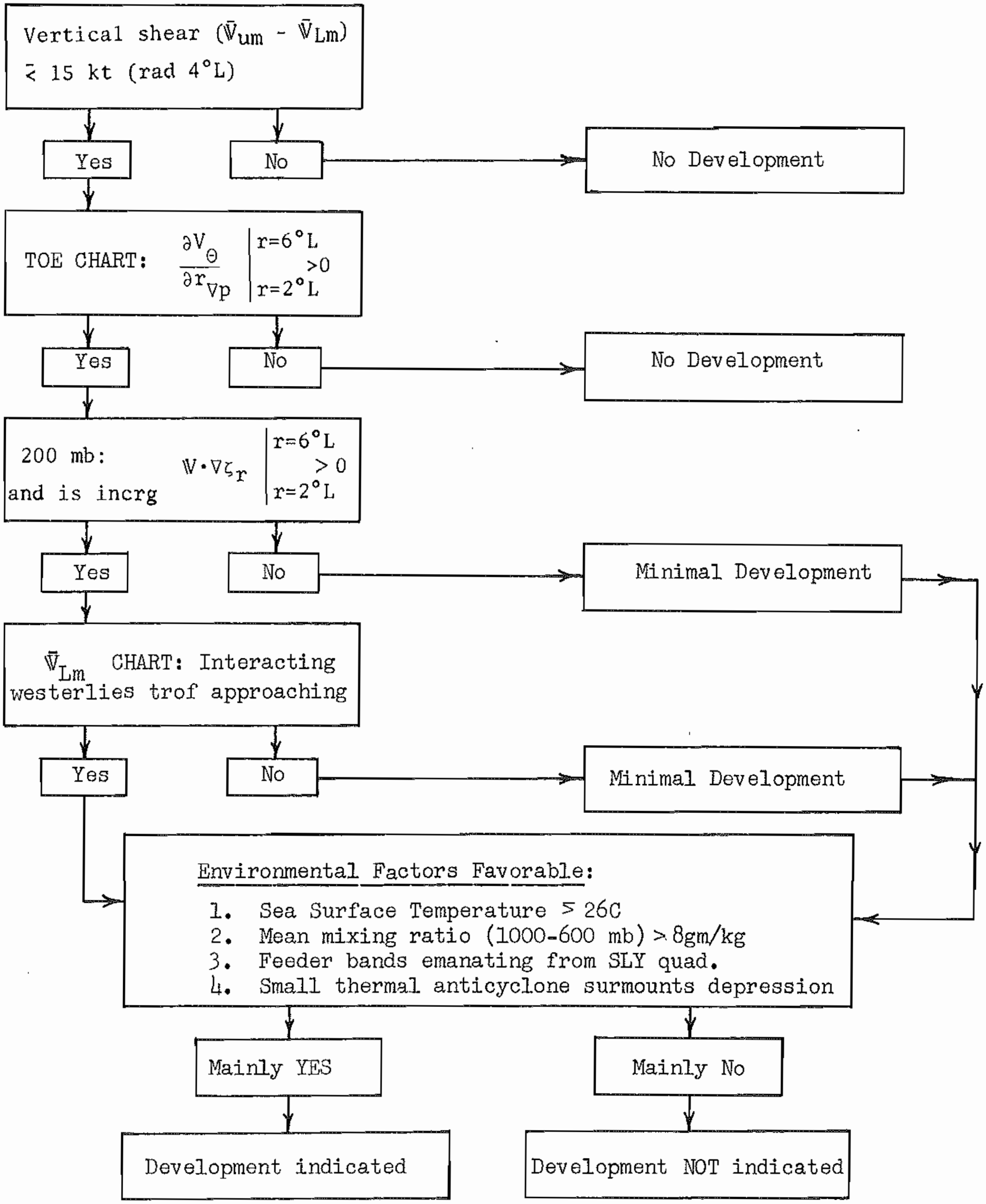


Figure 8.

VORTEX DEVELOPMENT POTENTIAL (24-hr)

