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ONR Tropical Cyclone Motion research initiative : first-year review, discussion and tentative hypotheses

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NAVAL POSTGRADUATE SCHOOL

Monterey, California

ONR TROPICAL CYCLONE MOTION RESEARCH INITIATIVE: FIRST-YEAR REVIEW, DISCUSSION AND TENTATIVE HYPOTHESES

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Table of Contents

Abstract

The Office of Naval Research Tropical Cyclone Motion initiative is a five-year program to improve basic understanding of tropical cyclone motion. On 27-30 January 1988, a meeting was held in Monterey, California to: (i) Review the first year's research activities; (ii) Discuss issues and plan future research; and (iii) Begin discussion of tentative hypotheses that might be explored in a field experiment in the western North Pacific region during summer 1990. Each of these topics will be briefly discussed to indicate the progress and plans of the initiative.

1. Introduction

A five-year basic research program to improve understanding of tropical cyclone motion began 1 October 1986 under the sponsorship of the Office of Naval Research Marine Meteorology Program (R. F. Abbey, Jr, Program Manager). This program involves theoretical studies, analysis of existing observational data, and a field experiment in the western North Pacific region during summer 1990. A series of workshop reports (Elsberry, 1986; 1987a; 1987b) describe respectively: the planning of theoretical studies; possible observing systems for tropical cyclone studies; and a reassessment of the program in view of elimination of aircraft reconnaissance in the western North Pacific during 1987.

A workshop was held on 27-30 January 1988 to review the progress in the first year of the initiative. A list of attendees is given in Appendix A. We continue to benefit by the participation of cooperating agencies, such as the Hurricane Research Division (HRD) of the National Oceanic and Atmospheric Administration (NOAA), the U.S. Air Force, and the Naval Environmental Prediction Research Facility.

The agenda for the workshop is provided in Appendix B. The objectives of the workshop were three-fold: (i) Present reports of progress during the first year; (ii) Discuss the status of the issues being addressed and identify future areas of research; and (iii) Discuss potential hypotheses for the 1990 field experiment.

R. Abbey of ONR opened the meeting by briefly describing the list of current contractors on the project (Table 1). Analytical studies are defined here to include observational analyses and primarily numerical approaches are grouped with theoretical studies. Although each contractor is listed in only one category, most investigators actually contribute in more than one category.

The first day and part of the second day of the workshop were devoted to progress reports by ONR contractors and by participants from cooperating agencies (see agenda in Appendix B). Although some of this work is nearing publication, other portions are recent results that may change with further investigation and analysis. Consequently, no attempt is made to describe these presentations in detail. Some of the presentors have provided summaries that are included in Appendix C.

Table 1. Contractors participating in the ONR Tropical Cyclone Motion Accelerated Research Initiative (provided by R. F. Abbey, Jr.)

Experimental
V. Lally, National Center for Atmospheric Research

Analytical Studies
R. Elsberry, Naval Postgraduate School
W. Frank, Pennsylvania State University
W. Gray, Colorado State University
G. Holland, Bureau of Meteorology Research Center
R. Merrill, University of Wisconsin
C. Ramage, University of Hawaii
T. Schroeder, University of Hawaii
T. Tsui, Naval Environmental Prediction Research Facility

Theoretical Studies
S. Chang, Naval Research Laboratory
J. Chi, University of the District of Columbia
T. Krishnamurti, Florida State University

B. Morton, Monash University
W. Schubert, Colorado State University
R. Smith, Monash University
B. Wan, University of Hawaii
T. Williams, Naval Postgraduate School

2. Discussion Sessions

Three sessions on the second day were devoted to open discussions of issues related generally to theoretical studies (R. T. Williams, discussion leader), observational studies (G. J. Holland, discussion leader) and numerical studies (W. Schubert, discussion leader). Since the format was left open, these discussion leaders used a combination of personal research with results presented in the progress reports to highlight achievements and raise questions/issues for discussion. Rapporteurs had been assigned to summarize these discussions. The summaries prepared by these rapporteurs are included below.

a. Theoretical Studies [H. Willoughby, Rapporteur]

(1) Accomplishments: Theoretical investigations under this initiative have focused on motion of barotropic nondivergent and divergent vortices. On an f plane, a spatially uniform environmental current simply advects the vortex with no distortion, provided that it induces little divergence. A rotating imposed divergence can induce trochoidal motions if it moves with the swirling wind where it is imposed. On a beta plane without environmental flow, the vortices' outer part plays a greater role than their cores in determination of the northwestward or westward

motion that arises. Vorticity advection -- expressed as a balance among radial advection of axisymmetric vorticity by the asymmetries, tangential advection of the asymmetric vorticity by the mean swirling flow, and meridional advection of planetary vorticity also by the mean flow (beta effect) -- is the primary physical process responsible for the motion (Fig. 1). This balance suggests that the asymmetries are Rossby waves that propagate on the radial gradient of relative vorticity in the cyclone and that the beta advection term, which is smaller than the relative vorticity advection, acts to force the waves. Although the linear theory of Willoughby (1987) seems to describe the westward drift and pattern of asymmetry of a vortex on a beta plane, an unreasonably fast motion to the northwest is predicted, which indicates that nonlinearity is important.

The flow in a moving vortex may be partitioned into the axisymmetric vortex, the relative environmental current, and the Rossby- or gravity-wave asymmetries. It is the wavenumber one asymmetry that influences the vortex motion most strongly. A horizontally shearing environmental current excites wavenumber two, which may interact nonlinearly with wavenumber one to influence both wavenumber one and the motion. Gradients of potential vorticity, which may be due either to horizontal variations of the environmental vorticity or to topography of the free surface that sustains the environmental flow, may affect the motion much as the beta effect does. More complicated and

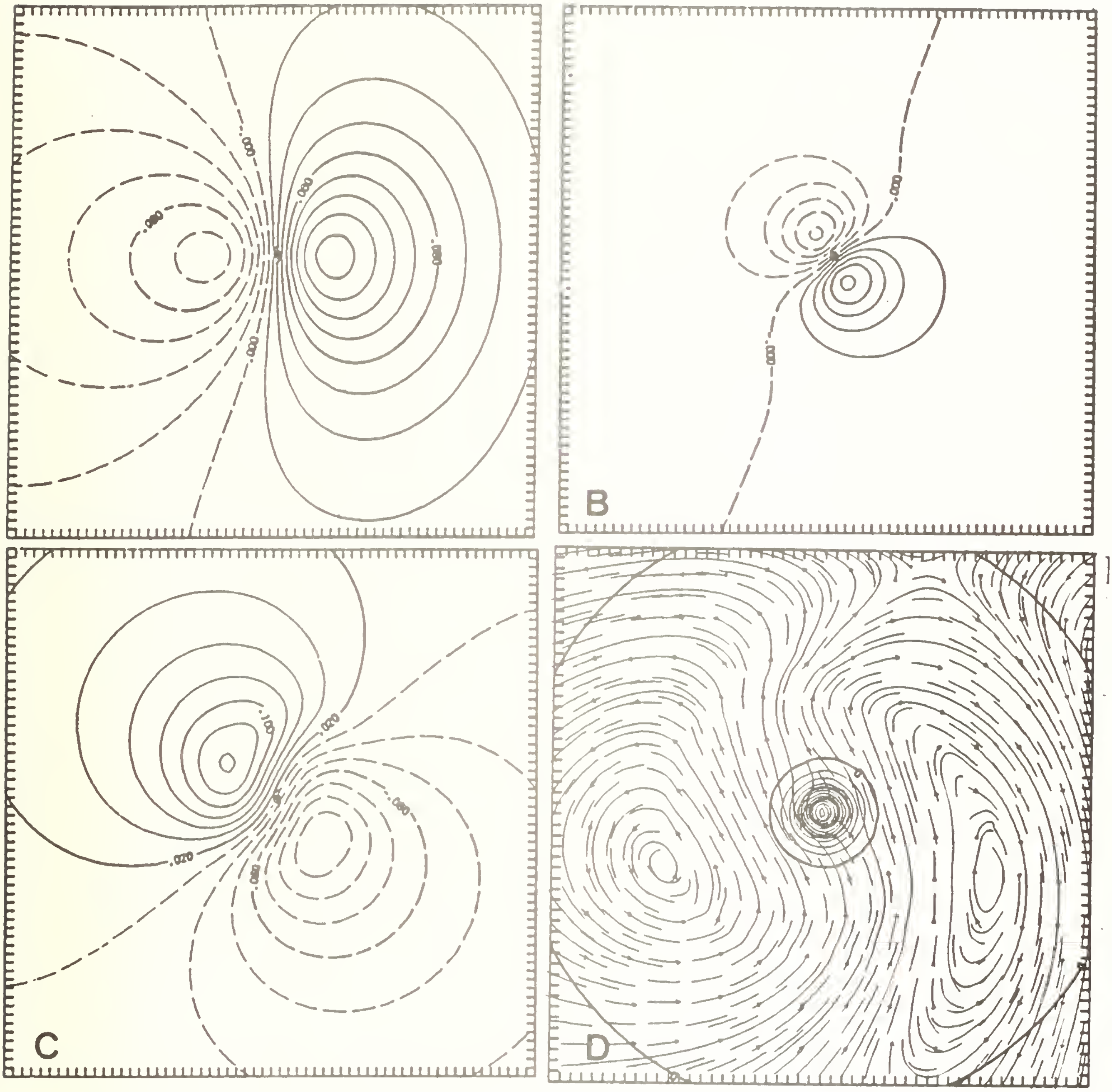

Fig. 1 Streamfunction tendency ($m^{-2}s^{-2}$) after 12 h in the nondivergent barotropic model simulations of Fiorino (1987) due to the (a) linear βv term; (b) advection of symmetric vorticity by the asymmetric flow; and (c) advection of asymmetric vorticity by the symmetric flow. Positive (solid) and negative (dashed) tendencies correspond to increasing anticyclonic and cyclonic circulations respectively. Since the contour intervals are 0.02, 0.10 and 0.02 respectively, the leading term is the advection of symmetric vorticity by the asymmetric flow, which is illustrated in panel d by the streamlines and relative vorticity contours (solid) after 72 h. Notice that the large-scale anticyclonic (cyclonic) gyres to the right (left) of the central region of high vorticity establish the asymmetric flow.

realistic environments would include subtropical anticyclones, Tropical Upper Tropospheric Trough (TUTT) cells, extratropical troughs and other tropical cyclones.

Vortex asymmetries, which are generally a pair of counterrotating gyres, occur in two kinds: the beta gyres, which are induced by advection of planetary vorticity or other synoptic-scale influences and are comparable in horizontal scale with the vortex; and the alpha gyres, which are confined to the vortex center and may be eliminated by a suitable redefinition of coordinates. Presence of alpha gyres makes the total-flow streamlines take the form of eccentric circles about the pressure center. In a baroclinic model, the alpha gyres may reflect a slope of the rotation axis. Minimization of the Lagrangian, which entails minimization of the amplitude of the alpha gyres, provides a basis for determination of vortex motion in a linear model.

(2) Opportunities for future research: Nonlinear processes -- interactions among asymmetric features and between the asymmetries and the axisymmetric vortex -- must be important to tropical cyclone motion, as must matching of the relative-vorticity Rossby waves in the vortex core onto planetary Rossby waves in the surroundings. The interactions and matching may involve inward communication of environmental influences or outward radiation of energy and angular momentum, perhaps acting to dissipate the mean vortex. In addition to nonlinear processes, linear

barotropic damping of the asymmetries by the horizontal shear in the mean flow may occur and asymmetric surface friction due to the vortex motion may excite wavenumber-one asymmetries that feed back on the motion.

Rossby-wave asymmetries in a stratified barotropic model without vertical shear have reduced equivalent depth and Rossby deformation radius, so that the beta effect should be reduced. With vertical shear, differential advection of the axisymmetric flow by the relative environmental flow and twisting of the horizontal environmental vorticity by the axisymmetric secondary circulation should induce asymmetries, and perhaps lead to inclination of the mean rotation axis.

Future research should focus on solution matching at the vortex periphery, frictional effects and baroclinity.

b. Observational Studies [J. C.-L. Chan, Rapporteur]

(1) General: The observational studies in this initiative have produced only some preliminary results. These results are significant for two reasons. First, they confirm some of the theoretical or numerical results. Second, some important discrepancies exist between these observational findings and those from the theoretical and numerical investigations. In this brief summary, these agreements and discrepancies are described. Questions raised during the discussion session are also summarized. Finally, future work to address these questions is proposed.

(2) Structure of the beta-gyres: Numerical and theoretical studies have shown that nonlinearity in a barotropic framework leads to the formation of asymmetric gyres on opposite sides of the vortex (Chan and Williams, 1987; Fiorino, 1987; Willoughby, 1987; Williams and Peng, workshop presentation). The gyres at radii 500-800 km from the center of the vortex that arise from the beta-effect are referred to as the beta-gyres. Observational studies (Chan, 1986; Holland, workshop presentation) have documented the existence of the beta-gyres that have the same spatial scale as those predicted in the theoretical studies. Holland found that these gyres appear to be oriented east-west across the vortex, develop after the cyclone forms and disappear as the cyclone decays.

The major issues that need to be addressed here include the structure and orientation of these gyres. How does the structure evolve with time or vary with different environmental and storm-related parameters such as size and intensity? Is the orientation of these gyres necessarily east-west? In Chan's (1986) study of Supertyphoon Abby, the gyres seemed to rotate as the heading of Abby changed from north-northwest to north-northeast. Fiorino (1987) also found the gyres in his model rotate as the vortex moved first toward the north and then toward the northwest.

Another question is whether the "gyres" identified in the observational studies are simply part of the large-scale environment. Holland's observations that these gyres seem to develop and move with the storm suggests that they are not simply due to the environment. One could resolve this issue if the large-scale environment could be identified clearly. However, the consensus during the workshop appears to be that a unambiguous definition of the "large-scale" remains elusive.

To substantiate further the existence and document the structure of these gyres, data from storms of different sizes and intensities (including monsoon depressions) need to be analyzed. The data sources include the Australian Monsoon Experiment (AMEX) data set and the reconnaissance aircraft data processed by Colorado State University. In the latter set, both composite and individual case studies should be attempted. The geographical as well as the storm-direction oriented coordinate systems should be used, but with the symmetric component of the vortex subtracted. The data can also be stratified based on synoptic flow patterns, such as the subtropical ridge or even derived quantities such as relative vorticity or its gradient. A spectral decomposition of the azimuthal eddy would provide the amplitude and phase of the wavenumber one asymmetry.

(3) <u>The westward drift</u>: In the numerical study of Fiorino (1987), a discrepancy exists between the vector of the vortex movement and that of the "ventilation flow" (asymmetric flow averaged within 300 km of vortex center). In his presentation at the workshop, L. Carr of the Naval Postgraduate School showed that the difference between the

two vectors consistently is about 0.3 m/s towards the west. In the linear model of Chan and Williams (1987), the displacement of the streamfunction minimum from the relative vorticity maximum is also about this order of magnitude.

