U. S. DEPARTMENT OF COMMERCE
ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION
Weather Bureau

ESSA Technical Memorandum WBTM SR-50

A REASSESSMENT OF THE HURRICANE PREDICTION PROBLEM

SOUTHERN REGION HEADQUARTERS
SCIENTIFIC SERVICES DIVISION
FORT WORTH, TEXAS
February 1970

A REASSESSMENT OF THE HURRICANE PREDICTION PROBLEM

Robert H. Simpson, National Hurricane Center, Miami

(Paper presented at the AMS Technical Conference, Miami Beach, 12-2-1969)

INTRODUCTION

This paper presents an assessment of the hurricane prediction problem from the perspective of the hurricane forecaster trying to identify sources of error, and searching for more objective means of making forecast decisions.

The hurricane forecaster needs to generate numbers relating to the development, movement, and storm surge potential of the tropical cyclone for each advisory he prepares, usually 4 times per day. These quantities are physically part of a continuum. However, the present state of our knowledge is such that each must be dealt with as a separate prediction problem involving procedures and models which are considerably "truncated". In many instances the forecaster must fall back on diagnostic tools and the extrapolation of instantaneous tendencies. We may list several reasons why prediction models remain so limited and inflexible in reflecting the changing character of the hurricane:

1. The tropical atmosphere is a two-layer circulating system, each layer structured and behaving as if it were independent of the other.

2. The problem of development and intensification now appears to depend upon subtle interactions between synoptic and convective scales of motion.

3. Machine analyses of circulations upon which predictions are initiated are error prone in the tropics where gradients are small, observations are widely spaced, vorticity is reflected mainly in horizontal shear, and divergence as frequently through wind speed gradients as through confluence.

Until analyses are improved, it will be difficult to deal effectively with the first two problems.

The two-layer atmosphere, properly analyzed, offers little difficulty for a sophisticated numerical model providing the boundaries are sufficiently remote from the hurricane system. Otherwise, however, the lateral boundary conditions for the lower and upper troposphere may need to be specified differently.

While it may be hopeless to seek observations which will directly describe the interaction between convective and larger scales of motion, it is quite possible to attack this problem by parameterizing the convective scale of motion using satellite cloud data.

The solution to none of these problems is clearly in view, and a considerably greater investment of resources must be made if real progress is to be expected soon.

STORM SURGE

Probably the most advanced of the prediction procedures is that of the storm surge or total storm tidal effect. Using the Jelesnianski model (1), an excellent approximation can now be quickly obtained for storm surge heights providing corrections for coastal profiles are known and the landfall of the storm and its intensity is well predicted. The greatest shortcoming of storm surge predictions at present comes from uncertainty as to the storm's landfall and intensity.

DEVELOPMENT

Most numerical models including those of Ooyama (2) and Kuo (3) show clearly that by clever parameterization of heat fluxes from sea to air, hurricanes inevitably and regularly develop within a typical tropical atmosphere. The problem is that so few hurricanes do occur. Only 1 out of 10 hurricane seedlings reach storm or hurricane intensity. The real challenge is to identify the constraints to development. Equally interesting and important is the need to understand why so many hurricanes bypass the tropical storm stage and go quickly to full hurricane intensity as in the case of Camille, while many others linger for days in the tropical storm stage as in the cases of Anna, Inga, and Kara of 1969. Finally, there is the problem of hurricane dissipation over warm tropical oceans. Each year one or more mature hurricanes collapse within an environment that by cursory inspection should clearly support hurricane intensity. Some tropical cyclones degenerate into an open wave and disappear entirely while others later regenerate. Changes of this kind could result from several causes:

1. Changes in the fueling of the system, either by lateral advection or in the sea-air fluxes.

2. The restriction of mass transport in the inflow or in the outflow layers.

3. Large scale changes of vorticity in the storm environment.

An investigation---still incomplete---of cases in which dissipation occurred over warm tropical waters suggests that this may result from the constriction of mass circulation in the outflow layer. In Fig. 1, consider what happens when a hurricane system approaches an upper-tropospheric shear line. A shear line of this kind is a semi-permanent feature in mid-Atlantic in summer. As the system begins to approach the wind speed maximum south of the line, the advection of vorticity associated with the horizontal shear accelerates the mass circulation. Here an initial intensification of the system may occur. However, as the system proceeds beyond the wind speed maximum, the opposite effect