DECISION LADDER

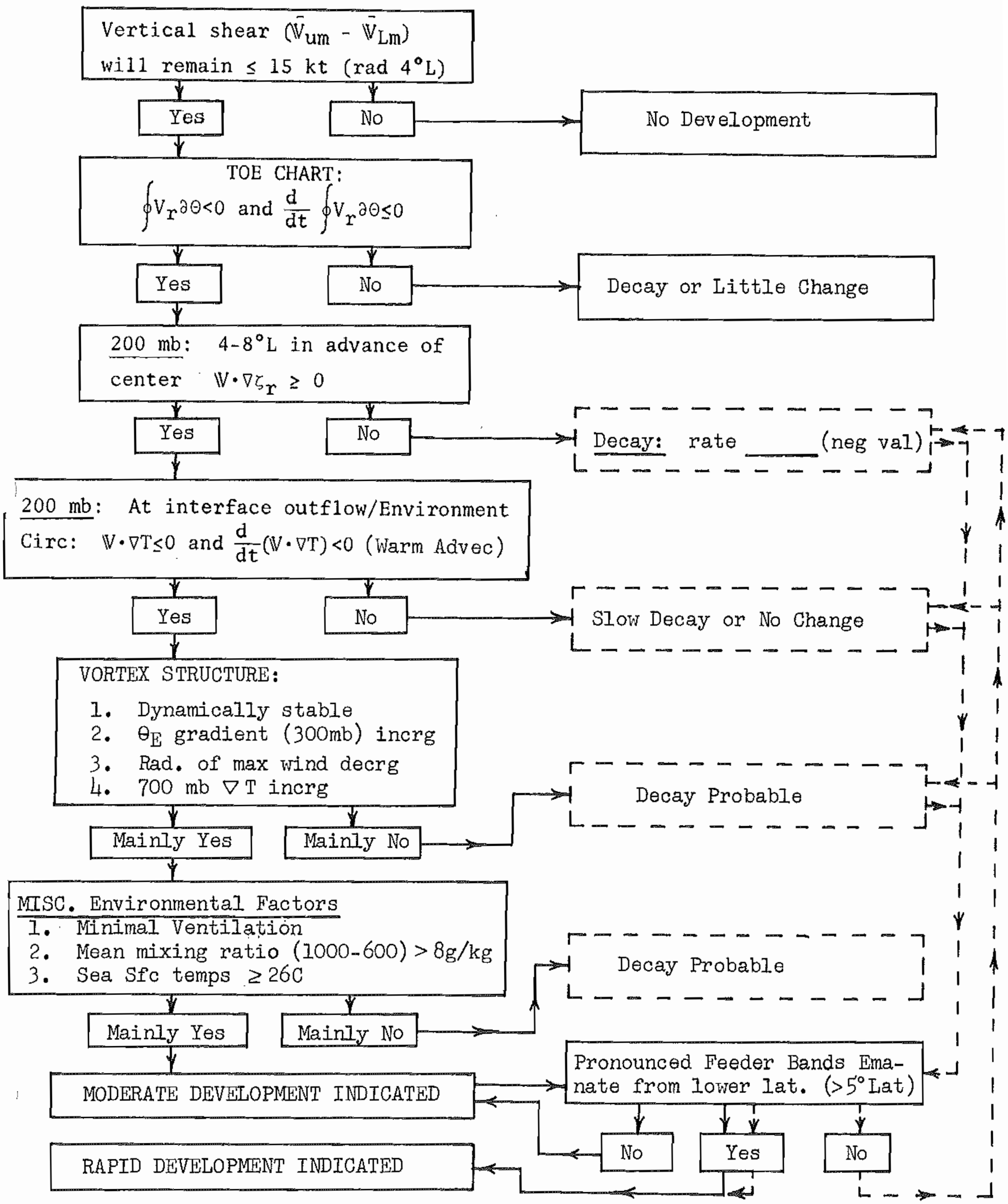


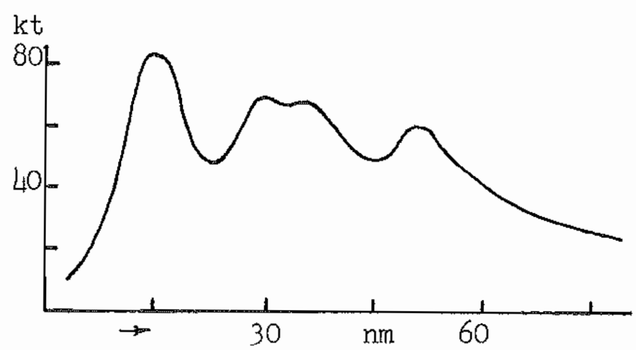
Figure 9.

Finally, the interaction between mid-latitude troughs and tropical waves generally favors development. A miscellany of other environmental factors may constrain or accelerate development. These include sea surface temperatures, moisture advection into the vortex, the geographic orientation of "feeder bands", and the establishment of a small thermal anticyclone to accelerate the synoptic scale outflow. The ladder provides a systematic pattern for screening these factors in deciding whether development is indicated or not. While it remains uncertain as to the weight to be given these various elements, the evaluation of experience in using these ladders will provide the forecaster with information on the emphasis that should be accorded each element and could provide a means of applying screening procedures to obtain an objective decision on the development potential.

In Figure 9 the decision rungs on the ladder are similar to those for the seedling. However, here it must be considered that organized mass circulation already exists and one must examine the stability of the vortex and its interaction with the environmental circulations in the inflow and outflow layers. For development there must not only be a net mass inflow at some nominal radius (8° Lat.), but this inflow must be increasing. In the outflow layer at the interface between the vortex and environment circulations there must not only be the advection of negative relative vorticity and pronounced warm advection, but the latter must also be increasing if development is to continue.

When immature hurricanes develop rapidly, the increase in maximum winds near the center has a tendency to outrun the accelerations at greater radial distances so that dynamic instability develops, angular momentum is transported outward, and maximum winds diminish. In some instances the vortex reflects a succession of such expansions with prominent secondary and tertiary wind maxima like those illustrated in the profile below. (Fig. 10)

Figure 10.



The maturity and stability of the vortex is also measured by the temperature gradient in the eye wall at 700 mb and the gradient of θ_E just below the outflow layer.

The new hurricane reconnaissance standard flight patterns mentioned earlier provide radial profiles of wind speed (essentially tangential winds), of D value, and of temperature. These are illustrated in Figure 11. These profiles indicate how close the vortex is approaching dynamic instability, reflect the storage of latent heat, the changes in asymmetry, and provide a measure of the maturity and stability of the vortex.

Finally, the vortex ventilation effect (Simpson and Riehl, 1959), best reflected in the upper layer mean analysis, must remain minimal, there must be no veins of drier air entrainment reflected in the lower layer mean analyses, and sea surface temperatures in advance of the vortex must remain 26C or greater.

Since the advent of the meteorological satellite, it has become apparent that development tends to occur steadily, even in the face of other conditions which may be adverse, if the principal "feeder band", or spiral rainband which often appears to represent the core of the inflow channel, emanates from lower latitudes (five latitude degrees or more). Rapid deepening apparently is not favored when the preponderance of inflow comes from the same or from higher latitudes. This may possibly stem from the trajectory deviation from that for constant absolute vorticity which would result in progressive stretching and saturation of the air for hundreds of miles as it spirals northward toward the vortex. As seen in the ladder, the presence of a northward spiraling primary "feeder band" is weighted very heavily in assessing development potential.

Instantaneous Steering of the Vortex. The vigor and vertical extent of interaction between the vortex and its environment increases in inverse proportion to the central pressure. For incipient tropical cyclones and storms whose central pressure is 990 mb or higher, experience indicates that the circulation of the deep layer mean from 1000-400 mb is the best index to the instantaneous steering. For deeper systems with central pressure 960 to 989 mb the layer 1000-300 mb is used; for the range 940-959 mb the layer 1000-200 mb is used, and for extreme storms (central pressure less than 940 mb) the layer 1000-100 mb. Ordinarily the steering implied from the deep layer mean circulation remains conservative for 6 to 12 hours in the absence of large intrusions of mid-latitude westerlies.

Identification of the Hurricane Watch Area. For the first time in 1970 the forecaster had available to him an objective procedure for delineating coastal areas for which a hurricane watch is needed. This procedure involves the HURRAN computation, and is illustrated in Figure 12. The HURRAN method is a hurricane analogue technique which calls upon the history of hurricane movements for the last 83 years. The history of all storms during this period has been stored on magnetic tape, and a machine program has been written which will select from this tape all cases of storms located within a radius of 100 miles of a specified hurricane position, moving within a given angle of the specified storm's