Carr also examined observational studies of George and Gray (1976), Chan and Gray (1982) and Holland (1984) in which storm translation was compared with a "steering flow", which was represented by the average around an annulus at a specific radii from the storm center. The difference between these two vectors is generally westward with a magnitude of about 1-2 m/s. This difference vector also rotates slightly and varies in magnitude for different stratifications. Holland reported that the difference vector is about 1-2 m/s in the AMEX data set, compared to the 0.3 m/s magnitude in the numerical experiments of Fiorino (1987).

The question is why a discrepancy exists between the numerical model and the observational results. Is it because of a data problem -- perhaps the annulus over which the flow is analyzed was not chosen correctly? Or is it because the model is too simple? What is the magnitude of this difference vector in other data sets?

Thus, the steering needs to be recomputed using different annuli and for different levels and deep-layer means with all available data sets. The workshop participants agreed that at least the flow at 850, 700, 500 and 200 mb as well as the 850-300 mb deep-layer mean should be analyzed. New data sets should include rawindsondes composites, reconnaissance aircraft data (both individual case and composites), AMEX data set and the Hurricane Research Division (HRD) data (including dropwindsondes). Composites can also be made based on vorticity gradient patterns to determine whether the discrepancies arise as a result of environmental vorticity gradients.

"Steering" flow also can be computed from numerical models using the same definition as in the observational studies. This can be done in the numerical experiments with and without basic flow included.

(4) Vortex profiles: In many observational studies (composites and individual cases), the tangential winds remain cyclonic out to 15° latitude radius unless the upper-level flow is included. Thus, observed tropical cyclones do not have a tendency to become angular momentum neutral as was suggested by Willoughby (1987) and Fiorino (1987). Further, although the relative vorticity becomes anticyclonic away from the storm center, it does so at radii that are at least a few times the radius of maximum winds. On the other hand, in most of the vortices used in numerical studies of DeMaria (1985), Chan and Williams (1987) and Fiorino (1987), the relative vorticity becomes anticyclonic at twice the radius of maximum wind.

The major question is therefore whether the numerical results are an outcome of the "unrealistic" specification of the vortex profile. What effects will the anticyclonic relative vorticity produce in the movement of the vortex? As observed vortices have positive tangential winds at such a large radius, is the concept of a "bounded" vortex realistic?

To address these questions, the models should be initialized with more realistic vortices. Vortex profiles in different basins can also be compared to determine their inherent differences (e.g., western Pacific tropical cyclones typically form in a monsoon trough whereas Atlantic cyclones form in a trade-wind regime).

(5) Summary: In addition to the three main topics discussed in the session, some potential new observing systems (e. g., satellite microwave sensors, Doppler radars, drifting buoys, etc.) that might be provided by the Air Force or the Navy were also described by C. Guard. They point to a significant increase in the amount of available data if these systems become operational by the time of the field experiment.

It appears that much more can be done with the existing data sets to either verify or point out the deficiencies of the model results. They also can provide some better insights into some of the physical processes that are responsible for tropical cyclone motion.

c. Numerical Modeling Studies [M. Fiorino, Rapporteur]

(1) Accomplishments: The major accomplishments during the first year of the initiative were: (i) An understanding of the role of the large scale flow and vortex structure in

tropical cyclone motion using nondivergent and divergent barotropic prognostic and diagnostic models (Fiorino, Williams, Willoughby, Chan and DeMaria); (ii) Upper-level flow influences using a limited-area primitive equation model (Chang); (iii) Real-data forecasts using a spectral global model (Krishnamurti); and (iv) Predictability of tropical cyclone motion (DeMaria).

Following a discussion of these accomplishments, Dr. Krishnamurti was asked to review the work at Florida State with global models and to provide additional results. He commented on the predictability limits derived by DeMaria based on a presumed observation spacing of 3000 km in the Atlantic. While this area has virtually no upper air observations east of 60° W to the African coast, the combination of many aircraft reports, satellite winds in the lower and upper levels, and ship reports, combined with a good 4-D assimilation system, tends to reduce the "effective" station separation. Thus, there may be optimism for accurate model predictions despite the sparsity of rawindsonde observations. Higher resolution may be needed in the Atlantic compared to the Pacific, although climatological or environmental reasons for this apparent requirement are not known. Krishnamurti also discussed the development of a "reverse" Kuo scheme in which satellite rainfall estimates are used to recover a thermodynamic/dynamic structure that will support the observed rainfall. The intent is to force the model to produce typical tropical rainfall rates at the beginning of the integration rather than relying on the model to generate rain from a nearly nondivergent initial flow. This spinup usually takes 18-36 h to build the precipitation to reasonable levels.

J. Chan commented on the performance of the European Center for Medium-range Weather Forecasts (ECMWF) model for typhoon Wayne of 1986. This cyclone made four loops in the South China Sea and the ECMWF model predicted two of the loops. In these two cases, the large-scale forcing appeared to be stronger. In the two cases in which the model failed to forecast a loop, the storm was weak or the synoptic flow weak. This suggested a vortex-structure effect that could not be handled due to the inability of the analysis to resolve cyclone scales.

M. DeMaria will reanalyze the cases in his predictability experiments in which there were large sensitivities to the initial conditions and/or synoptic flow.

(2) Future questions:

(i) Can theoretical studies of cyclone-generated asymmetries provide initial conditions for numerical forecast models?

(ii) What numerical experiments can be used to quantify the importance of baroclinic effects, friction, convection, etc., on tropical cyclone motion?

(iii) What model initialization and data assimilation techniques can be used to reconstruct the poorly observed vortex scales (e.g., the Adjoint method)?

(iv) How can models be designed to use wind profiler data?

These questions stimulated a discussion on the future role of numerical modelling in understanding tropical cyclone motion. Real-data global simulations provide an opportunity to test motion concepts developed with simpler numerical models and analytical treatments. In this scenario, the global model output represents a 4-D "data source" for comparisons with further work and rawindsonde or aircraft data sets.

3. Tentative Hypotheses

a. General Recurvature Forecast Problems [Provided by G. Holland]

Tropical cyclones in potential recurvature situations are some of the most difficult to forecast and these situations produce a significant percentage of the largest forecast errors (for example, Sandgathe, 1987; JTWC Annual Typhoon Reports; Bureau of Meteorology, 1978). A few schematic examples in the western North Pacific region from Sandgathe (1987) are shown in Fig. 2. Some systems unexpectedly turn into the subtropical ridge. Sometimes the ridge builds westward ahead of a recurving cyclone, which instead continues on a westward track. Cyclones approaching a midlatitude trough have been observed to recurve, to continue westward, or to 'step' or loop before returning to a westward movement.

These examples indicate the importance of understanding the interactions between cyclones and both the subtropical ridge and the environmental (midlatitude or TUTT) troughs. Unfortunately, much of our present knowledge consists of anecdotal accounts and empirical rules of thumb. In the following sections, working hypotheses are proposed. A structured research and field program aimed at improving our knowledge of these interactions is required (see Section 4).

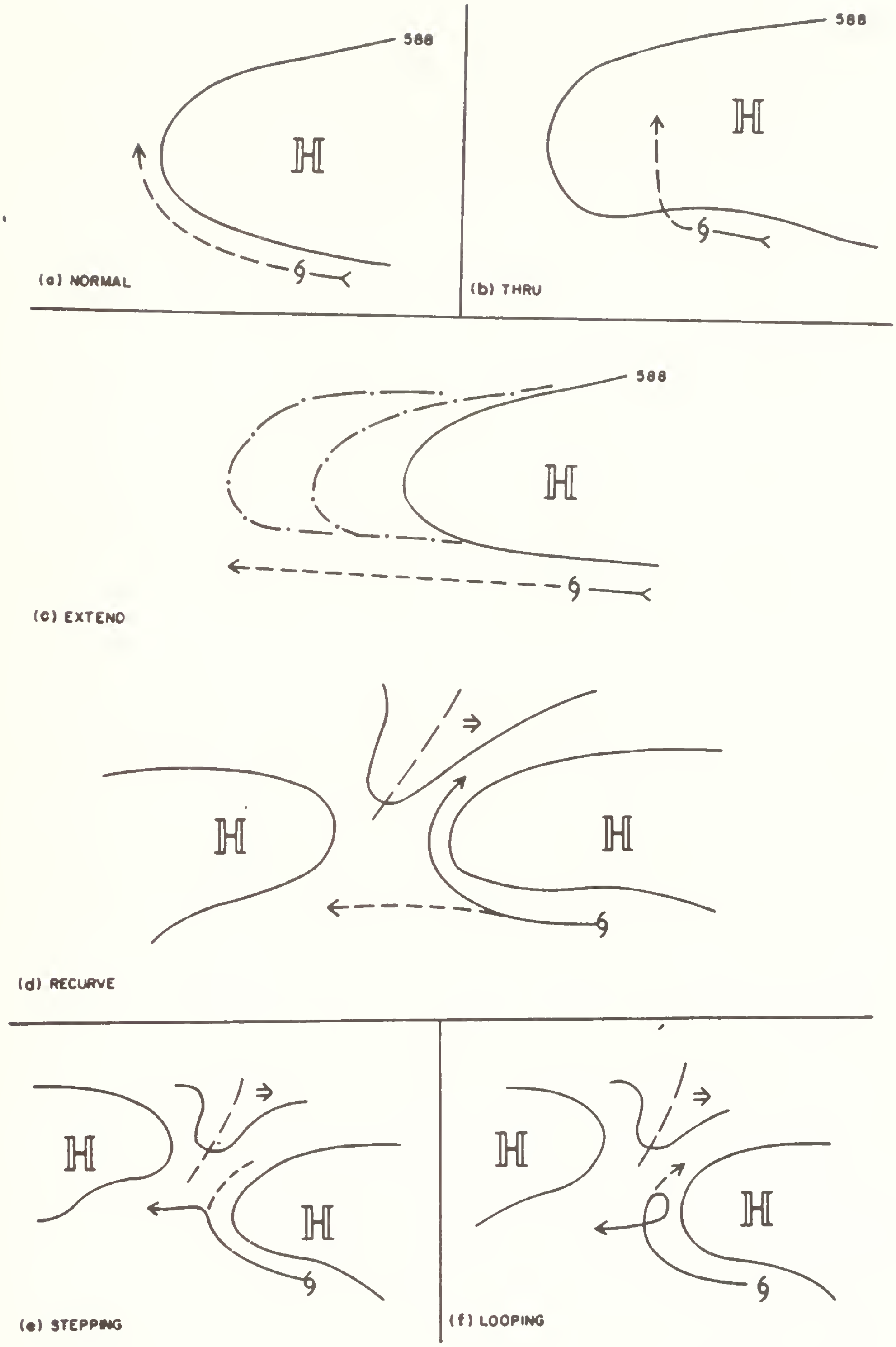

Fig. 2 Tropical cyclone motion during cyclone - subtropical ridge interaction for (a) normal motion, (b) through ridge, and (c) extending ridge, and during cyclone - midlatitude trough interaction for (d) recurvature, (e) stepping and (f) looping (after Sandgathe, 1987).

(1) Tropical Cyclone/Subtropical Ridge Interactions:

The aim here is to investigate the interactions that occur between the cyclone and the subtropical ridge that can lead to modification of one or both systems and thus affect the cyclone motion. Two specific working hypotheses are proposed:

(a) The beta gyres arising from Rossby mode dispersion of the cyclone in a gradient of earth vorticity can reach sufficient amplitude to modify the subtropical ridge. A schematic is shown in Fig. 3.

The issues to be addressed include the conditions in which significant amplitude gyres are generated, the conditions that affect their orientation, and the track modifications that result.

(b) Thermal and indirect circulation effects associated with the tropical cyclone outflow jets can produce a westward extension of the mid- to lower-level subtropical ridge and cause a continued westward motion of the cyclone.

The requirement here is to determine the conditions that generate and orient the outflow jets and the manner in which these jets can affect the lower troposphere.

(2) Tropical Cyclone/Environmental Trough Interaction:

The focus here is to investigate the interactions that occur when a tropical cyclone comes into close proximity to a progressive midlatitude trough in the westerlies or a TUTT cell, and to determine the types of interactions that are associated with the track types shown in Fig. 2. The specific working hypothesis is:

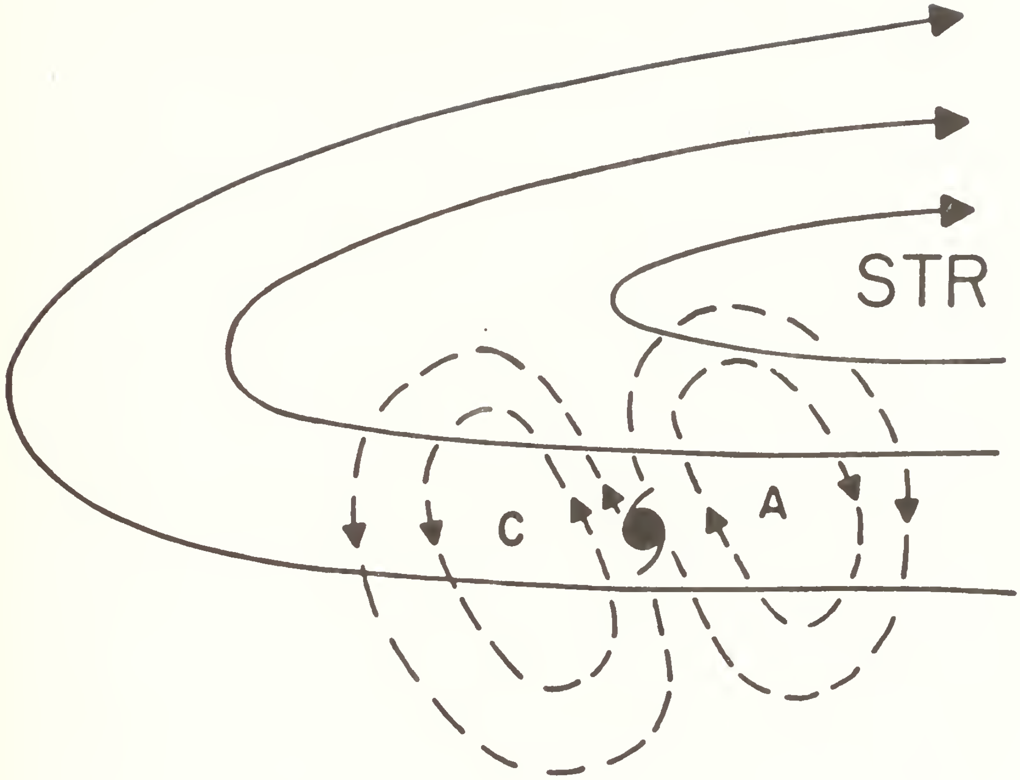

Fig. 3 Schematic of the beta gyres (dashed) as in the isolated vortex model of Fiorino (1987) overlaid on a subtropical ridge (STR). The anticyclone (A) - cyclone (C) couplet can potentially move the cyclone toward the ridge axis and also modify the ridge (provided by G. Holland).

> The approach of an environmental trough may excite barotropically unstable azimuthal waves in the tropical cyclone outflow layer that extend downward into the lower troposphere and affect the cyclone motion. A schematic is shown in Fig. 4.