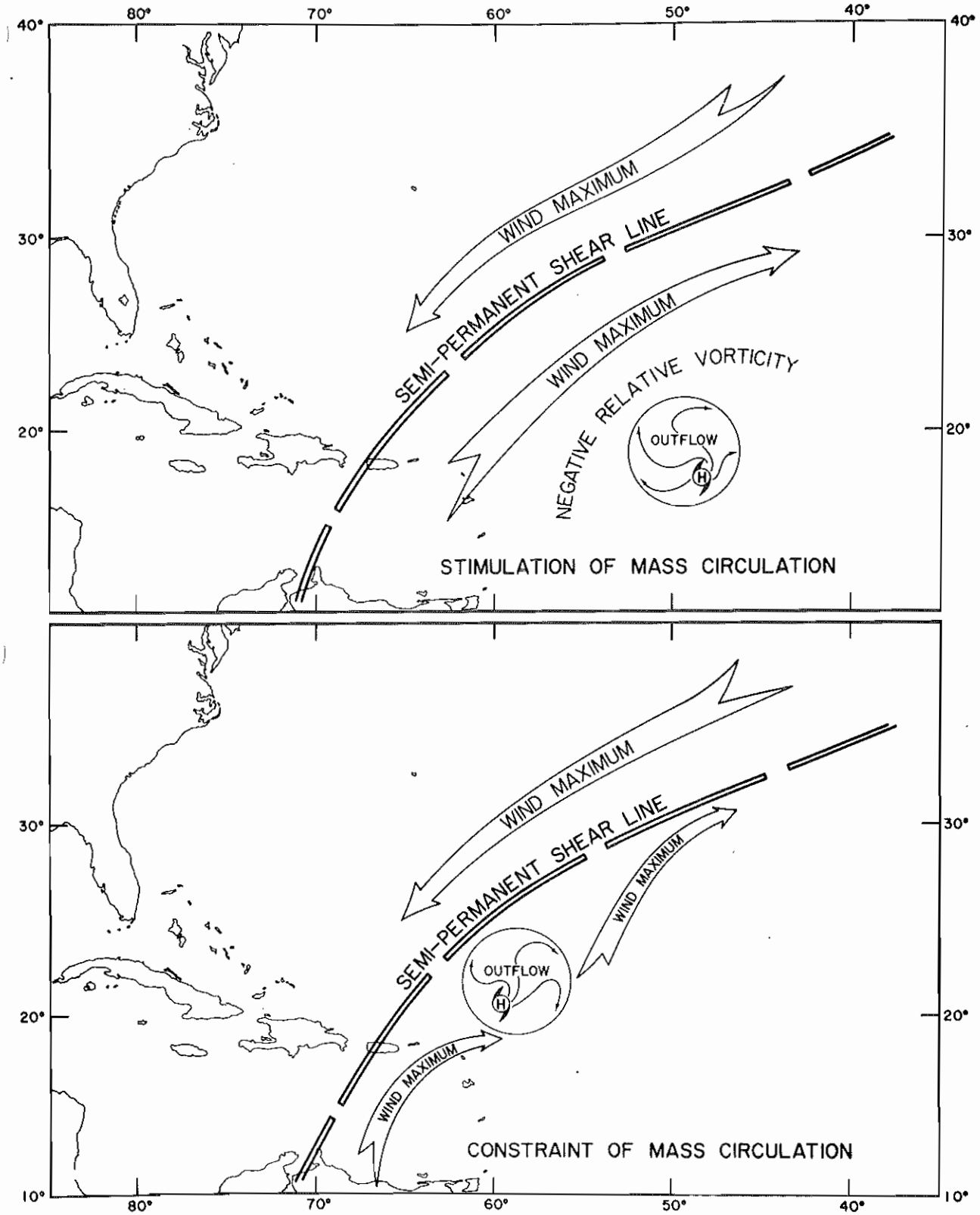


Figure 1. Role of the Upper Atlantic Tropospheric Shear Line in Stimulation and/or the Constraint of Mass Circulation in a Tropical Cyclone. As the cyclone approaches the wind maximum south of the shear line, mass circulation in the cyclone is stimulated. As the cyclone passes between the wind maximum to the south and that to the north of the shear line, mass circulation is constrained.

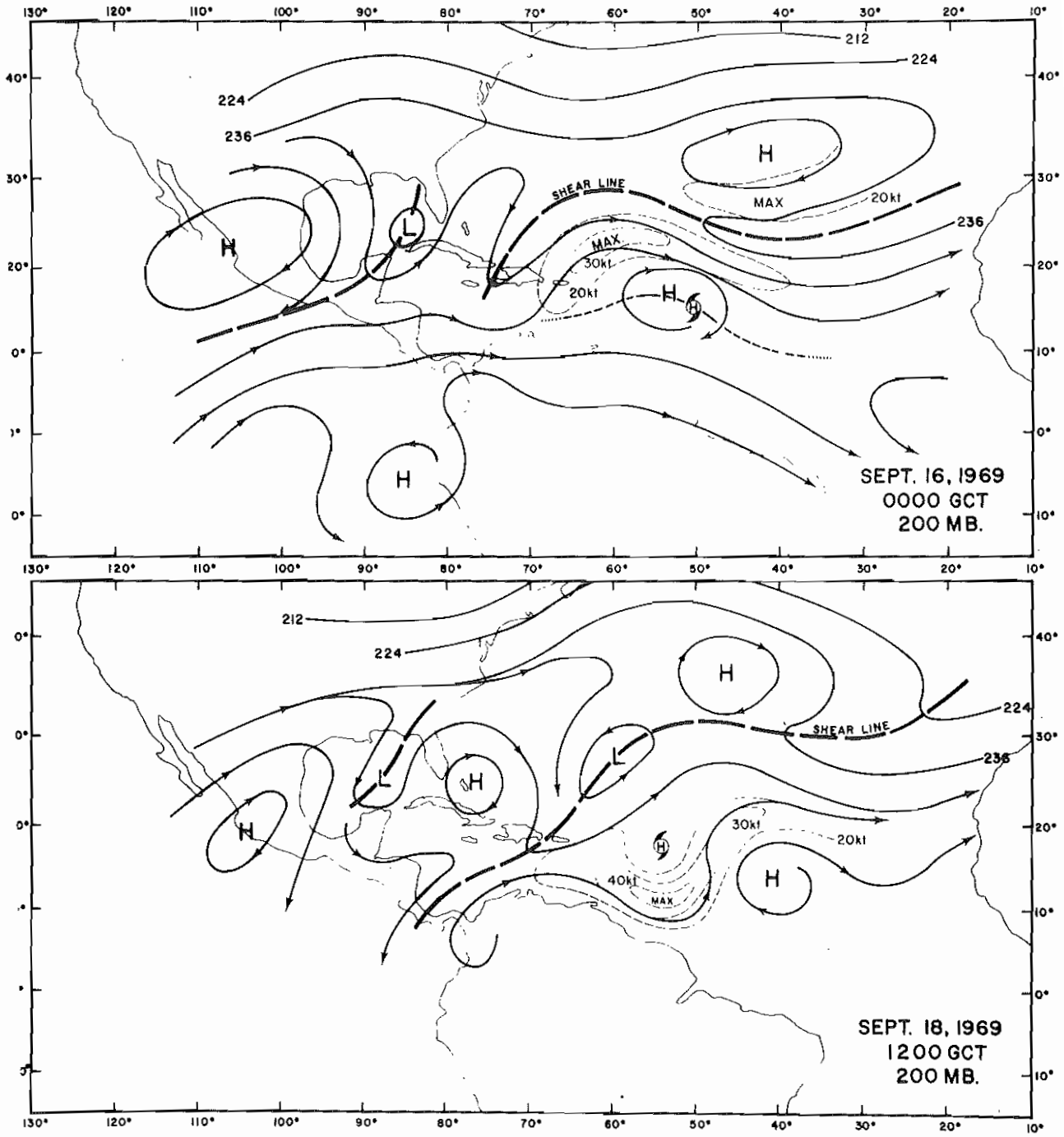


Figure 2. Influence of the Upper Troposphere Shear Line on the Development of Hurricane Holly. As Holly initially approached the shear line, it rapidly intensified to hurricane force. In this instance the shear line provided a field of anticyclonic shear as an environment for the outflow of the cyclone. Subsequently, as the cyclone proceeded westward to a point where the shear line provided an environment of cyclonic shear for the outflow, the cyclone rapidly lost intensity.

develops and persists, restricting the divergence fields and constraining mass circulation. Under these conditions hurricanes may lose intensity rapidly. Fig. 2 shows an example of such a development in Hurricane Holly September 16-18 this year.