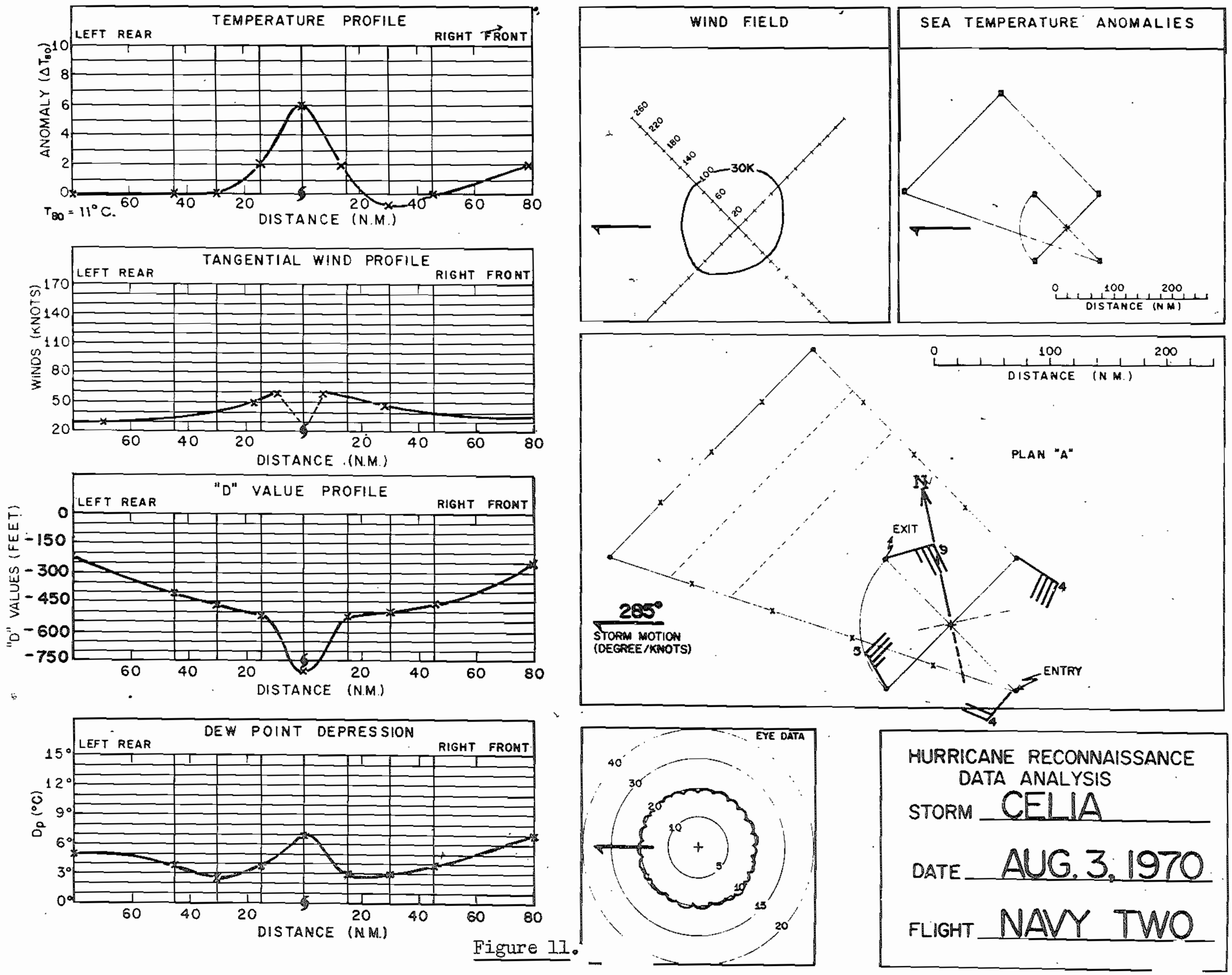
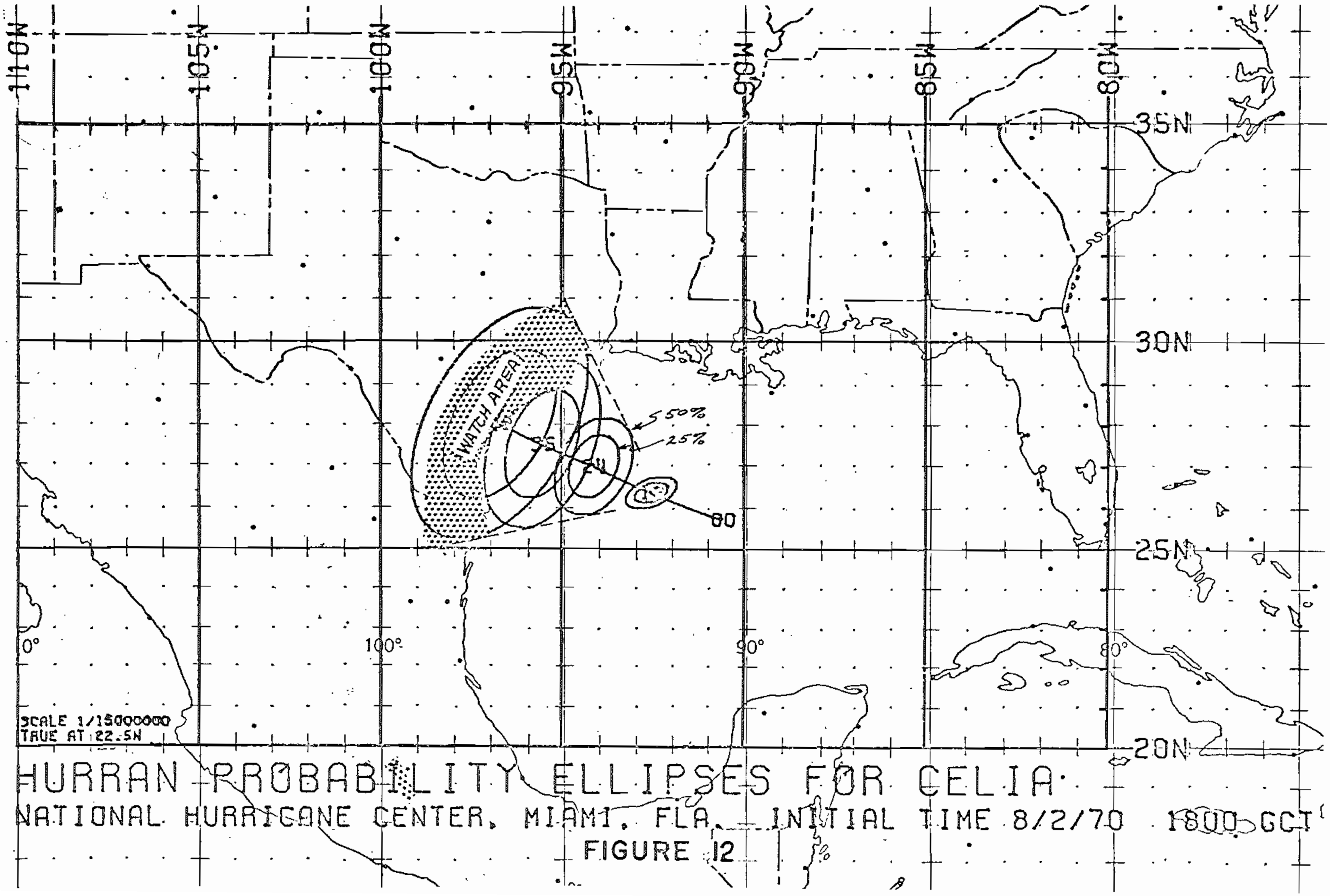