The AMEX analyses by Holland show evidence of barotropically unstable growth that causes an equatorward extension of the mid-latitude trough and affects recurvature. Additional studies are needed to determine the conditions under which barotropic instability is generated and released, the types of perturbations that result, and the manner in which they can affect the cyclone motion.

b. General Track Turning Problems [Provided by R. L. Elsberry]

A related topic to the recurvature forecast problem discussed above by G. Holland is the general topic of "how tropical cyclone turning motion is related to a time-changing environmental flow". As indicated in Fig. 2, a long-lasting tropical cyclone in the western North Pacific may have multiple interactions with midlatitude troughs prior to the actual recurvature. This leads to a "stepping" track in which the tropical cyclone "feints" a turn toward the north and then returns to a westward track.

Considerable literature exists regarding environmental influences, but conventional or inner-core reconnaissance observations do not appear to be adequate to understand (or forecast) the nonlinear processes that are likely to be involved. It is possible that the capability to remotely sense or to directly observe (via a dropwindsonde survey) the surrounding environment can now be exploited to improve

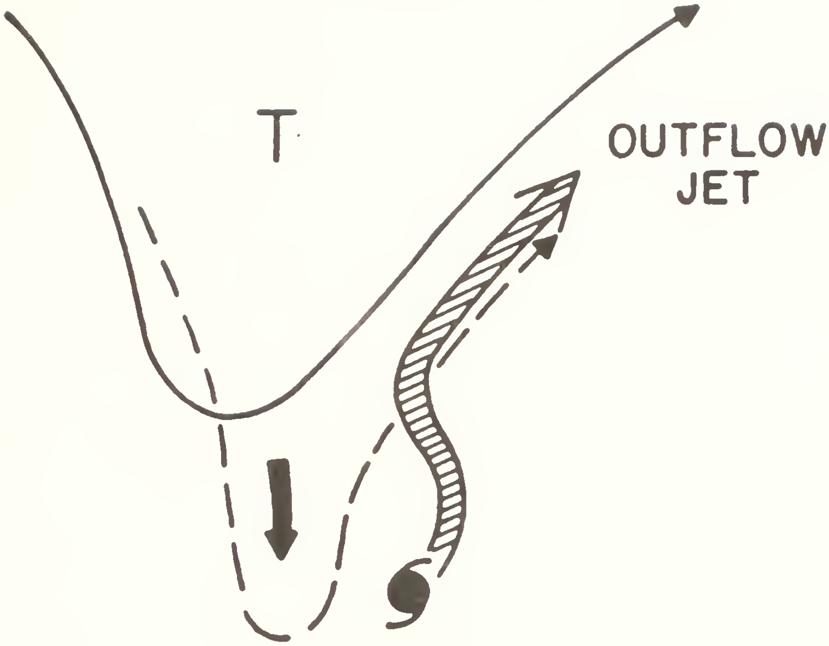

Fig. 4 Cyclonic midlatitude trough impinging on the anticyclonic outflow of the tropical cyclone may change the sign of the vorticity gradient and lead to excitation of barotropically unstable developments shown by the dashed line extending equatorward (provided by G. Holland).

understanding. The questions are: Where are the critical areas that need to be observed? What observations or diagnostic calculations need to be made to distinguish unambiguously these turning motions?

Fiorino (1987) indicates that tropical cyclone turning motion (associated with "external" (300 - 800 km) structure changes) is preceded (accompanied?) by reorientation of the spatially-averaged current. Sherman (1988) has examined gradients of relative vorticity (derived from operationally analyzed fields) in the environment of "stepping tracks." He finds that the tropical cyclone track tend to be oriented along (versus across) "channels" or "primary nodes" in the relative vorticity contours surrounding the tropical cyclone. These patterns may be related to the beta-gyres as in Fig. 3 or other interactions between the tropical cyclone and the surrounding flow. The operationally-analyzed fields are quite noisy and the delay in the time until the tropical cyclone turns is uncertain at this stage. Nevertheless, a tentative hypothesis might be stated:

> Tropical cyclone turning motion, or the absence of any turns in the immediate future, may be monitored by accurate representations of the large-scale vorticity patterns in the environment of the cyclone.

Additional studies are needed to determine whether Sherman's preliminary relationships between the vorticity features and storm turning are maintained. However, the coarse resolution and questionable data coverage in the tropics are not expected to allow conclusive tests. Some higher resolution analyses may be available from a more advanced numerical model being developed at NEPRF. In addition, the time-dependent "forcing" fields can be extracted from the history tape of the model predictions of recurvature and non-recurvature tracks. Even if these studies based on analyses and predictions seem to substantiate the hypothesis, a field experiment will be required to obtain the specific observations that demonstrate conclusively the physical relationships.

c. Interactions with TUTT Cells [Provided by C. Guard]

The western North Pacific basin has many special characteristics that affect the development, intensity and movement of tropical cyclones. For example, monsoon surge interactions may be related to genesis, to intensification, and to downstream influences on motion.

Another special influence (discussed in part by G. Holland above) may occur when intense TUTT cells extend downward into the mid-troposphere. Satellite imagery suggests that very active monsoon regimes also may be triggered by a sequence of TUTT cells aloft. A number of possible track effects are possible due to the interactions with the TUTT cells. Sadler (1978) has described multiple storm developments in active trough regimes. The intensity changes in association with outflow jets interacting with TUTT cells have been studied by Sadler, Merrill, Holland and others. TUTT cells that are within 10-12^{o} latitude west or poleward of a tropical cyclone may induce rapid deepening.

This deepening may alter both the intensity and outer strength of the cyclone and the outflow jet intensity, which may change the environmental flow around the tropical cyclone. Thus, interactions with TUTT cells may lead to track deviations. A preliminary hypothesis is:

> Significant tropical cyclone track direction changes (such as steps in Fig. 2) can occur during periods of direct or indirect (e.g., induced monsoon surges) interaction with TUTT cells.

Additional research is necessary to document potential track steps as the TUTT cells move past. Questions such as the amount of track deviation as a function of TUTT cell intensity, closest point-of-approach, and critical heights gradients need to be resolved.

d. Relation of Model/Analysis Resolution to Track Error [Provided by T. Krishnamurti]

Very high resolution (about 50 km) global model simulations suggest that tropical cyclone motion can now be addressed in a real-data environment. The summer 1990 field experiment may provide adequate observations to test the effects of numerical model and analysis resolution on the accuracy of the tropical cyclone prediction. Given adequate observations, the track prediction accuracy should improve with increased numerical model resolution. Specifically, the hypothesis is:

> Given adequate four-dimensional observations to define the initial conditions, the 24-h track prediction error should not exceed five grid points of the model resolution.

This hypothesis might be testable if sufficiently high resolution observations are available to define both the inner-core region and the environment in which the cyclone is embedded.

e. Cyclone Turning and Recurvature [Provided by W. Gray]

A number of studies have been carried out with rawindsondes composites of turning storms or recurving tropical cyclones. New studies are in progress with the aircraft reconnaissance data from the western North Pacific. These studies have not proceeded to the stage where a specific hypothesis can be stated. Nevertheless, it does appear that distinctive large-scale changes occur in these fields (and perhaps also in the satellite data) in advance of the cyclone recurvature or turning motion. In the future, a hypothesized sequence of events that accompany recurvature will be proposed for test and evaluation in the field experiment.

4. Preliminary Field Experiment Design Considerations [Provided by G. Holland]

The above hypotheses have been developed from recent work in the ONR Tropical Cyclone Motion research initiative. Further research is continuing using numerical models, the AMEX data, and case studies of recurving cyclones in the western North Pacific Ocean. This research can be expected to lead to further refinement of the hypotheses and perhaps development of new hypotheses.

An integral component of this research must be a testing of the final hypotheses with real data. Because of the highly transient and localized nature of many of the interactions described above, routine data collection will not be sufficient, and a special field experiment is required. The western North Pacific Ocean during August and September is a logical site for this experiment for the following reasons: (i) this is the major region of interest to the ONR program and has a substantially different environment relative to other cyclone regions; (ii) the frequent cyclone activity there provides a high probability of successful data collection in a number of cyclones; and (iii) the current observing infrastructure and available additional sites provide an excellent basis for an experiment.

It is proposed that the experiment be based on a fixed network of upper-air sounding sites that consists of an enhanced experimental array embedded within the current operational network. Additional support would be from mobile aircraft-based platforms, from satellite, from ground-based radar, and perhaps drifting buoys.

a. Upper-air Observing Network

The proposed upper-air observing network (Fig. 5) consists of a regular array of experimental stations embedded within the routine station network. It is envisaged that the experimental sites will consist of a combination of upgraded operational stations, portable sounding stations using either Loran or Omega, and vertical wind profilers.

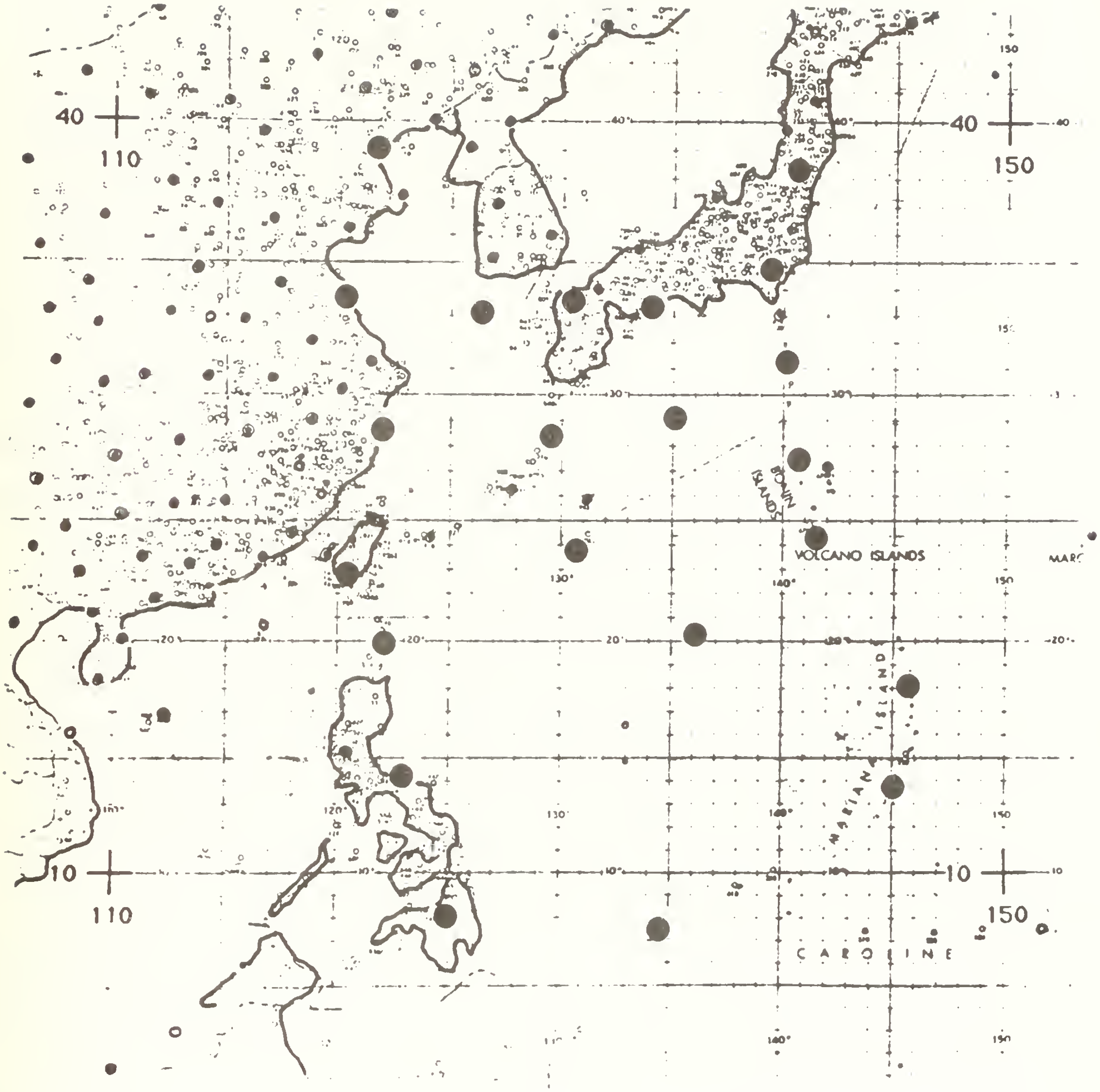

Fig. 5 Example of a possible experimental upper-air network (large circles) superposed on the present observing network according to Sandgathe, 1987.

The experimental network in Fig. 5 has been designed to be as regular as possible, to take advantage of the high density sites over Asia, and to cover the main regions in which the interactions described above will occur. For example, the meridional station chains can provide excellent location and structural descriptions of the subtropical ridge, and of the very large scale structure of the tropical cyclones. Further, good observations would be available for subtropical trough/cyclone outflow interactions in the vicinity of Japan. The regular nature of the network enhances the capacity for analysis on a rectangular grid with a minimal loss of information. Subsets of the network also could be used for detailed diagnostic calculations using line integral or other techniques.

This fixed network provides the basis for the experiment and should operate during all cyclone events for at least a two month period. It should be supported by ad hoc data collected from ships and aircraft of opportunity, and by sounding and remote sensing data from polar orbiting satellites and by the Japanese Geostationary Meteorological Satellite. The value of these data would be enhanced considerably if mobile platforms also were used to collect very high density data in specific regions of interest.

b. Mobile Platforms

Two types of mobile platforms are desirable. The first is aircraft with Doppler or dropwindsonde capacity to locate the tropical cyclone and monitor the structural changes within a few hundred kilometers of the center. Although the cyclone intensity does not seem to be important for motion, there is evidence that the structure, including patterns of precipitation on scales of 100-130 km, can be very important. Further, these aircraft could be utilized to monitor the detailed structure of (and changes in) the subtropical ridge during interactions with tropical cyclones.

The second mobile requirement is for high flying aircraft with dropwindsonde and remote sensing capacity that can monitor the outflow layer wind structure and interactions with subtropical troughs, with TUTT cells and with the subtropical ridge. These aircraft would need to be capable both of taking direct observations within the outflow regimes and providing high resolution dropwindsonde coverage from the upper troposphere.

5. Conclusions

The intent of this brief report has been to indicate the progress during the first year of the ONR Tropical Cyclone Motion initiative. Regular journal articles are being submitted on a number of topics, and new research areas are developing continually. It was particularly pleasing to see the confluence of thought on theoretical approaches, and the cross-fertilization with the observationalists based on the theoretical results. Finally, some tentative hypotheses for the 1990 field experiment are arising. Much remains to be accomplished to put these in the form of testable hypotheses, and to design the appropriate field experiment within the severe financial constraints.

The next ONR workshop is planned for 29 June - 1 July 1988 in conjunction with the tropical meteorology conference in Brisbane, Australia. Scientists attending that conference are encouraged to attend the ONR workshop. In addition to presenting progress reports, refinement of hypotheses will be a key objective. This will contribute to the preparation of an operations plan, which will be published in 1989.