Conditions for Development. No one has published a list of environmental conditions which are considered sufficient for tropical cyclone development. Palmen, Riehl, Dunn, J. Simpson, R. Simpson, and others have directed attention to various "necessary" conditions applying individually to the character of the outflow or inflow layers to ocean temperatures, sea-air heat fluxes, and ventilation of the incipient vortex. From experience in trying to apply these research results, the National Hurricane Center looks for the following conditions to be present if tropical cyclone development is imminent:

a. The presence of deep moist easterly flow from the surface through the middle troposphere over a radius of at least 400 miles of a pre-existing depression center.

b. Sea surface temperatures predominantly warmer than 27° C in the same area.

c. In the lower troposphere, an anticyclone or ridge which may serve as a mechanism for mass transport towards the depression center over a sector of more than 90 degrees, and with cyclonic relative vorticity in this sector extending outward at least 300 miles.

d. In the upper troposphere a thermal anticyclone usually of small dimensions making contact with a high speed baroclinic environmental flow which may conduct the effluent mass to a colder environment.

e. Vertical shear between mean lower troposphere wind and mean upper troposphere wind of less than 15 knots within a radius of 400 miles of the depression center.

f. Above normal temperatures at 500 and 200 mb within a radius of 400 miles of the center.

It is quite clear, however, that these conditions are not sufficient for hurricane development. We are persuaded to believe that those subtle features which complete the conditions for development involve either (1) the interaction of convective and synoptic scales of motion, or (2) certain asymmetries in the incipient synoptic or sub-synoptic scale circulation, or (3) the coincidence of unique S_2 wave (solar-lunar tides) values, or a combination of these.

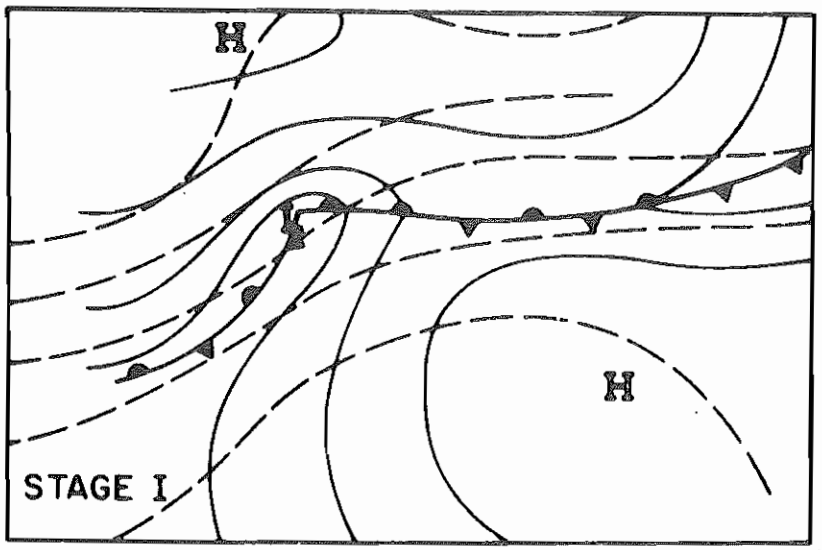
Tropical Cyclogenesis in a Baroclinic Field of Motion. In recent years the hurricane forecaster has been forced to acknowledge that baroclinic fields of motion sow many seeds from which tropical cyclones of full

hurricane intensity may grow. During the last 20 years 1 out of 5 tropical cyclones in the Atlantic has had its origin from seedlings which were products of baroclinic circulations and developed and lived its entire life in temperate latitudes. In these cases the initial emphasis for development comes from pressure falls or vorticity fields produced and supported by baroclinic energy releases. In some instances the system sustains gale force wind. Subsequent development depends upon latent heat energy sources as the environment gradually acquires a more barotropic character. This kind of development sometime referred to as sub-tropical cyclone development has been discussed by a number of authors including the present one, Simpson (4) and Ramage (5).

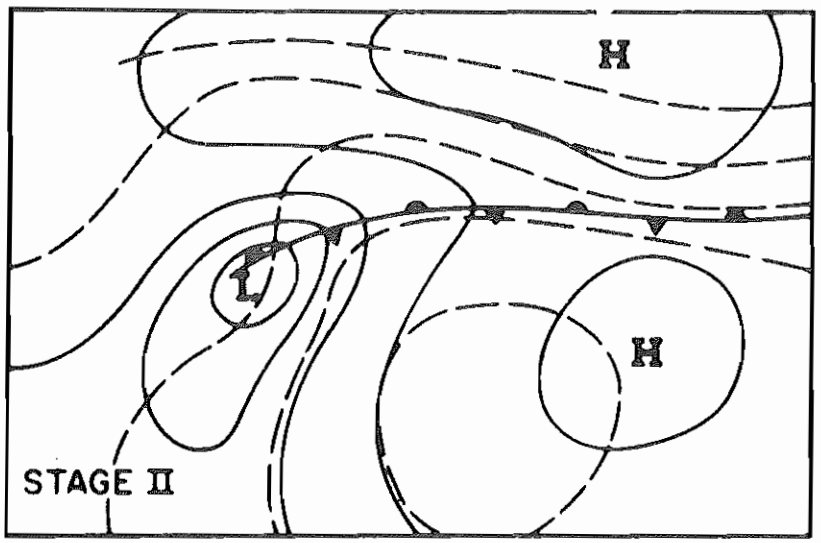
This is an intriguing and important problem for the hurricane forecaster because frequently it presents him with a potential crisis of a hurricane developing in his backyard, bringing a previously unannounced, immediate threat to some U. S. coastal area. Examples of such cases are Doria 1967, Dora 1963, and Eve 1969. The evolution of circulations in such instances is presented schematically in Fig. 3. Suffice it to say that predictions of development in real time must presently consist of successive approximations based upon diagnostic rather than prognostic tools.