TEMPERATURE PROFILE
LEFT REAR
RIGHT FRONT
ANOMALY (ΔT80)
T80 = 11°C.
DISTANCE (N.M.)
TANGENTIAL WIND PROFILE
WINDS (KNOTS)
"D" VALUE PROFILE
"D" VALUES (FEET)
DEW POINT DEPRESSION
Dp (°C)
WIND FIELD
30K
SEA TEMPERATURE ANOMALIES
DISTANCE (N M)
PLAN "A"
EXIT
ENTRY
285°
STORM MOTION (DEGREE/KNOTS)
EYE DATA
HURRICANE RECONNAISSANCE
DATA ANALYSIS
STORM CELIA
DATE AUG. 3, 1970
FLIGHT NAVY TWO

Figure 11.



HURRAN PROBABILITY ELLIPSES FOR CELIA
NATIONAL HURRICANE CENTER, MIAMI, FLA. INITIAL TIME 8/2/70 1800 GCT

FIGURE 12

movement, not more than twice nor less than half the speed of movement of the storm in question. The analogues are selected from cases which occurred within a specified number of days of the occurrence of the present storm in question. This system, developed by Neumann and Hope (1970) composites the analogue samples into a mean track for successive periods up to 72 hours and computes 25 and 50% probability ellipses for the center location after 24, 48, and 72 hours. It is the goal of the Warning Service to issue a hurricane watch approximately 36 hours before the center reaches a coastline. The HURRAN method is used to identify the appropriate coastal sector for the Watch in the following manner: When the 48-hour ellipse moves inland, tangents are drawn connecting the extremities of the 48-and 24-hour 50% ellipses. The sector of coastline enclosed by the tangents is identified as needing a Hurricane Watch.

Predicting the Landfall (a 24-Hour Forecast). The HURRAN computation is the most conservative predictor of hurricane movement presently available. While it obviously will perform less effectively when there are large seasonal circulation anomalies, the average displacement error for HURRAN during the 1970 season was lower than either the NHC-67 or the Sanders Barotropic (SANBAR) prediction methods. Tables 1 and 2 below compare forecasts by these methods with the official forecasts from the National Hurricane Center.

Table 1.

ALL FORECASTS, 1970

FCST	Official		HURRAN		SANBAR		NHC-67	
PERIOD	nm	cases	nm	cases	nm	cases	nm	cases
12	40	(46)	38	(31)	68	(8)	42	(40)
24	76	(34)	83	(25)	138	(11)	92	(30)
48	187	(12)	160	(11)	218	(3)	260	(13)
72	356	(2)	337	(2)	431	(1)	480	(2)

Table 2.

HOMOGENEOUS SAMPLES, 1970

FCST PERIOD	cases	Official nm	HURRAN nm	SANBAR nm	NHC-67 nm
12	(7)	40	38	65	36
24	(10)	71	94	134	83
48	(2)	145	274	241	373
72	(1)	417	689	431	659