ACKNOWLEDGEMENTS

The success of a workshop depends on a number of factors. The openness of all of the participants to discuss their research contributed to a lively and informative exchange of views. Discussion leaders R. T. Williams, G. J. Holland and W. Schubert were very effective. Rapporteurs H. Willoughby, J. C.-L. Chan and M. Fiorino are thanked for their written reports of the discussions. A conducive setting for discussions was provided through local arrangements by E. Saunders and J. Smith.

Preparation of the workshop report has been supported by the Naval Postgraduate School direct research funding. G. J. Holland reviewed the manuscript, which was skillfully prepared by Mrs. P. Jones.

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Appendix A LIST OF ATTENDEES

Name	Affiliation
R. Elsberry	Naval Postgraduate School
W. Gray	Colorado State University
J. Chi	University of District of Columbia
S. Chang	Naval Research Laboratory
T. N. Krishnamurti	Florida State University
M. DeMaria	Hurricane Research Division (NOAA)
Hugh Willoughby	Hurricane Research Division (NOAA)
Wayne Schubert	Colorado State University
J. C.-L. Chan	Royal Observatory, Hong Kong
Melinda Peng	Naval Postgraduate School
C.-S. Liou	Naval Postgraduate School
Bruce Morton	Monash University
L. Car	Naval Postgraduate School
J.-H. Chu	Naval Environmental Research Prediction Facility (NEPRF)
M. Fiorino	Fleet Numerical Oceanography Center
R. T. Williams	Naval Postgraduate School
C. Guard	Air Weather Service
R. Abbey	Office of Naval Research (ONR)
G. Holland	Naval Postgraduate School
J. Evans	Naval Postgraduate School
T. Tsui	NEPRF
R. Hodur	NEPRF
C.-P. Chang	Naval Postgraduate School
C. Fairall	Pennsylvania State University

Appendix B

21 Jan 88

ONR TROPICAL CYCLONE MOTION ACCELERATED RESEARCH INITIATIVE

FIRST-YEAR REVIEW

27-30 January 1988
Monterey, California

AGENDA

Wednesday, 27 January 1988

0830	Registration/Introductions
0835	Objectives of Workshop - R. L. Elsberry
0850	ONR Status Report - R. F. Abbey, Jr. Review, Issues, Concerns, Future expectations
0905	M. Fiorino - Effect of vortex structure on tropical cyclone motion
0950	Break
1005	H. Willoughby - Motion of a vortex in a shallow water barotropic model
1050	R. T. Williams, M. Peng - Beta-effect with no mean current
	J. C.-L. Chan, - Beta-effect with a mean current
1145	Lunch
1245	G. J. Holland - Research Progress Report
1330	W. M. Gray - Tropical cyclone inner-core steering and recurvature
1430	Break
1445	T. N. Krishnamurti - Tropical cyclone prediction using a global model and FGGE data
1530	S. Chang - Model-generated structure of tropical cyclones
1615	M. DeMaria - Predictability of tropical cyclone motion
1645	Close

Thursday, 28 January 1988

0830	J. Chi - Heat, moisture and momentum fluxes in hurricane vortices
0900	B. Morton - Prospects for laboratory modelling relevant to tropical cyclone motion
0940	W. Schubert - Future plans
0950	T. Tsui - Future Plans
1000	Break
1015	Discussion session #1: (R. T. Williams, Discussion Leader; H. W. Willoughby, Rapporteur) - Status of the theoretical studies
1145	Lunch

1245 Discussion session #2: (G. J. Holland, Discussion Leader; J. C.-L. Chan, Rapporteur) - Status of Observational Studies
1445 Break
1500 Discussion session #3: (W. Schubert, Discussion Leader; R. Hodur, Rapporteur) - Status of Numerical Prediction Model Studies
1630 Close

Friday, 29 January 1988

0830 Summary of discussion session #1 - Willoughby
0900 Summary of discussion session #2 - Chan
0930 Summary of discussion session #3 - Hodur
1000 Break
1015 Field experiment status report - R. L. Elsberry
1045 Discussion of potential hypotheses
  Recurvature - G. J. Holland
  Recurvature - R. L. Elsberry
1145 Lunch
1245 Continue discussion of potential hypotheses
1500 Break
1515 Continue discussion of potential hypotheses
1630 Close

Saturday, 30 January 1988

0900 Wrap-up session
  Coordination of write-ups
1030 Close

Appendix C

Summaries or short abstracts of accomplishments during the first year of the ONR Research initiative have been submitted by Chi, Elsberry, Holland, Krishnamurti and Williams. DeMaria and Willoughby of the Hurricane Research Division (NOAA) submitted abstracts of their research that is relevant to this research initiative.

Heat, Moisture and Momentum Fluxes in the MPBL of Tropical Cyclones

Joseph Chi, Ph.D.
University of the District of Columbia

Summary

Under the ONR Grant, UDC has used state-of-the-art turbulence theory to simulate the marine atmosphere in tropical cyclones. Three main accomplishments are briefly described:

1. Developed a mathematical model for the hurricane vortex flow over the sea surface. The model uses the second order turbulence closure equations.

2. Developed computer program for calculating velocity, enthalpy, moisture, and turbulence energy distributions in the MPBL of the hurricane vortex flow over the sea surface.

3. Developed a laboratory model of vortex flow over the water surface to compare calculations of turbulence theory with experimental data.

Lists of publications supported by this research grant are also given. Finally, research needs in the future for conceptual advances to be made in the area of dynamics of marine atmospheres in tropical cyclones are presented.

SCIENTIFIC ACCOMPLISHMENTS

Second Order Turbulence Model for Hurricane Vortex MPBL

A second order turbulence model has been developed for the marine planetary boundary layer of tropical cyclones. The model uses a cylindrical coordinate system. It permits three dimensional simulations of tropical cyclones that include influences of the centrifugal force, Coriolis force, air/water interface waviness and interface liquid droplet entrainment. A complete set of conservation equations, Reynolds stress equations and turbulent flux equations for the three dimensional flow have been derived. Details of the mathematical model for the tropical cyclone are documented in a report entitled "A Turbulence Theory for Vortex Marine Planetary Boundary Layers." Some solutions for these equations have also been obtained.

Computer Simulation of Vortex Boundary Layer Flows:

A computer program has been developed to simulate the turbulent MPBL of tropical cyclones over the sea surface (Figure 1). It includes the boundary layer heat, moisture and momentum transfer; turbulent energy production, dissipation and diffusion; strong influence of the gravitational, Coriolis, and centrifugal forces; influence of sea water entrainment in the vortex; and influence of air/water interface roughness. Figure 2 shows a set of typical results of distributions in the hurricane MPBL of the radial component of wind velocity, the tangential component of wind velocity, the moist static enthalpy, the total moisture ratio and the turbulent kinetic energy, respectively.

Laboratory Experiments of Vortex Flows Over a Water Surface

In order to increase confidence in the computer simulation, a laboratory model shown in Figure 3 for air vortex flows over the water surface has been designed and fabricated. The model's overall dimensions are 55 cm diameter by 90 cm high. The vortex is generated by forcing air through 24 evenly spaced vanes of 15 cm high placed on a 30.48 cm diameter pitch circle. The swirling air discharges from the model through a 3.81 cm diameter hole located at center of the model's top disk. The bottom of the swirling air is in contact with a pool of water that can be maintained at a constant depth and at desired temperatures. Figure 4 shows calculated distributions in the boundary layer over the water surface of the radial component of air velocity, the tangential component of air velocity, the static enthalpy, the moisture ratio and the turbulence kinetic energy, respectively. Measurements in the boundary layer have been planned using a laser doppler anemometer that is currently under development at UDC. Some preliminary experimental results of flows in boundary layers over solid surfaces (instead of water surface) have been obtained from measurements using the hot-film anemometer system. These data are plotted in Figure 5 for comparison with results of the computer simulation. Excellent agreement between theory and experiments can be seen in this figure.

LIST OF PUBLICATIONS SUPPORTED BY ONR FUNDS

Chi, J., "A Turbulence Theory for Vortex Marine Planetary Boundary Layers", Report No. UDC/MHEG0011, June 1985.

Chi, J., and Y. L. Young, "Heat Moisture and Momentum Transfer in Turbulent Vortex Flows over the Sea Surface", Report No. UDC/MHEG0012, June 1986.

Chi, J., and G. Hinds, "Experiments on Vortex Boundary Layer Flows over a Water Surface", Report No. UDC/MHEG0013, June 1986.

Chi, J., "Heat, Moisture and Momentum Transfer in Turbulent Vortex Flows over the Water Surface", Proceedings of the ASME/JSME Thermal Engineering Joint Conference, Vol. 3, pp. 627-633, March 1987.

FUTURE RESEARCH NEEDS

It is suggested that both the UDC computer model for MPBL of tropical cyclones and the UDC laboratory model for the vortex boundary layer over the water surface should be expanded. For the computer model, the axisymmetrical flow assumption in the vortex simulation should be removed. Then, to increase calculation efficiency, the finite-element numerical scheme should be developed to replace the finite-difference calculation scheme. Instrumentation for the laboratory model should be improved to facilitate simultaneous measurement of air velocity, temperature, moisture ratio, and turbulent fluxes. For this purpose, optical instruments should first be developed to eliminate interference of instruments with the vortex flow.

FIG. 1 HURRICANE VORTEX MPBL SCHEMATIC
FOR TURBULENCE MODELING

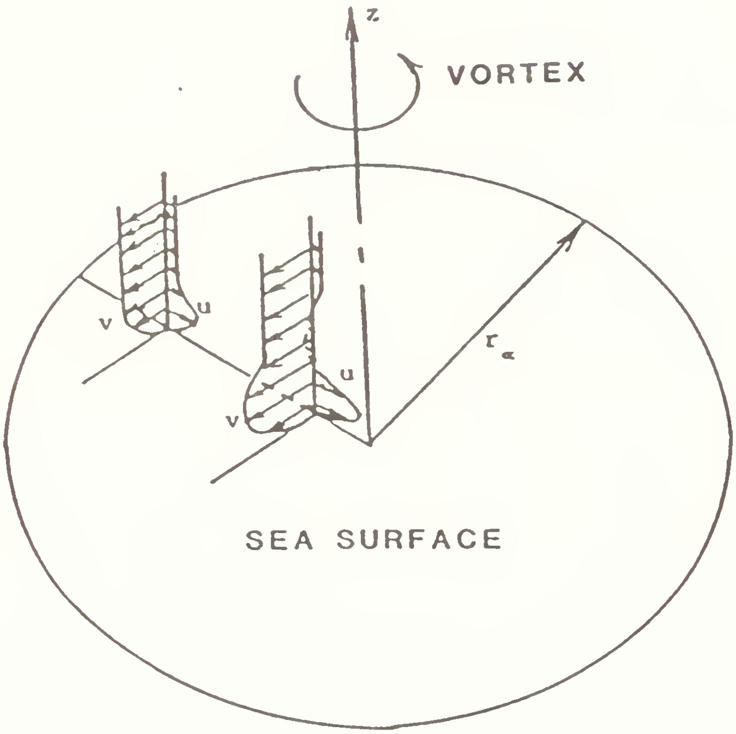
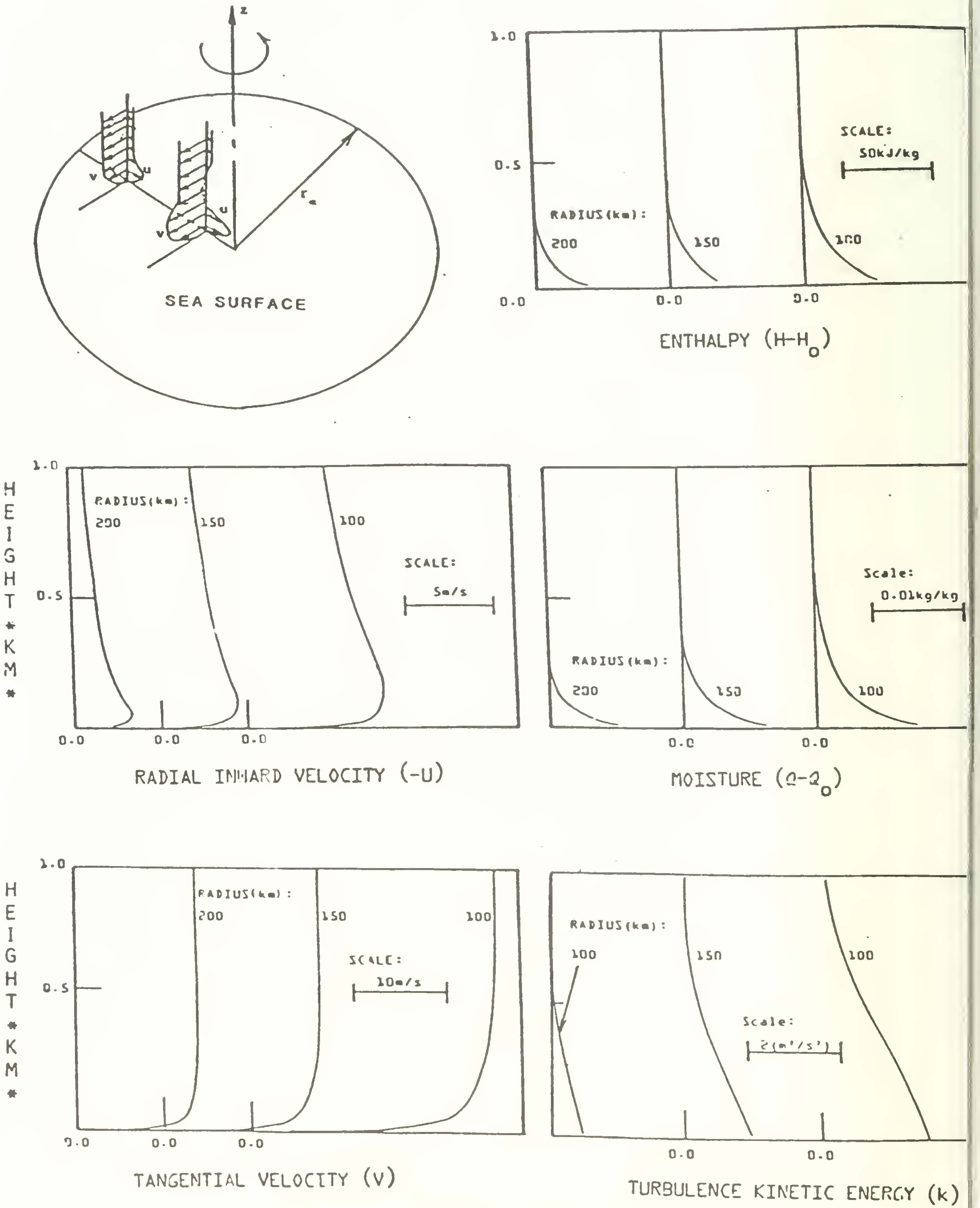