MOVEMENT

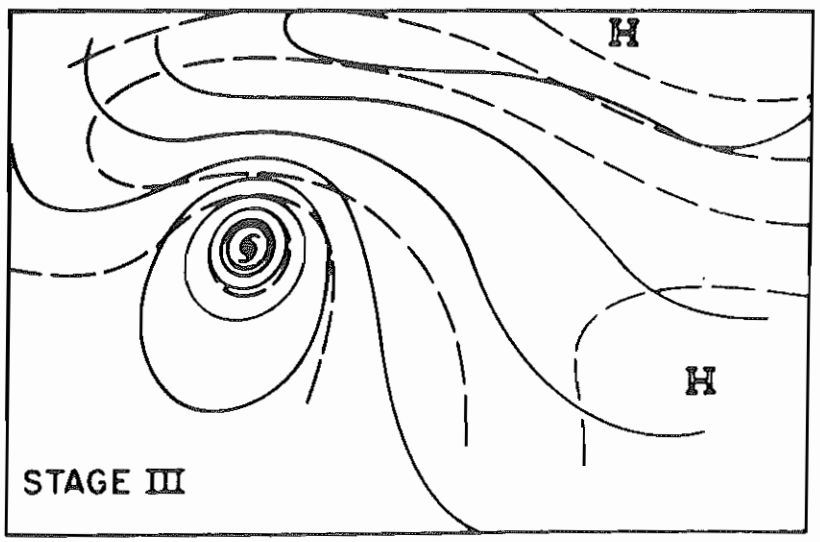
The most critical problem in hurricane forecasting is the prediction of changes in azimuth of the projected track. While the timing of arrival of the system presents difficulties in a few instances as in recurving fast moving storms reaching the New England and Long Island coasts, it is the direction of movement which determines the success or failure of a forecast. For a storm approaching normal to a coastline at 15 kts., a 24-hour prediction error of 10 degrees in storm course can provide a landfall error of 75 miles, or if approaching at a 30 degree angle to the coast, 120 miles. An intense hurricane might carry sustained winds of 180 mph. and 22 ft. storm tides for a limited area of the coastline to the right of center. Consider such a storm approaching, for example, the Tampa Bay area from the Gulf of Mexico (Fig. 4). If the center were predicted to cross the coast near Clearwater, the greater Tampa Bay area southward to Sarasota would need to be evacuated to higher ground inland, and maximum security measures taken for all structures. If, however, the prediction error were just 10 degrees and the center crossed to the south, maximum sustained winds in the Tampa Bay area would not reach hurricane force, and tides might actually be below normal. If the predicted and observed landfall positions were reversed, adequate preparedness measures might not be completed in time. Within reasonable rationalization we were vulnerable to just such an error in Camille this year, as is readily apparent from the successive objective movement predictions shown in Fig. 5.



A frontal wave has formed in subtropical latitudes. In lower layers warm moist air is fed into the system from the tropics while a migratory anti-cyclone to the north moves eastward.



The wave formed disappears as the baroclinic environment is modified, and pressure falls stem mainly from the release of latent heat. Associated with these releases are the rising heights at 500 mb to north of the low pressure system.



The environment has been modified to a near barotropic state, and pressure falls due to latent heat have continued as a circular storm with tropical cyclonic characteristics emerges.

Figure 3. Evolution of a Tropical Cyclone from an Initially Baroclinic Environment. Solid lines are surface isobars, and broken lines are 500 mb heights.