72-HOUR TRACK PREDICTION

DECISION PROCEDURE

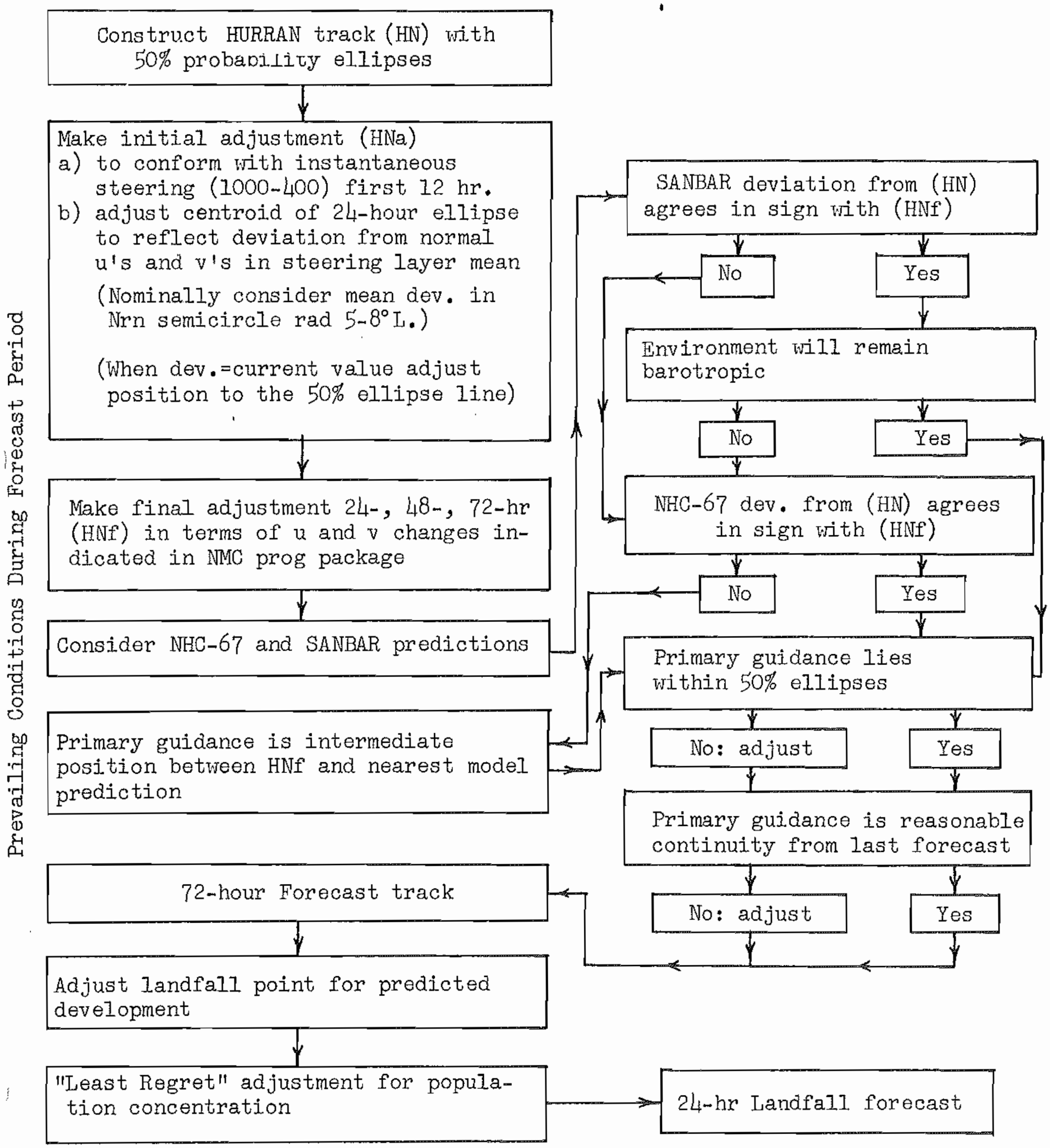


Figure 13

All forecasts of hurricane displacement are based upon the HURRAN track as a first approximation, with successive adjustments made to account for seasonal anomalies and for large scale circulation changes anticipated by the NMC prognostic charts. The decision procedures and ladder for constructing the 72-hour track and for identifying a specific 24-hour landfall position are presented in Figure 13. All adjustments are required to remain in the respective 50% probability ellipses, except where a vortex has become stationary and its future movement is uncertain. In this event the vortex will be predicted to remain stationary within the 12-or 24-hour ellipse for all periods up to 72 hours.

The first adjustment of the centroids (HN) of the 50% ellipses is to the 12-hour position. The adjustment here is to conform with the instantaneous vortex movement implied in the steering layer mean circulation. The second adjustment is to the 24-hour (HN) position. Here the u and v components from the steering layer circulation over a sector 5-8° L from the center in the northern semicircle are compared with the monthly normal values. The anomalies of the last 10-day mean u's and v's are compared with the anomalies for the latest observation to determine whether a decided trend is present. If so an intermediate value of anomaly is applied in adjusting HN. For positive u anomalies HN is adjusted eastward, if negative westward, and similarly for v anomalies the adjustment is to the north or south.

Insufficient experience is available to derive a useful regression for these adjustments. However, as a guideline, the forecaster is asked to adjust HN to the edge of the elliptical area if the anomaly of each component is of the same magnitude as the current value of the component. In no case is the adjustment extended outside the elliptical area. The new 12-and 24-hour adjusted positions are designated HNa.

The final adjustment for 24-,48-,and 72-hour positions is made in terms of the changes in u and v components anticipated by the NMC prognostic charts. Again, the adjustments are limited to the elliptical area.

The track connecting these final adjusted positions (HNf) is the basis for selecting or deriving the primary guidance for predicting vortex movement. The two principal methods for predicting movement are the SANBAR and the NHC-67.

The SANBAR (barotropic prediction) Technique for vortex displacement (see Sanders, 1968, and Sanders and Burpee, 1968) is the best available dynamical prediction model. This forecast is made from a deep layer mean circulation. It suffers at times due to lateral boundary transport problems; however, when this method predicts a track which follows closely the instantaneous steering of the deep layer mean for the first 12 hours, and does not deviate substantially from the adjusted HURRAN track for the second 12 hours, it generally offers the most dependable prediction of landfall.

The NHC-67 Prediction Method. The NHC-67 technique developed by Miller, Hill and Chase (1967) and Miller and Chase (1966) is a statistical screening method which predicts the track of a hurricane for periods up to 72 hours on the basis of the current analysis and observed tendencies. Because of limitations in the regression data over Central America, in the Eastern Atlantic, and generally south of the 15th parallel, its performance is most likely to be dependable in the Western Atlantic and Eastern Gulf of Mexico. Prior to the development of the Sanders Barotropic Prediction model the NHC-67 was the most used objective prediction tool available to the forecaster at NHC. The primary limitation of its use is the difficulty in conducting error analyses of the prediction in real time. It draws upon predictors which range over a wide geographic area extending to the Pacific Northwest and eastward to the vicinity of the British Isles.

As in the case of the SANBAR prediction, the first criterion in assessing the validity and usefulness of NHC-67 predictions is the degree to which they follow the instantaneous steering of the deep layer mean during the first 12 hours and the adjusted HURRAN track the second 12 hours. Other factors equal, the NHC-67 solution is to be favored over the SANBAR solution in the presence of a strongly baroclinic environment, or when the vortex is approaching such an environment.

Several other unofficial methods are available and have often been considered by the forecaster. However, as indicated earlier, these methods frequently produce very conflicting results and the forecaster has had few objective means for selecting one over the other. A good example of the confusion that sometimes occurs from a variety of prediction results is shown in Figure 14.

The selection of the primary guidance, using HNf as a baseline, is outlined in the decision ladder in Figure 13 and illustrated in Figure 15. The SANBAR prediction becomes the primary guidance if it lies in the same elliptical sector as HNf, providing the vortex is not expected to be largely influenced by a baroclinic environment. If these two conditions are not met, NHC-67 becomes the primary guidance providing it lies in the same elliptical sector as HNf. If neither qualify as primary guidance, the forecast track is constructed to fit 24-,48-,and 72-hour positions which are located intermediately between HNf and the nearest guidance positions, either NHC-67 or SANBAR.

Final Adjustments to the Track Leading to Landfall. The track of a hurricane which is rapidly changing in intensity tends to be subject to a displacement---not a translation---toward or away from the sector of strongest pressure gradient. Nominally, if a hurricane is developing rapidly its center will be displaced towards the sector of strongest pressure gradient, and when it is decaying rapidly will be displaced in the opposite direction. This is a kinematic accommodation of increasing (or decreasing) vorticity of the system. During the rapid decay it will be displaced slightly to the left of the steady state projected path. Such changes will not be anticipated by any of the prediction models and must be made subjectively by the forecaster.