FIG. 2 COMPUTER SIMULATION RESULT FOR HURRICANE MPBL



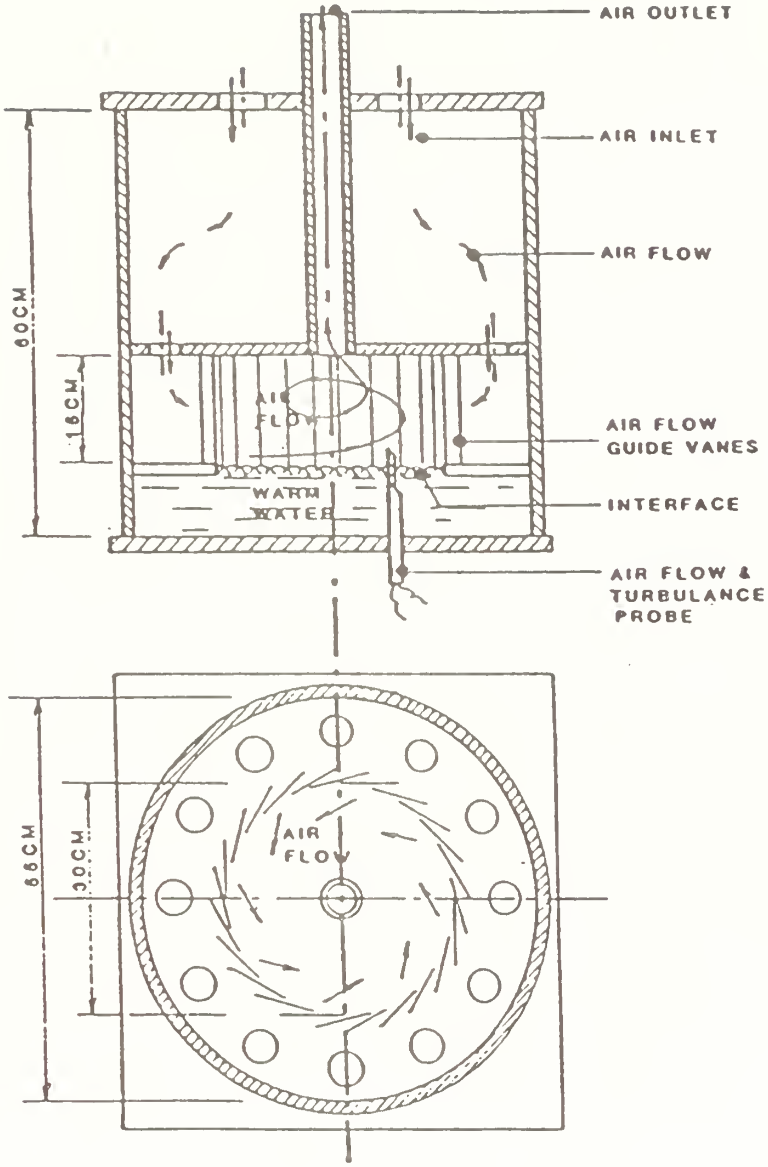
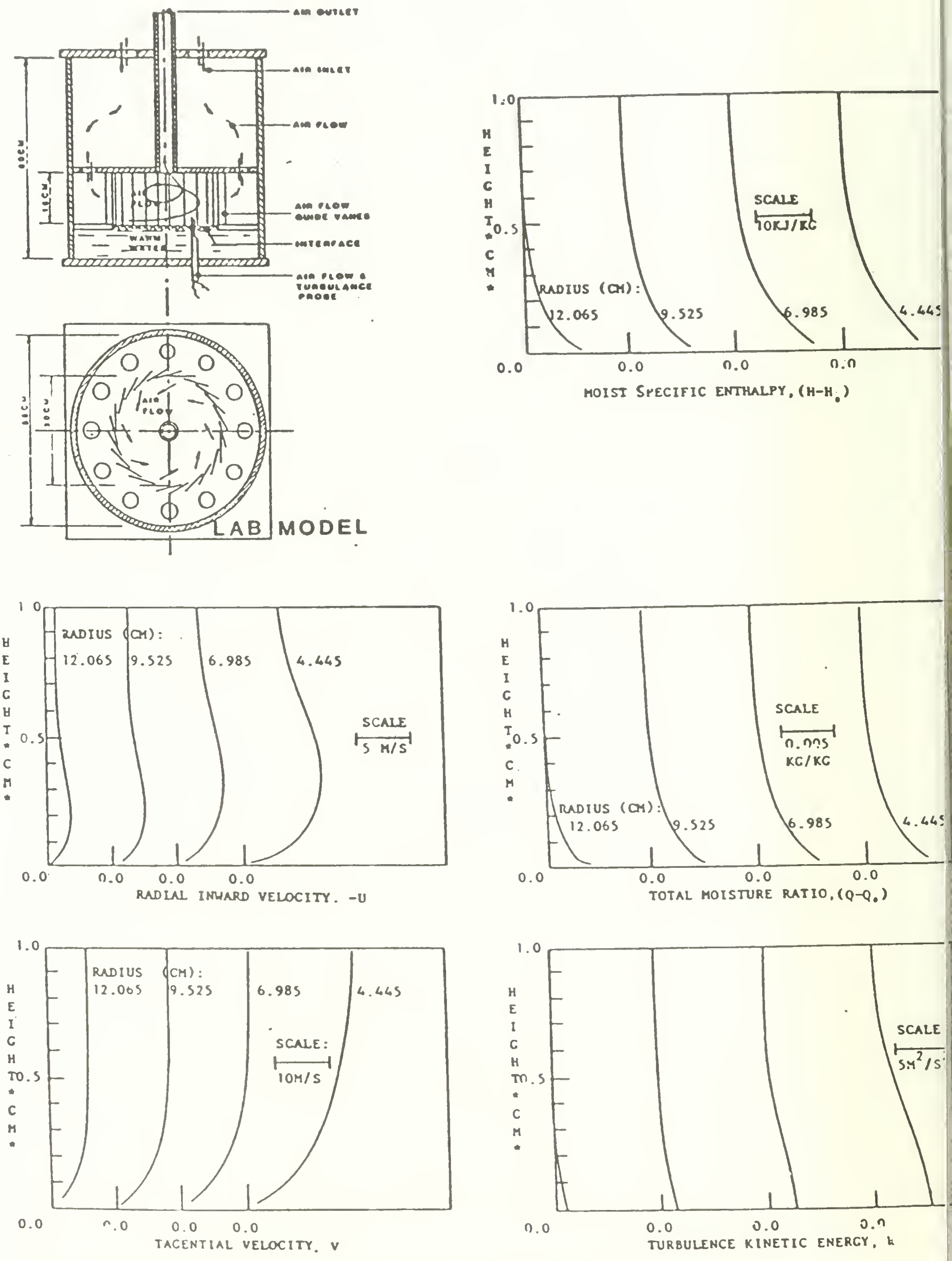


FIG. 3 LAB MODEL SCHEMATIC

FIG. 4 COMPUTER SIMULATION RESULT UNDER LAB CONDITION



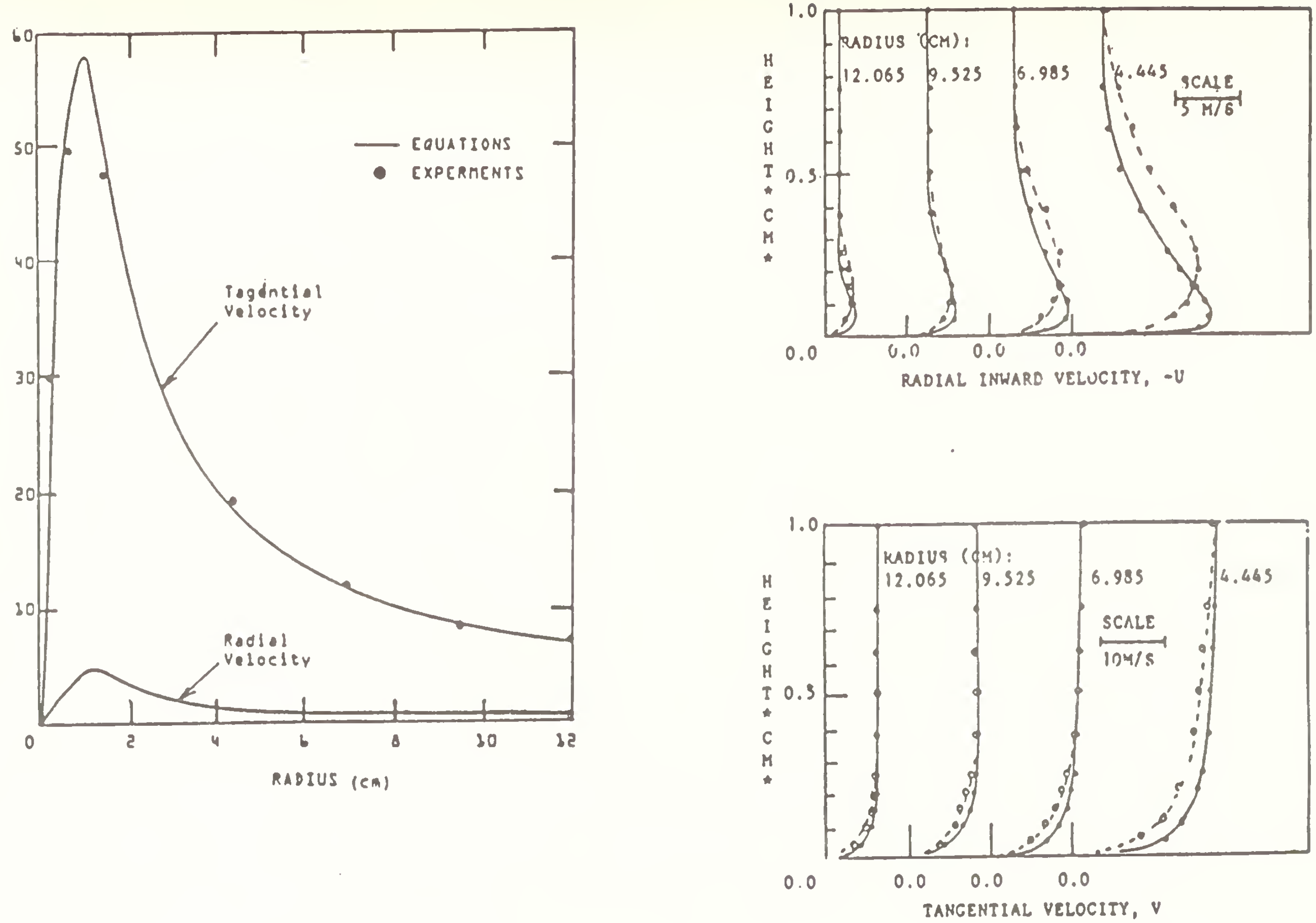


FIG. 5 COMPUTER VS LAB DATA COMPARISON

Predictability of Tropical Cyclone Motion

Mark DeMaria

Hurricane Research Division, AOML, NOAA
4301 Rickenbacker Causeway
Miami, FL 33149

Abstract

The dynamical method of the study of atmospheric predictability is applied to the tropical cyclone track forecasting problem. This method estimates the growth of forecast errors by comparing several numerical model simulations with slightly different initial conditions. The barotropic vorticity equation is initialized with vertically averaged winds from NMC analyses and is solved using the spectral method with spherical harmonic basis functions. The model uses triangular truncation at wavenumber 128 (about 100 km resolution) and 39 forecasts of Atlantic tropical cyclones which occurred between 1979 to 1985 are considered.

The effect of initial position errors is studied by running each forecast with the initial vortex center displaced from the observed initial position. These results show that initial position errors have little effect on the total forecast errors after about 12 hours. This can be explained by geometric considerations and the fact that the distance between the displaced forecast track and the original forecast track remains small compared to the forecast error. The effect of initial position error becomes more significant if errors in the initial motion of the storm are introduced.

The effect of inadequate data coverage is studied by comparing forecasts with various wavelengths filtered from the NMC analyses. Using this method, the lower limit to track forecast errors can be estimated for a given data resolution. These results show that inadequate data coverage introduces large errors in the forecast tracks. For Atlantic storms east of 70 W, the observed track forecast errors are close to the estimate of the lower limit of error, suggesting that little forecast improvement can be made without improved data coverage. However, for Atlantic storms west of 70 W, the observed errors are larger than the lower limit suggesting that further improvements can still be made.

Progress Report on Tropical Cyclone Motion Studies

R. L. Elsberry

Motivation from the DOD viewpoint for the Tropical Cyclone Motion Initiative included the Typhoon Abby (1983) case in the western North Pacific. Nearly all of the DOD assets were put on alert (unnecessarily in most cases as it turned out) because the operational forecast tracks were in error. The actual track of this very large and dangerous typhoon deviated significantly to the right of the "steering flow". One of the basic questions to be addressed was whether this anomalous track behavior could be attributed to the anomalous structure of the vortex.

The Ph.D. dissertation of Mr. Michael Fiorino at the Naval Postgraduate School addressed this question. Fiorino used a numerical model to study a vortex structure that included stronger winds at large radii than are found in the normal typhoon. He also studied more intense inner-core wind effects to determine whether this aspect of Typhoon Abby was the cause of the anomalous track. Fiorino's numerical tests demonstrate clearly that the strength of the winds in the outer regions (beyond 300 km) could account for the differences in track, whereas an increase in inner core intensity by 50% has a mininal effect on the track. The translation speed is almost linearly dependent on the wind strength in the outer (300-1000 km) radius of the vortex.

This result has implications for the strategy of observing tropical cyclones and for proper initialization of the numerical track prediction models. First, observations are required at much larger distances from the storm than are generally available. Without aircraft reconnaissance, new remote-sensing techniques need to be developed and tested that will detect the differences in vortex structure. New Loran-based (or in the future, Global Positioning System based) dropwindsondes should be deployed in the outer regions of storms. Complete coverage over the required observational regions may not be achieved until the Laser-wind satellite system is available! Second, many of the present numerical track prediction models have a systematic deviation in the track that might be explained by Fiorino's results. New observations to define accurately the actual outer wind structure need to be incorporated in these numerical models to improve the track predictions. For example, that part of the vortex motion (speed and direction) due to the so-called beta effect is <u>closely</u> related to the ventilation flow averaged over the inner 300 km of the storm.

SUMMARY OF TROPICAL CYCLONE MOTION RESEARCH
JANUARY 1988

[1]Greg J. Holland (Principle Investigator)
Naval Postgraduate School, Monterey

Lance Leslie and [2]Chris Veldon
BMRC, Melbourne, Australia

[3]Jenni Evans
Naval Postgraduate School, Monterey

An overview of our current tropical cyclone motion research at BMRC and NPS and of additional relevant work at BMRC is provided. This work includes an analysis of the AMEX tropical cyclones, numerical modelling studies, an examination of the processes that lead to cyclone recurvature, and forecast developments. Some preliminary collaborative work on track predictability with Klaus Fraedrich also is described.