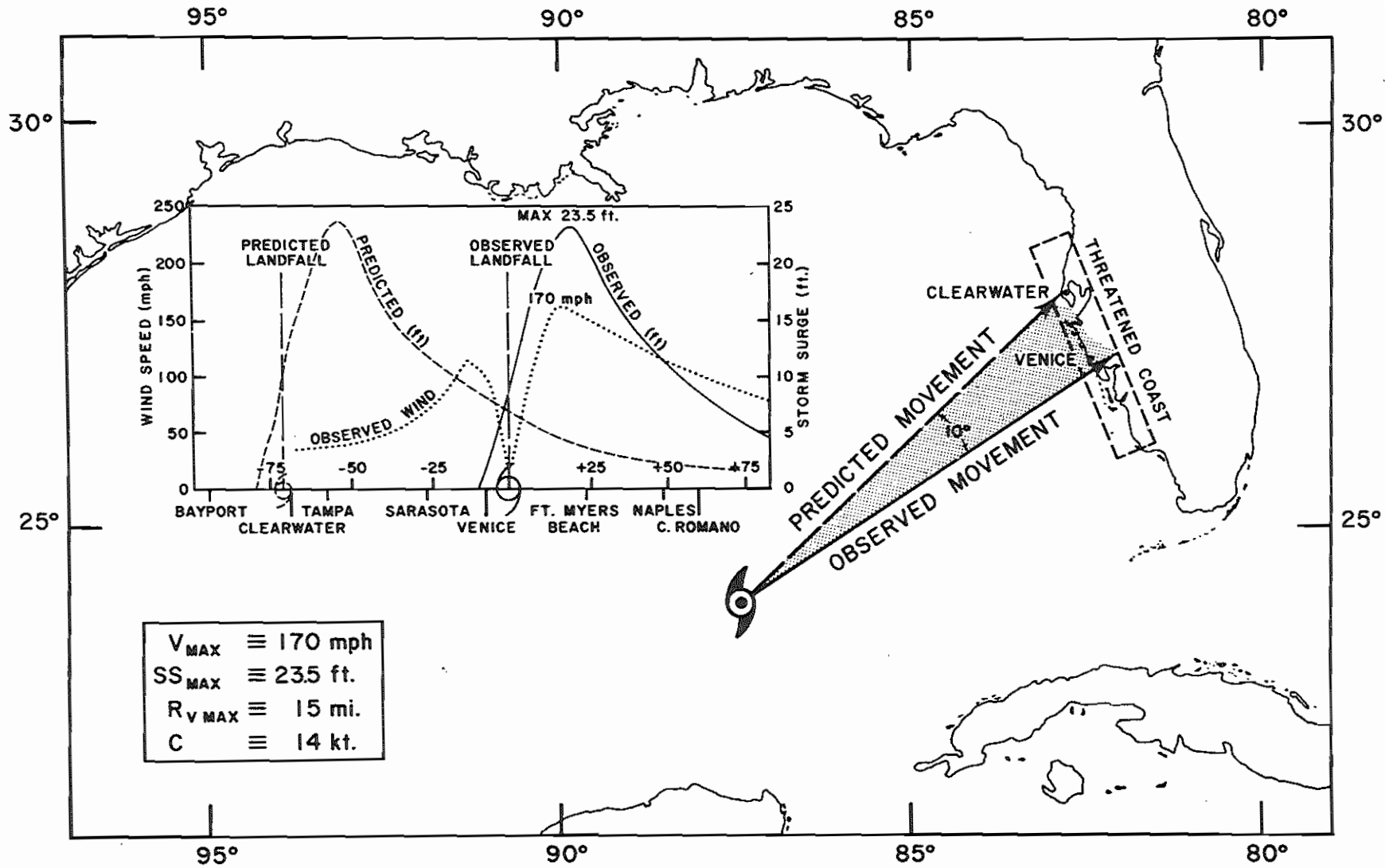


Figure 4. The Consequences of a 10° Error in Predicting the Track of a Hurricane. Warnings based upon wind and storm surge, if issued explicitly for the predicted landfall, would involve serious consequences for the coastal residents. In one instance protective measures and evacuations would have been 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.

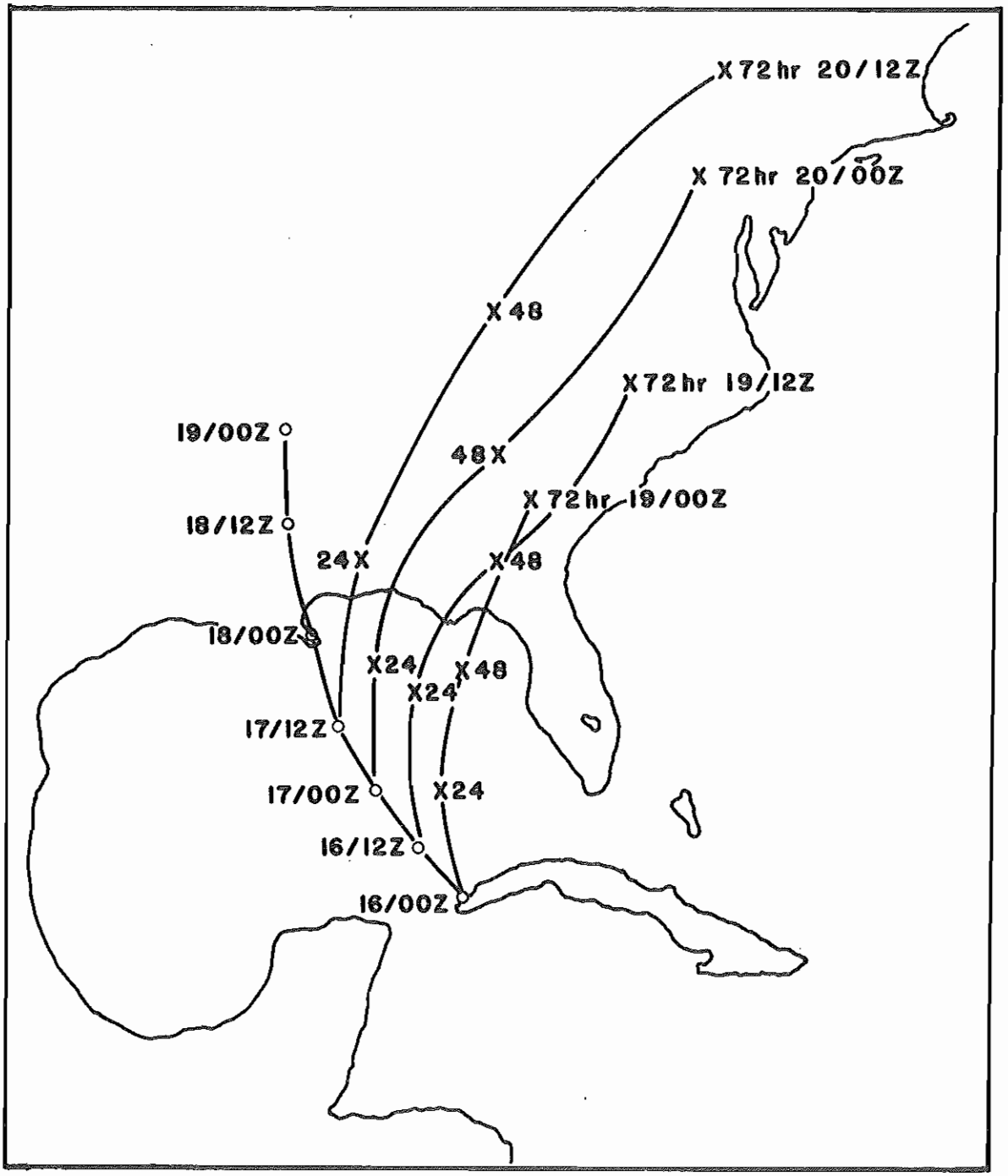


Figure 5. Verification of the Predictions of Movement of Hurricane Camille. The track which follows the open circles is the observed track of Hurricane Camille. The succession of tracks, all to the right of the observed movement, represent the 24, 48, and 72-hour predicted movements for successive periods using the official objective forecast technique at NHC.

The Steering Mechanism. The pressure change mechanism which accounts for movement of a hurricane center is as illusive and subtle as those for development. No physical numerical model of the hurricane and its environment has ever succeeded in predicting the movement and development of a hurricane to a useful approximation in real time. Yet, movement and development are so closely interrelated that to attempt a purely physical prediction of one without considering the other would appear to impose severe limitations on the prediction accuracy at the very moment the most important changes were occurring.

Nevertheless, because of the limits of understanding, and in part because of computational limitations, all operational numerical models have to consider movement and development as separate modeling problems.

To date most models for predicting movement input information from at most 2 levels, and most either eliminate the hurricane vortex or ignore the interaction of the vortex with the environment.

We have come a long way since the day when forecasters sought a "magic" steering level in the upper troposphere which gave a best index to the instantaneous and short period direction of motion. The Riehl-Haggard(6) method of computing the forces acting on the vortex at 500 mbs has given way to more sophisticated statistical screening methods which culminated in Banner Miller's method known as NHC-67. Miller, Hill and Chase (7) At present this is the main objective tool employed by NHC in predicting movement. This draws upon a large scale field of gradients and instantaneous tendencies to predict displacement for 12-hour increments up to 72 hours. It uses no prognostic charts. The weakness of this method is, first, its great sensitivity to errors of analysis and, secondly, it incorporates such a large number of predictors it is difficult for the forecaster to reason concerning the probable sources of error.