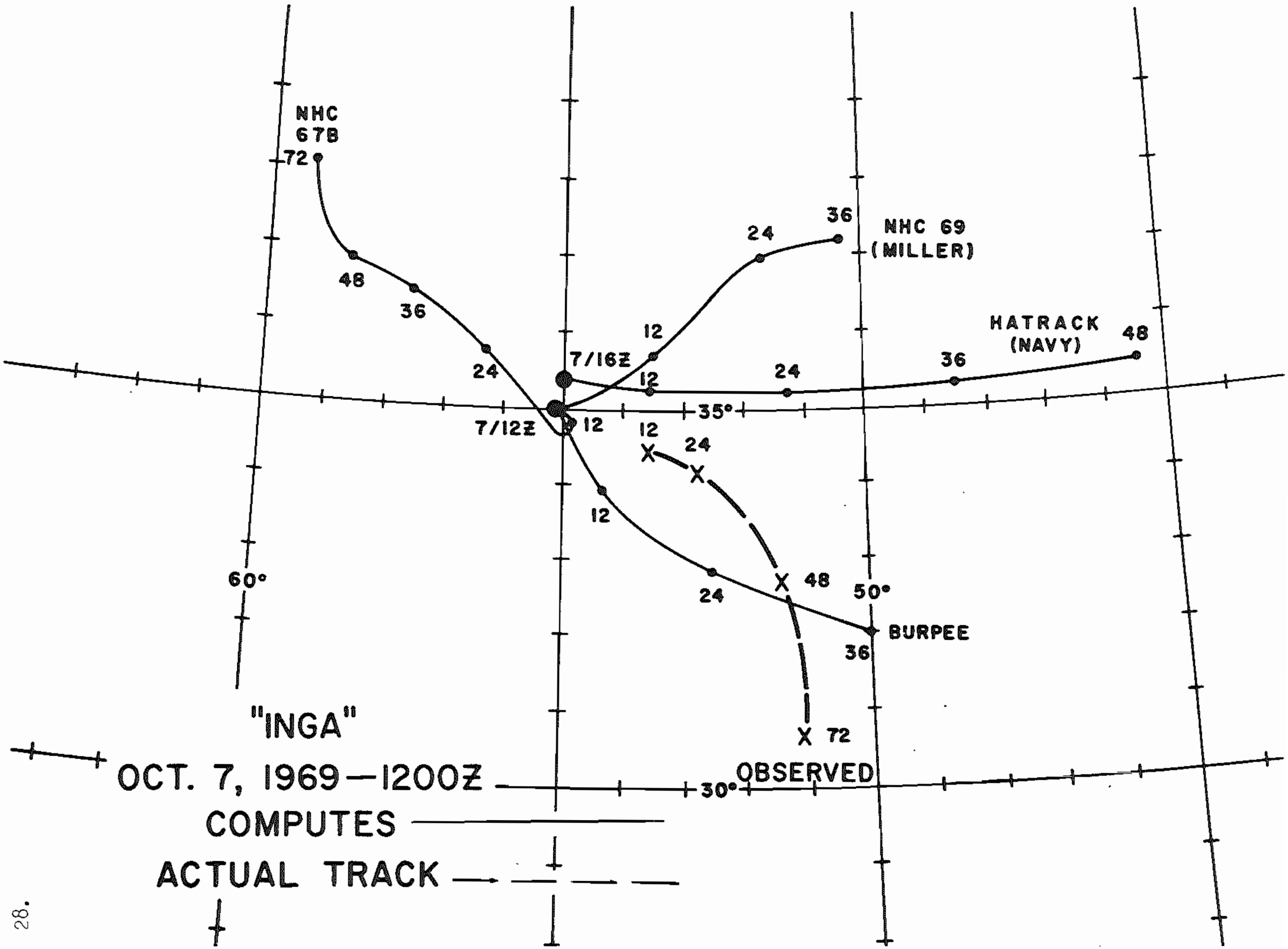


Figure 14. Verification of Various Objective Techniques for Predicting Hurricane Movement During Hurricane Inga, October 7, 1969. All computations are based upon 1200 GCT data. The case shown is an extreme example of the differing inferences concerning movement which may be drawn by the forecaster in trying to apply two or more objective prediction methods.