1. AMEX Tropical Cyclones Irma and Jason

a) Diagnostic Analyses: Tropical Cyclones Irma and Jason formed in the Gulf of Carpentaria and spent their entire lifecycle within the AMEX observing network. Irma moved continuously westward, Jason moved westward for three days, decayed overland, then moved southeastward and reintensified over the ocean. The BMRC 11 level, 6 hourly and 125 km resolution analyses have been converted to a cylindrical grid to facilitate a diagnostic analysis of the azimuthal mean and eddy circulations in the cyclones.

A major finding has been the identification of a wave number one eddy structure, with an anticyclonic circulation to the east and a cyclonic circulation to the west of the AMEX cyclones. This feature seems to develop with the cyclones then disappears as they decay. This supports earlier speculation by Anthes and Holland, and recent modelling results by Fiorino, that such structure would result from Rossby wave distortion in a varying earth vorticity field. Further work is aimed at more precisely defining this structure, its development mechanisms, and its

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[3] Permanent affiliation, Monash University, Melbourne, Australia

relationship to the moving cyclone. Use is being made both of the analyzed fields and of the model simulations described below.

b) Numerical Modelling Studies: The BMRC Tropical Model has provided 48 hour simulations of both Irma and Jason that closely follow the observed tracks. This is a 12-level, semi-implicit primitive equations model with a stability dependent boundary layer, Kuo and shallow convection, evaporative cooling from both large-scale and convective precipitation and a simple radiation scheme. The model is initialised with the high resolution AMEX analyses and continues to use the analyses to provide 'perfect' boundary conditions during the integration cycle.

The model is now being used in an examination of the effects of cyclone bogussing, of horizontal resolution, of cyclone structure, of diabatic heating and of the proximity to land (Leslie and Holland, 1988).

A shallow water equations model also has been developed for simulations using deep-layer-mean (DLM) fields from the AMEX data. This model has the same numerics, surface topography and horizontal boundary conditions as the BMRC Tropical Model. Veldon et. al. (1988) are examining the sensitivity to different DLM fields, to horizontal resolution, to surface topography and cyclone structure, and to variations in analysis data. Leslie and Holland also are comparing the two models in a preliminary assessment of the effects of baroclinity.

c) Other Studies: The AMEX data have been provided to Rich Hodur and Simon Chang for numerical modelling studies. Model intercomparisons between the BMRC Tropical Model and the ECMWF model are being undertaken by Kamal Puri at BMRC. An intensive reanalysis has commenced for a two day period in Hurricane Jason to incorporate additional satellite data and high density cloud drift winds.

2. Tropical Cyclone Recurvature

The aims of this study are to examine the processes that are associated with different types of tropical cyclone recurvature utilising earlier work at NPS by Sandgathe and Sherman.

A set different types of recurving Northwest Pacific typhoons have been selected for analysis using a barotropic model. A beta-plane, shallow water equation model has been developed and is being tested. This model will be used for simulations of an isolated vortex on a beta-plane and compared to the vorticity model simulations by Fiorino. Simplified flow fields typical of the recurving typhoon examples will then be incorporated to provide an initial diagnosis of the interactions that occur between the cyclone, the subtropical ridge, and mid-latitude westerly troughs. Further investigations will depend on the results of this preliminary examination.

3. Forecast Developments

A new forecasting technique, PTCM87 has been developed from the linear motion tendency equations of Holland (Evans and Holland, 1988). The equations are first inverted to derive a basic current from the past cyclone motion. This is combined with an analytically defined cyclone to provide sufficient bogus rawinsonde observations to ensure that a tropical cyclone is maintained in the initial analysis. A deep layer mean from 850-200 mb is next derived and filtered to remove cyclone scale perturbations. The equations are then iteratively solved at 6 hour time steps to provide a forecast cyclone track. In 100 test forecasts, the scheme performed significantly better than an analogue technique and better than the current operational forecasts. Real-time testing is being made during the current Australian tropical cyclone season.

The basic scheme has been incorporated in the NEPRF ATCF package and is being modified to suit northwest Pacific typhoons. Plans are to make it available to forecasters in Guam during the next typhoon season.

4. Tropical Cyclone Predictability

A preliminary examination of the chaotic nature of tropical cyclone tracks in the Australian region has been completed by Fraedrich (1988) in collaboration with Leslie and Holland. All cyclone tracks were normalised to a common initial position and the time rate of separation of initially close pieces of trajectories was examined. These empirical results indicate that the mean separation growth after 12-24 hours is quasi-linear and resembles the growth that could be expected from random walk cyclone tracks. Further work is needed to examine the boundary conditions imposed by different atmospheric flow regimes.

5. Bibliography

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Fraedrich, K., 1988: Tropical cyclone track chaos. Preprints, Int. Conf on Trop. Met., Brisbane July 4-8 1988.

Holland, G.J., L.M. Leslie and N.E. Davidson, 1988: Tropical cyclone outflow layer interactions during AMEX. Preprints, Int. Conf on Trop. Met., Brisbane July 4-8 1988.

Leslie, L.M. and G.J. Holland, 1988: Numerical modelling of tropical cyclone motion during AMEX. Part II: The BMRC Tropical Model. Preprints, Int. Conf on Trop. Met., Brisbane July 4-8 1988.

Veldon, C.S., G.J. Holland and L.M. Leslie, 1988: Numerical modelling studies of tropical cyclone motion during AMEX. I: Barotropic model. Preprints, Int. Conf on Trop. Met., Brisbane July 4-8 1988.

<u>Title</u>: Formation of Hurricanes with Very High Resolution Global Models

<u>Author</u>: T.N. Krishnamurti

<u>Affiliation</u>: Department of Meteorology
Florida State University
Tallahassee, Florida 32306-3034

<u>Abstract</u>:

With the use of the FGGE IIIb data sets and a detailed version of the global model, considerable success was demonstrated in the formation of several hurricanes and typhoons. (These results are not published at the present time except for an extended abstract which appears in AMS proceedings of the Baltimore meeting, February 1988). Since writing that abstract we have continued a rather extensive numerical prediction program on this problem. It should be stated that in these experiments we have started with an incipient wave or a weak depression which is resolved by the FGGE data. In many ways this appears to be one of the most promising areas of our current research. After carrying out a series of some 12 experiments at a resolution of T42 and eleven vertical layers we recognized that this resolution was inadequate to address the hurricane formation problem. The European Center's final IIIb analysis includes a multi-variate optimal interpolation and a 4 dimensional data assimilation. This data set is made available to the users at a resolution of 1.875° latitude/longitude mesh. Experiments were carried out at resolutions of T21, T31, T42, T63 and T106 for four different initial dates. In addition data sets for these same cases were also extracted from the operational NMC analysis to conduct parallel experiments.

<u>A summary of the recent results</u>:

- A T42 version of the model with 11 vertical levels, with a vertical resolution of roughly 50 mb below the $\sigma = 0.8$ surface fails to show development of tropical storms. The failure is largely diagnosed to the vertical resolution near the earth's surface. All of these experiments utilize the ECMWF final IIIb data sets).
- A T42 version of the model with 12 vertical levels with an explicit constant flux layer near the earth's surface (located at $\sigma = \sqrt{0.99}$) was able to predict the formation of hurricanes (and typhoons). This was tested for 4 different storms of 1979. The size of the storms and the location of maximum wind from the storm center was too large. Storms also formed at the resolutions of T31, T63 and T106 when the same vertical descretization was used. The model failed to predict storms at a resolution of T21. The best results in terms of the track and strength of winds were obtained at a resolution of T106. It was also apparent that the results gradually improved as the resolution was increased to T106. When the horizontal resolution was increased for this 12 layer model, the air-sea flux of water vapor dramatically increased. This appeared to be one of the important factors in the development.
- At a resolution of T106 it was apparent that mesoscale (≈ 300 km)

horizontal shear zones form in the vicinity of the storm area; in the region of strong cyclonic shear convection organized into the familiar rain-bands and eye-wall. At a lower resolution these features were less apparent or absent. Figure 1(a,b) illustrates an example of the field of the horizontal windspeed at a resolution of T42, T63 and T106 at the end of days 1 and 3 respectively. It is apparent that the higher resolution model is capable of tapping much information from initial data at larger scales and of developing mesoscale organization during the course of integration. An example of the evolution of precipitation (24 hourly totals) at the end of hours 24, 48 and 72 are shown in figure 2 for the T106. The maximum rainfall rate approaches 168 mm/day by hour 72. The rainfall evolves into a banded character.

- An illustration of the predicted wind field at 850 mb for Typhoon Hope and its track are shown in figure 3. The formation and landfall were quite reasonably handled by the T106 version of the model. This storm (July - August 1979) moved to the region of Hong Kong after 5½ days. The predicted storm moved to that same region some 6 hours later.
- The NMC operational data sets (IIIa) failed to capture the incipient wave at time $t=0$ for these storms and as a consequence the forecasts were generally poor.

The tropical data coverage of the FGGE IIb is much superior to the operational NMC IIa data sets. The analyses, based on these, are used in these intercomparisons. Furthermore differences perhaps also arise from the shorter cut off time on the GTS for the data receipt at NMC and also from the larger covariance matrix of the multivariate OI of the ECMWF IIIb. There are also major differences in the 4D assimilation methodology. These are major issues that will be addressed in the continuation of this study. This is an extremely difficult proposition for outside users of various data sets who cannot make judgments on data quality without recourse to the total working codes that generated these data sets in the first place! We shall keep an open dialogue with the data producers in order to address this question further.

It has been possible to extend the resolution of the global model to 170 waves triangular for 12 vertical layers. This contains a transform grid of 512 by 256 grid points. With a nearly fully vectorized code it should be possible to carry out a few experiments on the landfall of hurricanes to a time frame of 24 to 36 hours. We feel that this is very worthwhile. This will be included in our proposed list of experiments.

An advantage of this type of experimentation is that at the same time we are able to examine the results of the high resolution global forecasts over all of the tropics (as well as over the globe). It should be possible to compare the tropical prediction of monsoons, trades, tropical jets, equatorial waves and any other phenomena of interest that are covered by the initial state. Several masters' degree students are engaged in these studies on diagnosing the model output over the global tropics. Studies on model output diagnostics over the tropics (based on ECMWF model) have been very effectively demonstrated by Reed et al., (1986,1987).

Motion of Typhoon Abby:

This storm formed east of Guam on August 7, 1983. This was a major supertyphoon of the year 1983. Fig. (4) shows its track. Around August 11 it recurved north-north-eastward. The revurvature of this storm has been studied in much detail by several investigations. This storm attained a maximum surface wind of 145 knots on the 10th and had a minimum surface pressure of 888 mbs. Chan (1986) reported on the results of several forecasts that were carried out with a multilevel regional model. A striking feature in these forecasts was a pronounced westward drift while the storm was infact recurbing and moving towards Japan. Abby weakened as it moved over Central Japan on August 17th. Heavy rains caused severe flooding and landslides in Japan. Several people were killed as this storm traversed across central Japan. The systematic westward drift in the early numerical weather prediction experiments, fig. (5), reported by Chan (1986), were attributed to a spurious intensification of the subtropical high in the models.

In our studies we carried out a forty eight hour forecast of Typhoon Abby starting on August 8, 1983. We used the 12 layer version of the model at a resolution of Triangular 106 waves. Our interest in these forecasts was to examine the nature of the track forecasts at very high resolution in the global spectral model. We have used the operational data from the European Center to initialize our model with the nonlinear normal mode initialization with Physics.

Figure (6) illustrates the motion field based on the ECMWF analysis. Here we show the streamlines and isotachs at 850 mb from August 8, 12 UTC to August 10, 12 UTC, 1983 at intervals of every 12 hours. The analysis shows a maximum intensity of 28 ms^{-1} on August 8 when the storm had infact reached supertyphoon intensity. The ECMWF analysis utilizes a transform grid of T63 for the four dimensional data assimilation. The transform grid around 15N has a grid resolution of roughly 160 km. At this resolution the model is incapable of identifying features in the inner storm area. Another factor is of course the distribution of data sets around the storm. The operational data includes cloud winds tracked from the Japanese Satellite commercial aircraft wind reports and the conventional observations from the World Weather Watch.

The predicted motion field at intervals of 12 hrs are shown in fig. (7). These are at 850 mb. The predicted sea level pressure fields are shown in fig. (8). The predicted motion of typhoon Abby corresponds very closely to the best track position; the 24 and 48 hr position errors are around 1° latitude. These forecasts do not exhibit a westward drift in the single short term integration. The sea level pressure drops from an initial value of 1006 mbs to a value of 996 mbs by hour 48. The observed minimum pressure attained by the storm, on hour 48, was around 990 mbs. At the resolution of T106 the maximum winds in the storm reached 25 ms^{-1} while the observed maximum wind was roughly 60 ms^{-1}. The differences are largely a function of the resolution, the transform grid at T106 corresponds roughly to 100 km. The evolution of the predicted wind at 850 mb in Typhoon Abby shows a pronounced asymmetry with respect to the storm center. The prediction appears quite impressive at this resolution. It is difficult to interpret the reasons for the lack of a spurious westward drift. The prediciton of subtropical highs are very sensitive to the radiative forcing. Our use of a sophisticated radiative parameterization has contributed to an improved prediction of the subtropical high and the Hadley cell. We feel that the lack of westward drift of the storm in the prediciton may be related to an overall improvement of the tropical prediction.

Proposed Studies

Our emphasis for the improvement of tropical prediction using the global model requires that we address all tropical large scale phenomena that are contained within the global tropical belt. Although the inner rain area of the hurricane is evidently on the mesoscale, however, the pressure field of a hurricane (or typhoon) does cover the synoptic scale. During the months June through October it is not uncommon that we find one or more such storms within the domain of our integration in any given initial state. In order to improve tropical numerical weather prediction we feel strongly that attention has to be paid to various problems associated with the tropical cyclone. Some of the major problems are: formation, landfall, recurvature and precipitation. The initialization of a pre-existing hurricane within a given initial state is a very complex problem. Our current focus is on the initial formation of such storms from incipient weaker larger scale disturbances which we have found somewhat tractable with high resolution global models. In these studies we shall be carrying out medium range prediction experiments for cases that include the formation and the landfall phases. In section 1.4 we have outlined some of the early results that were most promising.

Specifically we shall be addressing the following types of studies:

a) Mixed resolution experiments. We are interested in examining dynamics at as high a resolution as T170 and physics at T106. Our current feeling is that this might handle the phase speed and amplitude reasonably well. This requires some major code modifications that we shall be implementing. This problem is trackable on the CRAY/XMP since the dynamics are fully vectorized. We have applied for computer resources to carry out these experiments.

b) We shall analyze and write a detailed report on the completed experiments on the formation of hurricanes Frederic and David, and Typhoons Abby and Hope all from the FGGE year. All of these experiments were carried out at a resolution of T106 except for studies on Typhoon Hope which were carried out at all of the resolutions (T21, T31, T42, T63 and T106). This analysis will include a study of the physical parameterization at the different resolutions. Budget studies of these completed experiments will provide a better interpretation of the model - cyclogenesis - these will be carried out for each of these storms.