A recent method developed by Renard (8) eliminates the vortex and the perturbation components of hemispheric circulations and moves the point vortex with the remaining large scale circulation. Separate computations are made for 1000-700-500 and 300 mbs, and the forecaster is left to his own devices in choosing a steering level. Aside from this subjectivity the method, known as HATRACK, depends upon application of a vector correction based upon the observed errors in the first 12 hours of movement.

The Sanders-Burpee barotropic prediction model (9) described in the last paper is conceptually a giant step forward in dynamical prediction, mainly because it considers a deep tropospheric weighted mean wind as the basic medium for a simple barotropic prediction model. Whatever else has been learned from experience, it is clear that the movement of the hurricane vortex is influenced by the mean flow of a deep atmospheric layer, and that changes in any one layer tend to change the displacement of the vortex. The weakness of this model, as I view it, is first that for weak or moderate storms too much weight is given to the momentum of

upper layers. Secondly, it is exceedingly sensitive to the initial analysis, and has difficulty with boundary problems. NHC is working with Banner Miller to develop a model which varies the depth of mean flow as a function of the central pressure.

Operational Decisions. The forecaster normally has available in real time the NHC-67 computation, the Sanders-Burpee, and the HATRACK predictions as guidance in addition to the NMC 500 mb prog package. When extrapolation and climatology normally give reasonable solutions, these methods usually agree fairly well and are accurate. But when critical forecast decisions must be made and the circulation anomalies are large, these computations often produce quite conflicting solutions, and as might be suspected are much more error prone. An example might provide some indication of what the forecaster faces from his guidance. (Fig. 6)

When this happens the forecaster faces the need for leaning heavily upon diagnostic tools and subjectively upon his personal experience. The NHC is devoting a great deal of attention and effort to the development of diagnostic tools to reduce the subjectivity of decision making when the prognostic tools encounter error proneness, Simpson (10).

Diagnostic Tools. Fig. 7 shows the primary diagnostic tools in current use at NHC. These consist of a deep layer mean chart 1000-400 (increasing to 1000-200 mbs in more intense cyclones) for assessing the instantaneous steering, the geopotential forces across the vortex which accompany the present movement, and the instantaneous tendencies which may cause changes in the steering.

Two layers of equal weight, 1000-600 and 600-200 mbs, are used to examine the changing vorticity patterns in the hurricane environment at the inflow and outflow layers respectively. These provide an indication of the effectiveness of mass circulation and the efficiency of the heat engine.

The subtraction of the lower-mean winds from upper-mean winds provides a view of the mean vertical wind shear and of the troposphere mean temperature fields. Experience with this chart has shown that development does not occur when wind shears in the cyclone environment exceed 15 kts. (radius of 400 miles).

Finally, (Fig. 8) a new statistical analogue, known as the NHC HURRAN, Hope and Neumann (11) method, is applied to determine the most probable track of the hurricane. Suffice it to say here that this method, used experimentally this year, has provided impressive results, and next year will become the basis for objective decisions on the issuance of hurricane watches at coastlines.