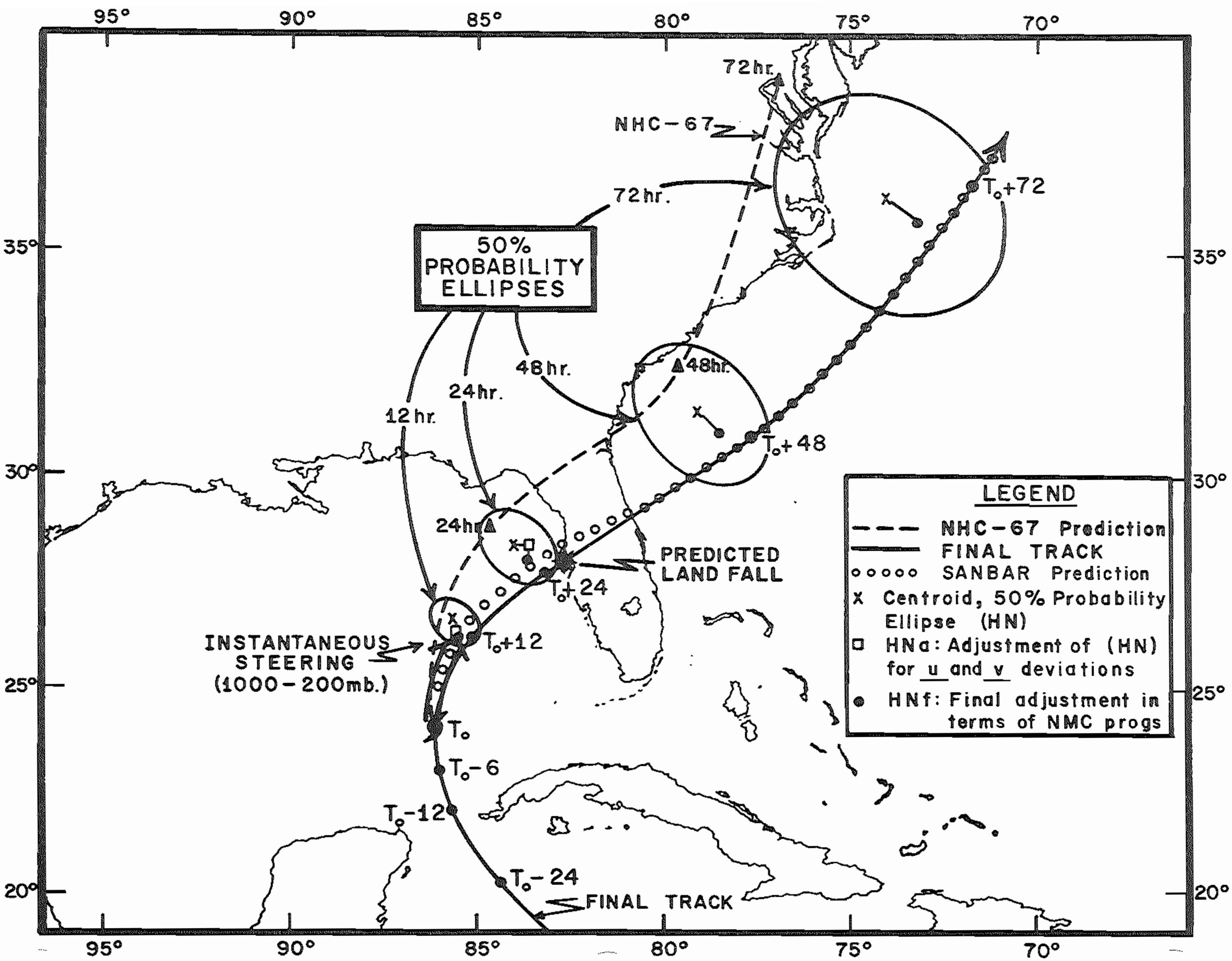

95°
90°
85°
80°
75°
70°
35°
30°
25°
20°
50% PROBABILITY ELLIPSES
12 hr.
24 hr.
48 hr.
72 hr.
NHC-67
72 hr.
48hr.
24hr.
T_o+72
T_o+48
T_o+24
T_o+12
T_o
T_o-6
T_o-12
T_o-24
FINAL TRACK
PREDICTED LAND FALL
INSTANTANEOUS STEERING (1000-200mb.)
LEGEND
NHC-67 Prediction
FINAL TRACK
SANBAR Prediction
x Centroid, 50% Probability Ellipse (HN)
HNa: Adjustment of (HN) for u and v deviations
HNf: Final adjustment in terms of NMC progs

Figure 15.

The final adjustment of the track is that which, in the face of uncertainty about the point of landfall, follows the "course of least regret" relative to population centers where large numbers of people may have to be evacuated from exposed beaches.

PREDICTION OF STORM SURGE

Until recently the prediction of maximum storm surge heights and high water profiles has been done in a very subjective fashion, relating the maximum heights primarily to central pressure. Since large variations in these heights can be expected in connection with various configurations of the coastline and variations in normal water depth near the coast, these forecasts have involved gross approximations.

Beginning with the 1970 season, however, a new machine computation technique was available to the forecaster for predicting storm surge maximum heights and water profiles relative to the center. This technique developed by Jelesnianski (1967) produces a profile of water heights with respect to the predicted landfall and provides alternate profiles in the event the landfall errs by 100 miles to the right or to the left of the predicted point. This method has proved itself admirably, first in a research environment during 1969 and in operations in 1970. Even in Camille, an extreme hurricane, the technique predicted a maximum storm surge of 25 feet, which is within a foot of the observed maximum height. Figure 16 shows a machine printout of the profile used by forecasters in predicting storm surges in Celia.

TORNADOES AND FLASH FLOODS

Tornadoes sometimes pose a major hazard in hurricanes, as the eye approaches the coast. In Hurricane Beulah there were at least 49 tornadoes observed inland. The precise conditions which trigger tornadic activity in the hurricane spiral rain bands is not known. However, Gray* hypothesizes, and presents some data in support of the notion that the increase in vertical shear as hurricane force winds in the boundary layer move inland, involves a local tilting of the vortex tubes which generate tornado funnels. The general location of tornadoes is primarily in the right front quadrant generally outside the area of hurricane force winds and near the threshold of sustained gale force winds. The distribution of tornadoes in hurricanes reported by Smith, (1965) is shown in Figure 17. A similar distribution was reported in a Gulf of Mexico Study by Hill, Malkin, and Schutz (1965).

The initial index to the wetness or the potential for heavy rains in a hurricane is from meteorological satellite pictures of the storm core. Where many spiral rainbands of penetrative convection contribute to an exceedingly bright core near the center very heavy rainfall rates are observed. These rainfall rates can be more precisely

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*Gray, W.: "On the Development of Tornadoes in Hurricanes", Seminar at the NHC, April 16, 1970.