Navy Interests

Specifically the Navy interests are in cyclone motion forecasting, understanding of the recurvature problem and towards preparation of a numerical weather prediction relevant to a proposed field experiment in the western Pacific Ocean. The very high resolution global model can systematically explore the cyclone motion and recurvature problem in the real data environment. We can address issues such as the motion of the storm under barotropic conditions and all the way to the highly convective situations: We can rather clearly lay out the tracks as predicted by dynamics and various complexity of the physical processes. We are developing our codes to specifically adress the storm motion problem in a modular fashion when we permit the dry dynamics to coexist with the physical processes. We strongly believe that a high resolution model, such as these we are developing, can answer these questions in a very realistic manner.

For the field experiment we wish to propose a limited area dense observing system within a 150 km^2. The region centered over a storm within the Greg Holland's western Pacific Network should have 3 to 4 levels of flight level observations and dropwindsonde from research aircraft. An outer box roughly 500 km^2 should also be covered with dropwindsonde. Such a probe of the storm should be continued for a 3 to 4 day period as the storm traverses the Greg Holland Network. A 4-D assimilated analysis of this data would then be analyzed starting from 10 km^2 to 100 km^2 at several resolutions. The hypothesis we propose to test is that given adequate 4-Dimensional observations to a certain resolution the 24 hour prediction error would not exceed 5 grid points at that resolution. Experiments starting from a 10 km horizontal (with a multilevel regional PE model) can be important for exploring improvement of the state of the art of storm motion forecasting.

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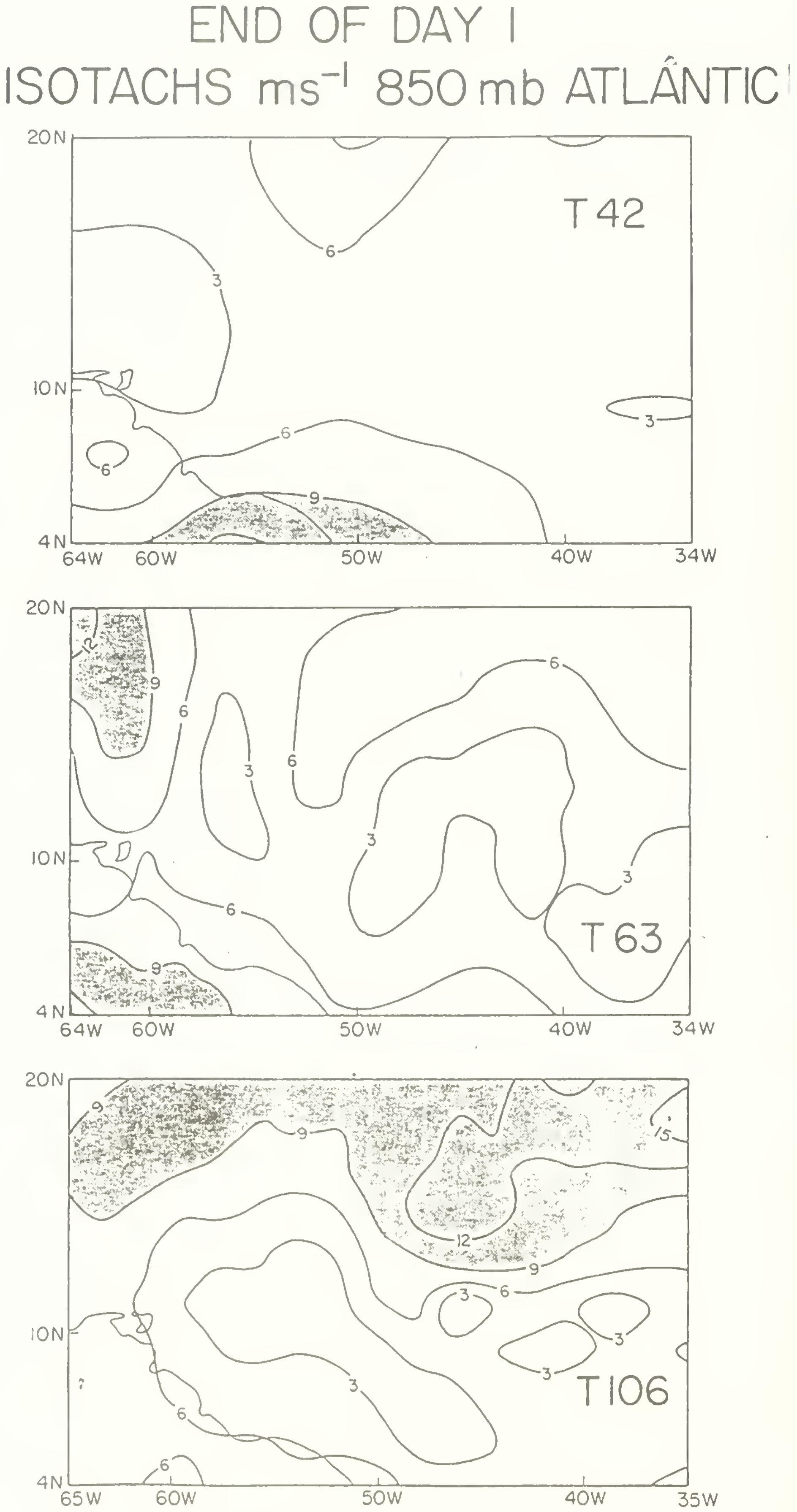
Acknowledgements:

This work could not have been completed without the support of Bob Abbey. The funds came from ONR Contract No.

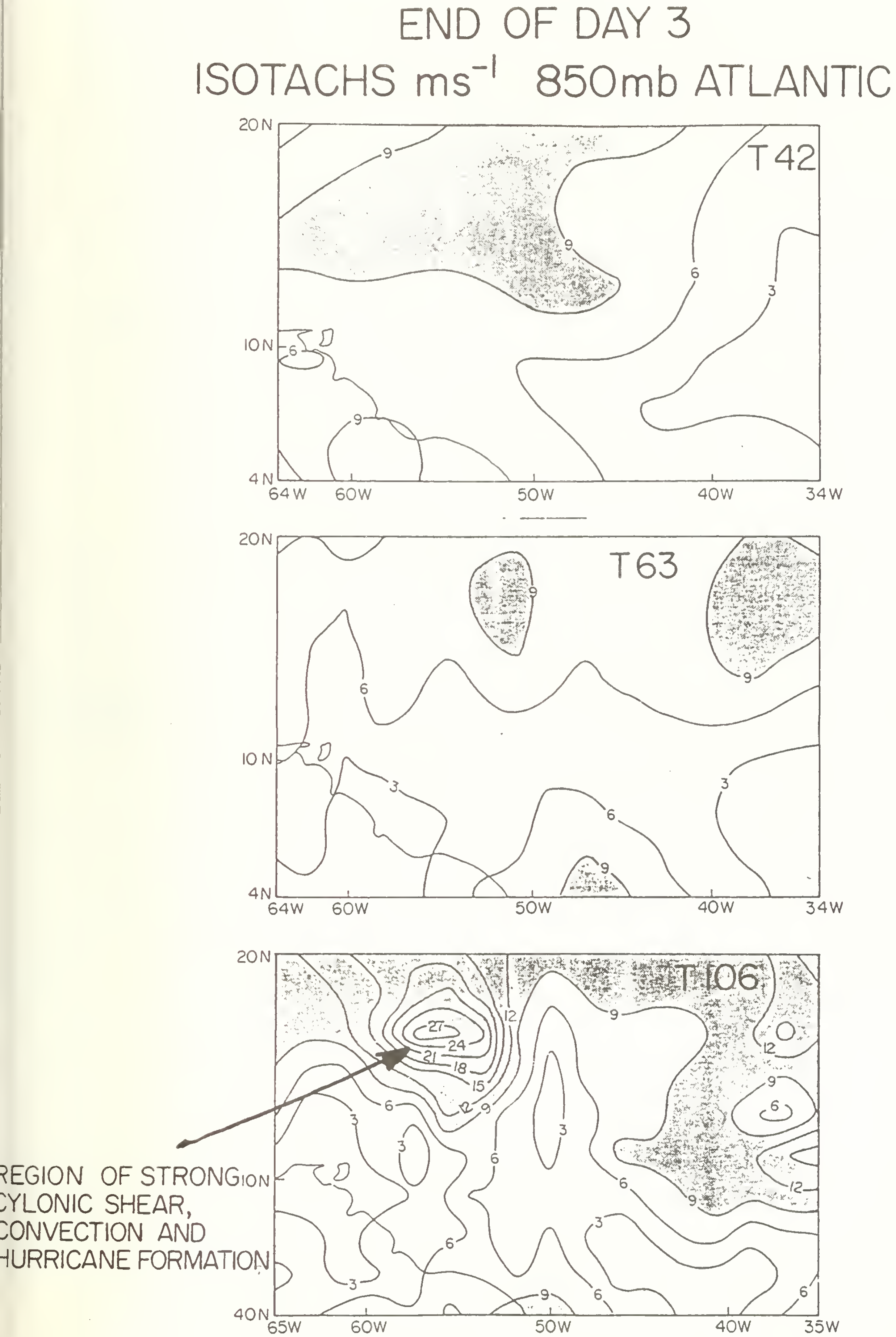
Figure Captions

Fig 1a	Predicted isotachs. Hour 24 of forecast for T42 (top), T63 (middle) and T106 (bottom). 850 mb. Hurricane Frederic (1979).
Fig 1b	Same as Fig 1a for Hour 72 of forecast.
Fig 2	24 hourly predicted precipitation, Typhoon Hope (1979).
Fig 3a	Predicted winds at 850 mb. Typhoon Hope (1979) every 24 hours.
Fig 3b	Observed and predicted track. Typhoon Hope (1979).
Fig 4	Observed and predicted track. Typhoon Abbey (1983).
Fig 5	Predicted and observed tracks of Typhoon Abbey (1983) made from different models, Chan (1986).
Fig 6	850 mb ECMWF analysis, Typhoon Abbey (1983).
Fig 7	Predicted 850 mb winds, Typhoon Abbey (1983).
Fig 8	Predicted sea level pressure, Typhoon Abbey (1983).



Isotachs (ms^{-1}) over the Atlantic Ocean day 1 of forecast at 850 mb for three different resolutions. Hurricane Frederic.

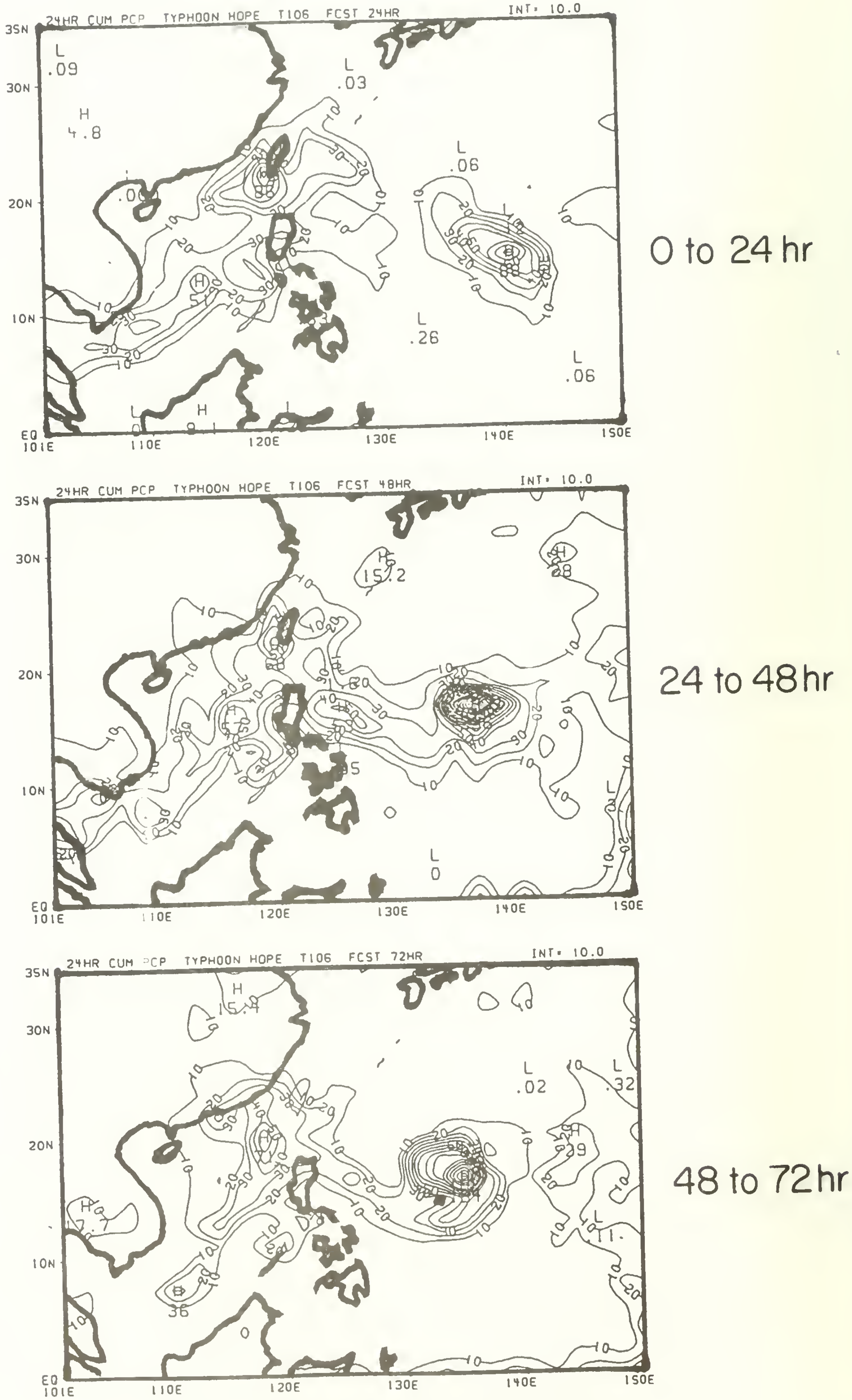
Fig.



Isotachs (ms^{-1}) over the Atlantic Ocean day 3 of forecast at 850 mb for three different resolutions. Hurricane Frederic.