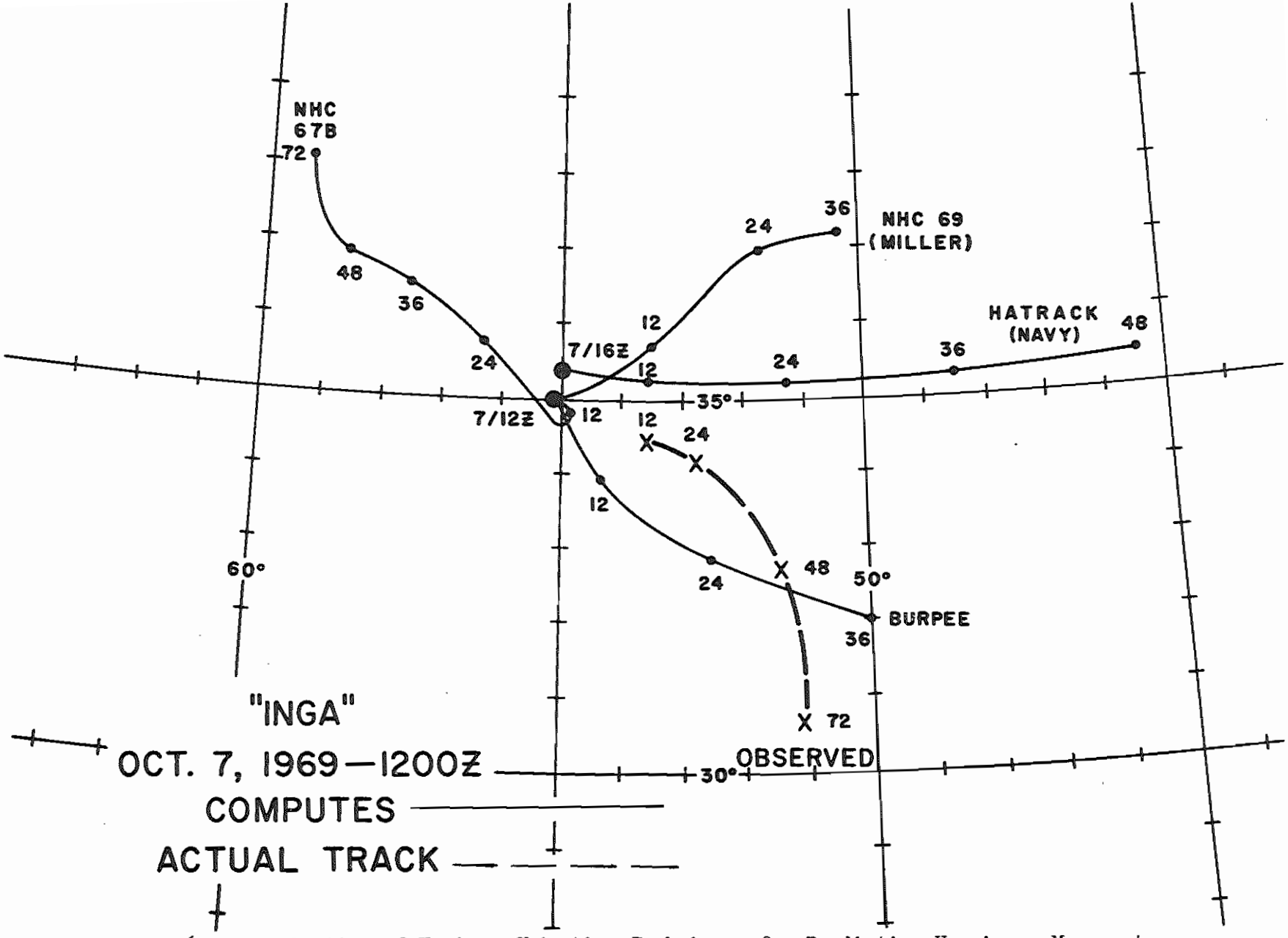


Figure 6. Verification of Various Objective Techniques for Predicting Hurricane Movement During Hurricane Inga, October 7, 1969. All computations are based upon 1200 GCT data. The case shown is an extreme example of the differing inferences concerning movement which may be drawn by the forecaster in trying to apply two or more objective prediction methods.

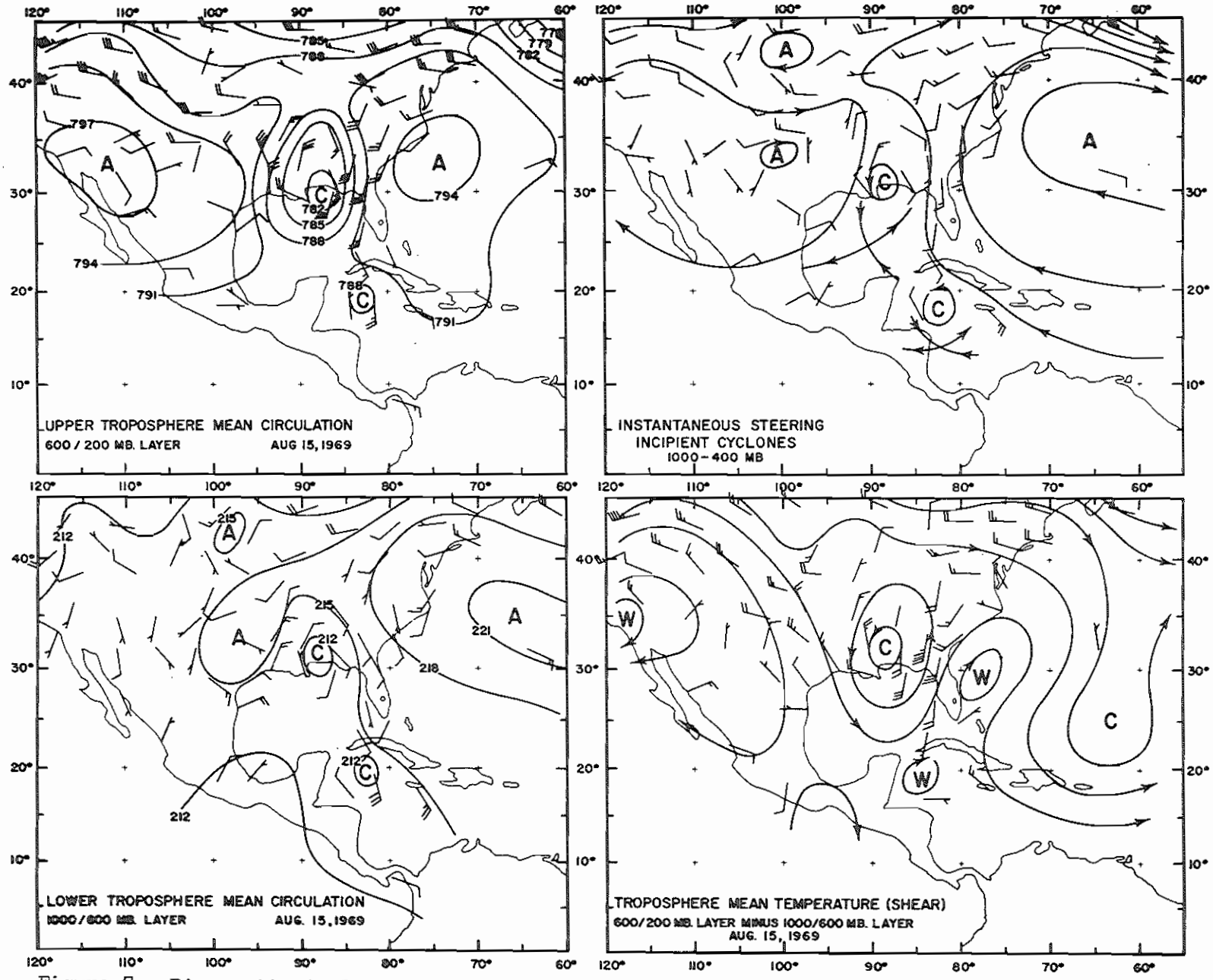


Figure 7. Diagnostic Analyses Used by the National Hurricane Center for the Detection and Tracking of Disturbances and for Predicting the Instantaneous Movement and Potential Development of Tropical Cyclones.