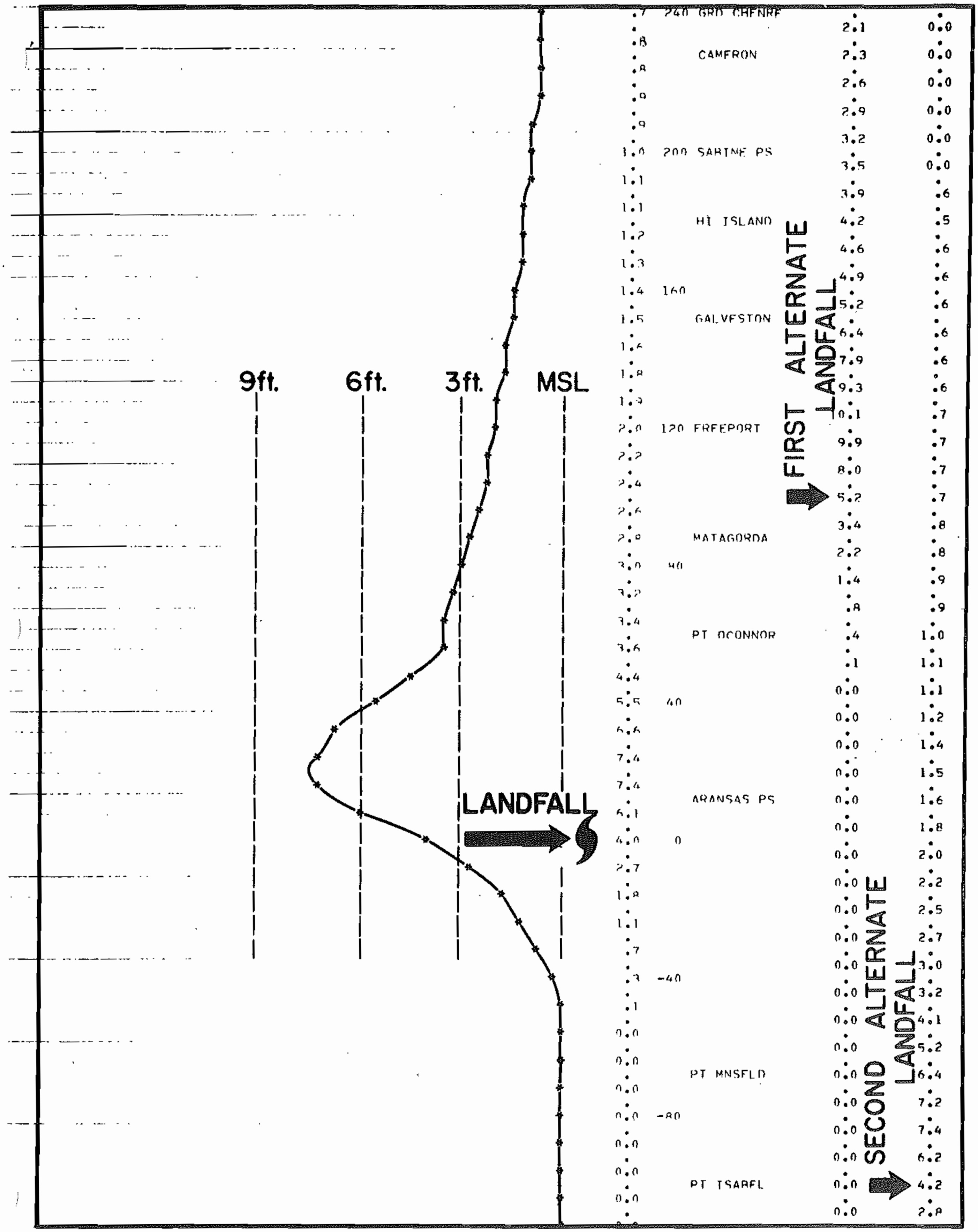

Fig. 16 STORM SURGE PROFILE

verified when the storm comes within range of land based radar. The problem which the forecaster faces is not simply the estimate of total rainfall accumulation at a single spot, but rather the areal potential for a flash flood which may develop if the soil is already saturated or if the storm moves inland in a mountainous or hilly area, or if the vortex stalls under circumstances which permit it to continue depositing heavy rains for many hours after winds have decayed to less than gale force.

On some occasions a hurricane, whose lower troposphere circulations have decayed, retains a vigorous circulation in the upper troposphere carrying its mechanisms for vertical motions far inland. When the system encounters a baroclinic environment or a mountainous terrain, torrential rains may develop and create devastating floods within hours, even though the system may have been a relatively low rain producer in its earlier history. Camille was such a storm in 1969 as it moved over the Virginia and West Virginia mountains. On such occasions the forecaster can only remain alert to the potentiality of such floods and draw upon radar vigilance to monitor the initiation of heavy rains.

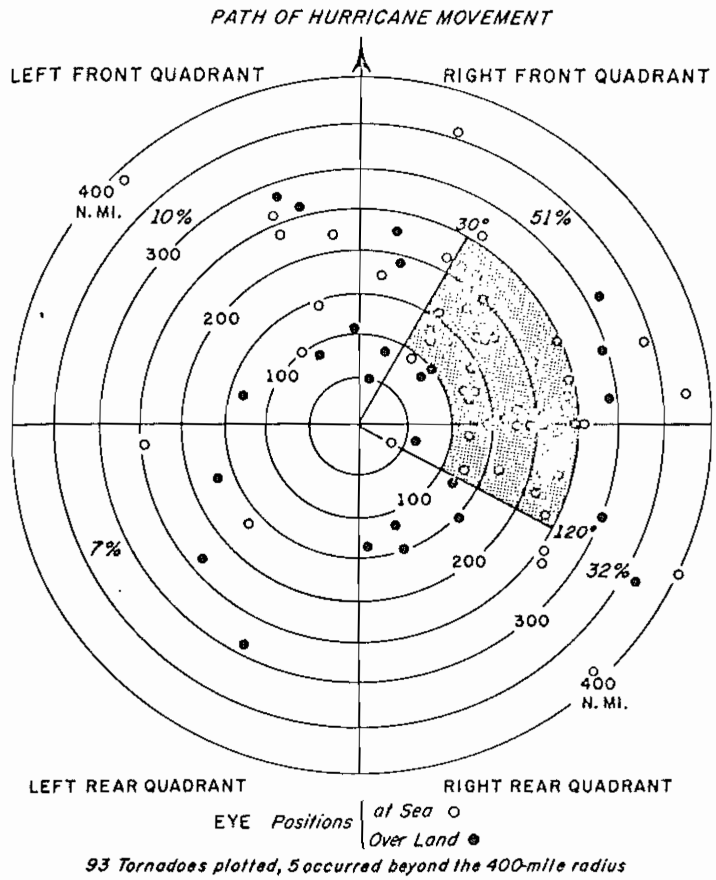

Figure 17. (After Smith, 1965) Tornadoes associated with hurricanes (1955-62) with reference to center and direction of movement of the hurricanes. Hurricane center positions at sea and over land are shown by open and solid circles respectively. Range marks are 50 nm apart. "Significant Sector" (shaded area) contains 56 percent of the tornadoes.

CONCLUDING REMARKS

From these discussions it is clear that the success of a hurricane forecast depends upon much more than the prediction of displacement of an ideal vortex in terms of the changes which may occur in the environment. One of the most critical tasks is that of the initial data problem which involves careful analyses in the immediate environment of the vortex, and of the vortex itself. This can be accomplished only by more precise and systematic acquisition and processing of data from the vortex and its environment by reconnaissance aircraft and by meteorological satellite. It is unlikely that either of these can fully meet the data acquisition requirements in the foreseeable future.

The effectiveness of warnings for a major hurricane depends mainly upon the ability to predict accurately the landfall position of the vortex center at least 24 hours in advance. This depends in turn upon the forecaster's ability to locate the center precisely at the time of the forecast, and the accuracy of the vortex displacement prediction. The former can and probably will become a near certainty with the installation of improved aircraft reconnaissance systems and of ground processing facilities for data acquired by these aircraft. The latter poses a number of less tractable problems, not the least of which is the effective parameterization of interactions between meso-convective scales of motion in hurricane vortex with the synoptic scales of motion in the environment. It may well be a decade or more before storm modeling research identifies the mechanism involved and clarifies the initial data problem, and technology provides a means of effectively acquiring the data needed for more reliable and timely predictions of hurricane landfall.

Meanwhile, the decision procedures described here will provide not only a means of constraining the subjectivity of choice by the forecaster, but will provide a systematic means of organizing and critiquing the prediction experience in each hurricane. Each rung in the decision ladders as presently defined comprise a postulate drawn from the inferences of new found knowledge of the hurricane structure and energetics, or from forecaster experience. As such they provide a means of applying scientific methodology to expand the baseline of knowledge as each rung is replaced successively by a more intelligent postulate based upon forecast experience.

Through these means hurricane prediction as practiced today is beginning to emerge from its perennial classification as an art to one which systematically applies science and engineering to decision making processes.

ACKNOWLEDGMENTS

This paper reflects the collective experience and many staff discussions of these experiences with the hurricane specialists at the National Hurricane Center. I wish to recognize particularly the wise council and contribution of Mr. Arnold Sugg, Dr. Neil Frank, and Dr. Banner Miller. Messrs. Robert Powell, Robert Carrodus, and Dale Martin assisted with the graphics, and clerical and secretarial services were provided by Ruth Goodin and Lilas Wilson.

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