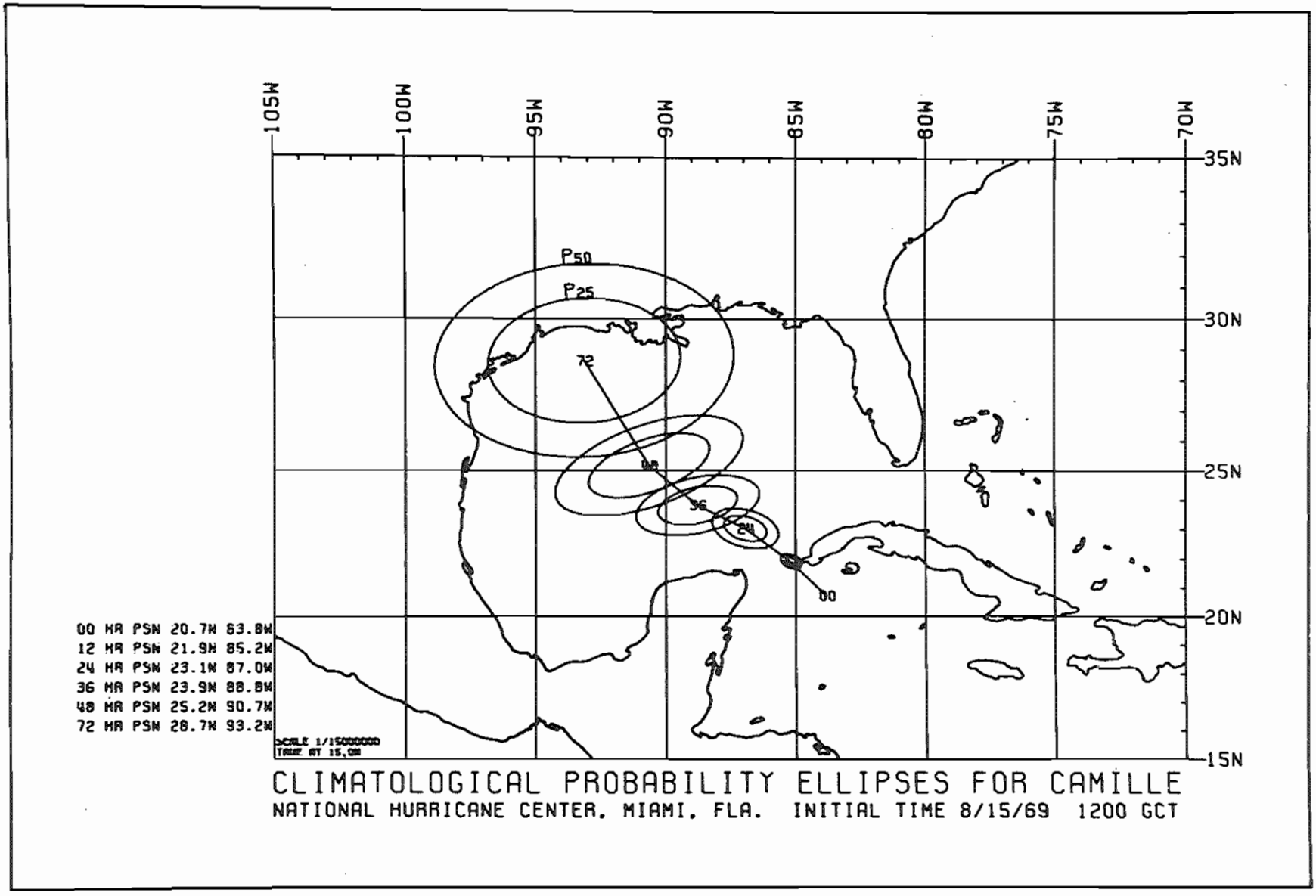


Figure 8. The HURRAN Method Used by the National Hurricane Center to Determine the Most Probable Track of Hurricanes. A present example is the 72-hour projection of the movement of Hurricane Camille. The family of ellipses for each predicted point along the track represents the 25% and 50% probability areas for hurricane position surrounding the most probable location.

The primitive equation prediction model of NMC for 500 mbs remains a very reliable tool for inferring movement, especially recurvature movement, north of the 30th parallel. However, south of this line, which includes over 70% of the forecast decisions, the progs are often more misleading than useful. This is mainly for two reasons. First, the error field is not conservative for low latitudes and, secondly, the tendency to predict trends toward a lower circulation index overplays the meridional components of movement. Nevertheless, for 48-72 hour movements, they are generally the best indicators of movement providing the center displacement of the first 24 to 36 hours has been properly predicted.

SUMMARY COMMENTS

The prediction of storm surge, the greatest killer, for a moving plane of reference fixed with the storm system is the least difficult of the forecaster's tasks. However, its effectiveness in hurricane preparedness measures depends entirely upon an accurate prediction of the hurricane landfall. This is the most difficult and important task, yet the one with the highest potential error.

The present understanding of hurricane dynamics, and our limited ability to observe and describe the storm in real time restricts the development and application of physical numerical models for predicting intensity and movement. The techniques which have been developed predict each of these individually, and are error prone at the times of most crucial decisions. Hence, the forecaster at present must lean heavily upon diagnostic tools for his most important forecast decisions.

The development of more sophisticated prognostic models will require considerable new resources, and their application when completed still additional resources, not only for costs of computation but also for more complete (probably airborne) surveillance and description of the hurricane and its environment as a starting point for the prognostic computations.

REFERENCES

1. Jelesnianski, C. P., "Numerical Computations of Storm Surges with Bottom Stress", Monthly Weather Review, Vol. 95, No. 11, 1967, - pp. 740-756

2. Ooyama, K., "Numerical Similation of the Life Cycle of Tropical Cyclones", Journal of the Atmospheric Sciences, Vol. 26, No. 1, 1969, pp. 3-40

3. Kuo, H. L., "On Formation and Intensification of Tropical Cyclones Through Latent Heat Release by Cumulus Convection", Journal of the Atmospheric Sciences, Vol. 22, No. 1, 1965, pp. 40-63

4. Simpson, R. H., "Evolution of the Kona Storm-A Subtropical Cyclone", U. S. Weather Bureau Manuscript, Honolulu, 1952

5. Ramage, C. S., "Problems of a Monsoon Ocean", Weather, Vol. 23,No. 1, 1968, pp. 28-37

6. Riehl, M., Haggard, W. H., and Sanborn, R. W., "On the Prediction of 24-hour Hurricane Motion", Journal of Meteorology, Vol.13, No.5, 1956, pp. 415-420

7. Miller, B., Hill, E. C., and Chase, P.P., "A Revised Technique for Forecasting Hurricane Movement by Statistical Methods", Monthly Weather Review, Vol. 96, No. 8, 1968, pp. 540-548

8. Renard, R. J., and Levings, W. H. III, "The Navy's Numerical Hurricane and Typhoon Forecast Scheme: Application to 1967 Atlantic Storm Data", Journal of Applied Meteorology, Vol. 8, No. 5, 1969, pp. 717-725

9. Sanders, F. and Burpee, R. W., "Experiments in Barotropic Hurricane Track Forecasting", Journal of Applied Meteorology, Vol. 7, No. 3, 1968, pp. 313-323

10. Simpson, R. H., "Synoptic Analysis Models for the Tropics", Meteorological Technical Exchange Conference, Colorado Springs, Colorado, 1969

11. Hope, J. R. and Neumann, C. J., "Climatology of Atlantic Tropical Cyclones by Two and One-Half Degree Latitude-Longitude Boxes", ESSA Technical Memorandum WBTM-SR-44, 1969