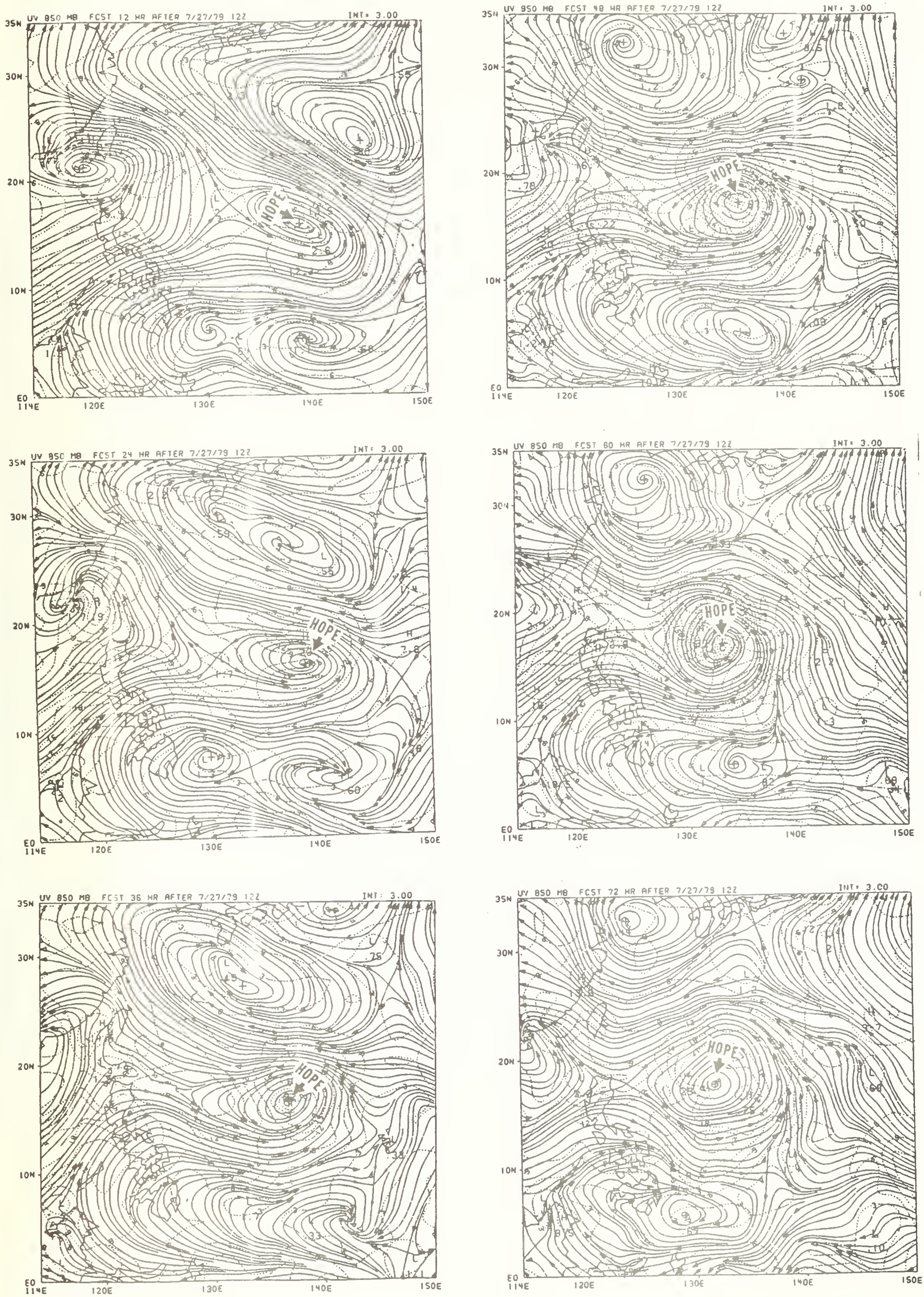
Fig. lb

TYPHOON HOPE,
T 106 PRECIPITATION mm



Typhoon Hope. Precipitation (T106).

Fig.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HOPE
UV 850 MB FCST 48 HR AFTER 7/27/79 12Z INT= 3.00
HOPE
UV 850 MB FCST 24 HR AFTER 7/27/79 12Z INT= 3.00
HOPE
UV 850 MB FCST 60 HR AFTER 7/27/79 12Z INT= 3.00
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HOPE
UV 850 MB FCST 72 HR AFTER 7/27/79 12Z INT= 3.00
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20N
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130E
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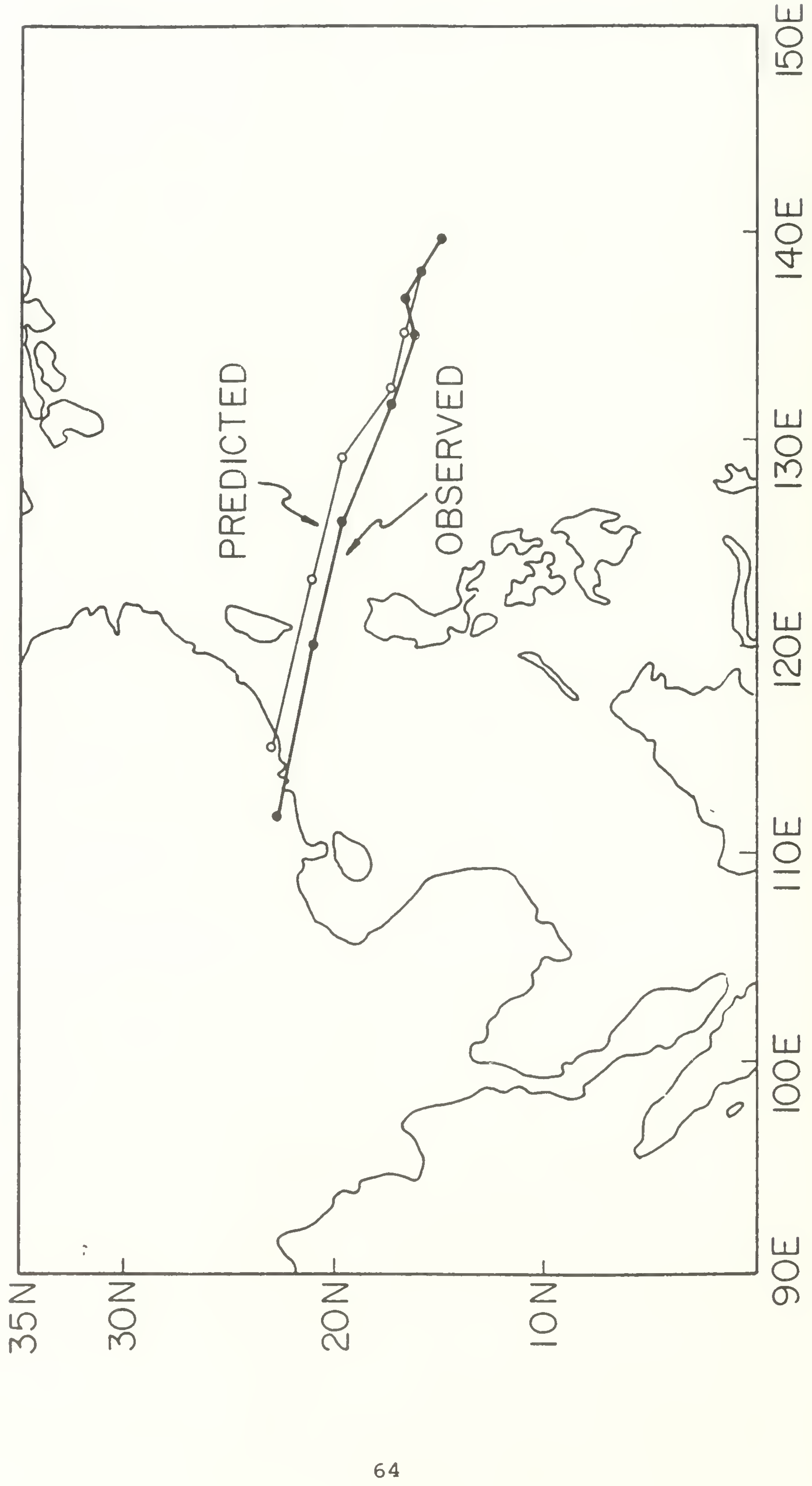
150E

Fig. 3a


PREDICTED
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100E
110E
120E
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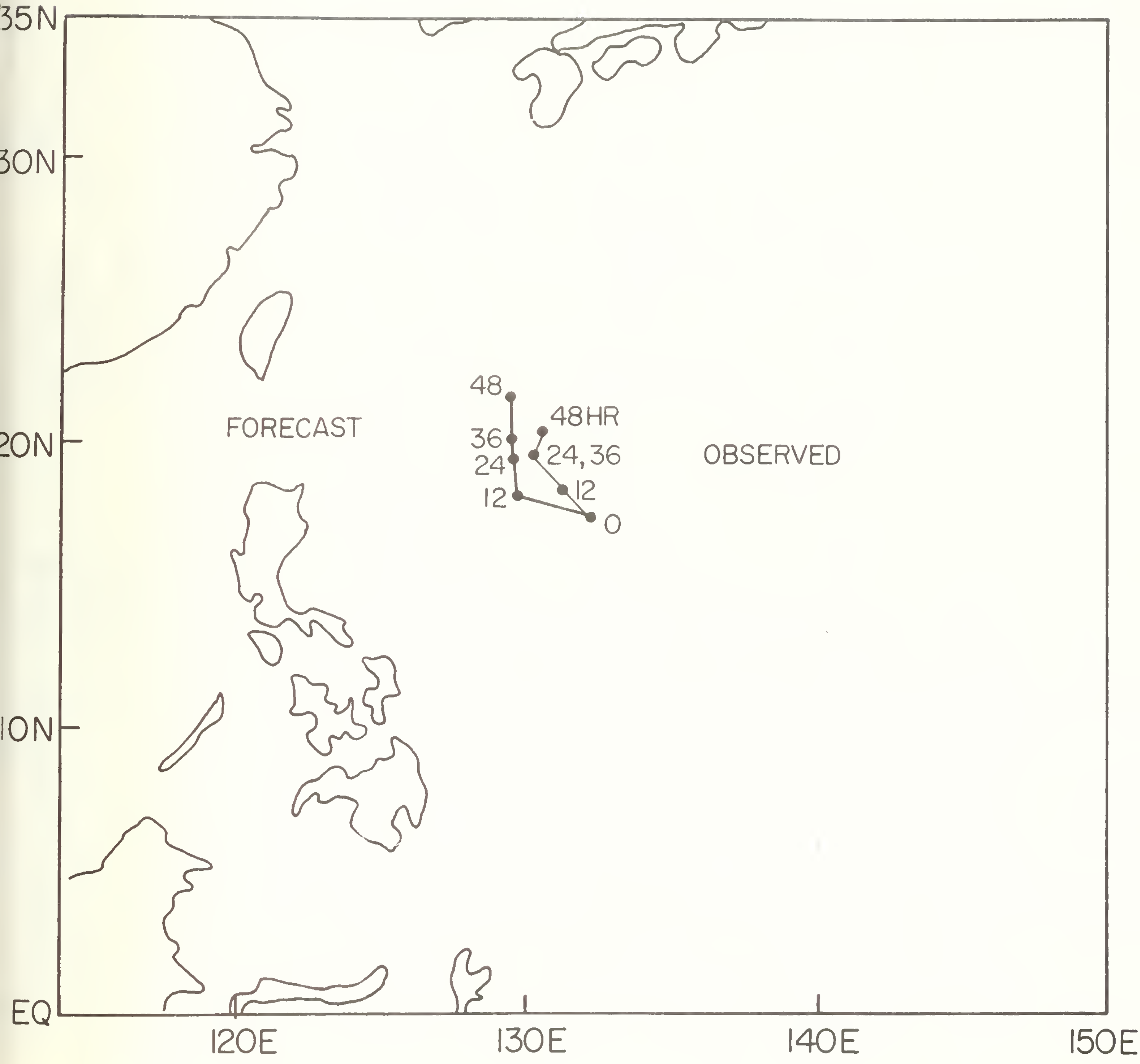
140E
150E

Fig.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10N
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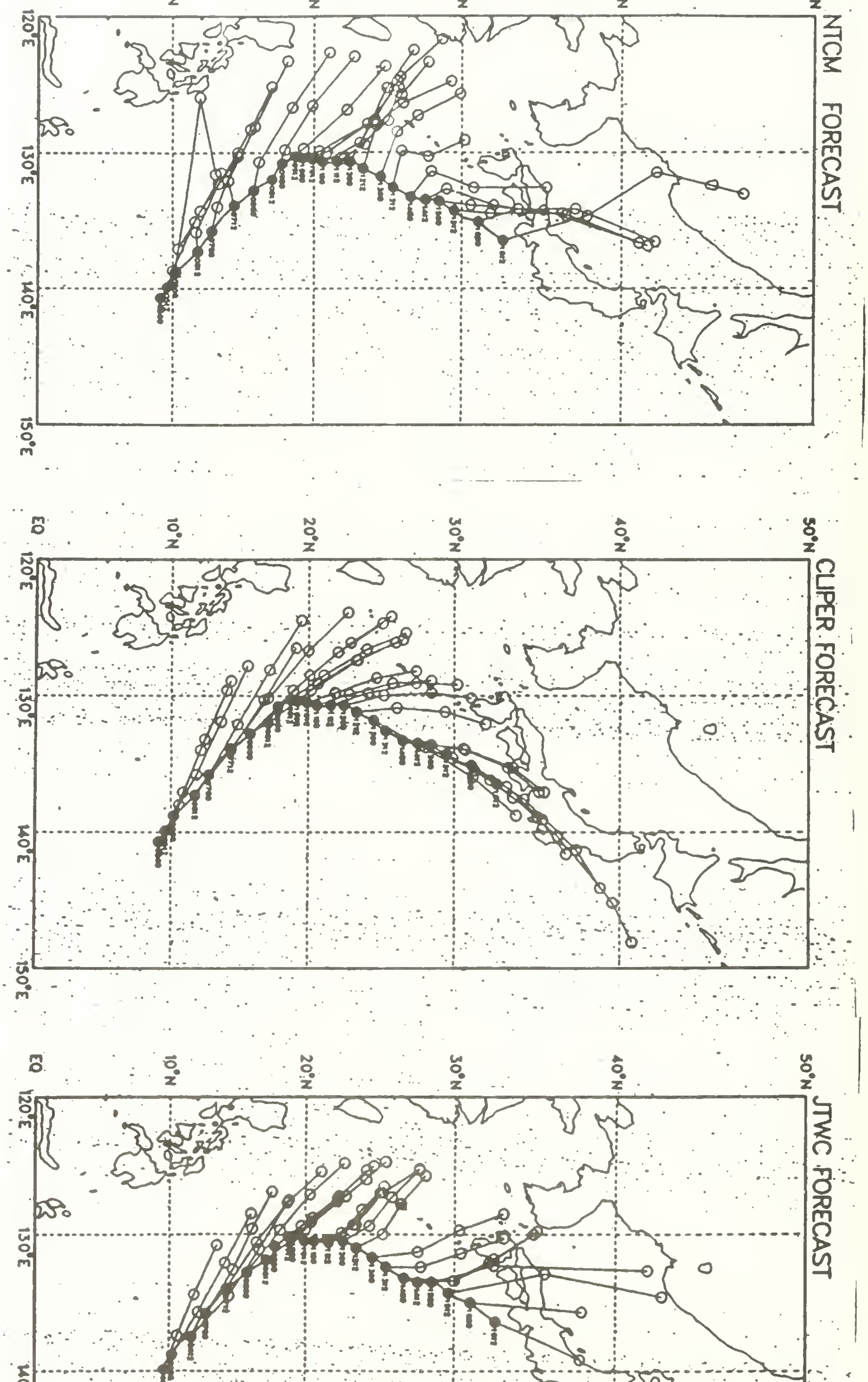
0

Fig. 4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CLIPER FORECAST
JTWC FORECAST
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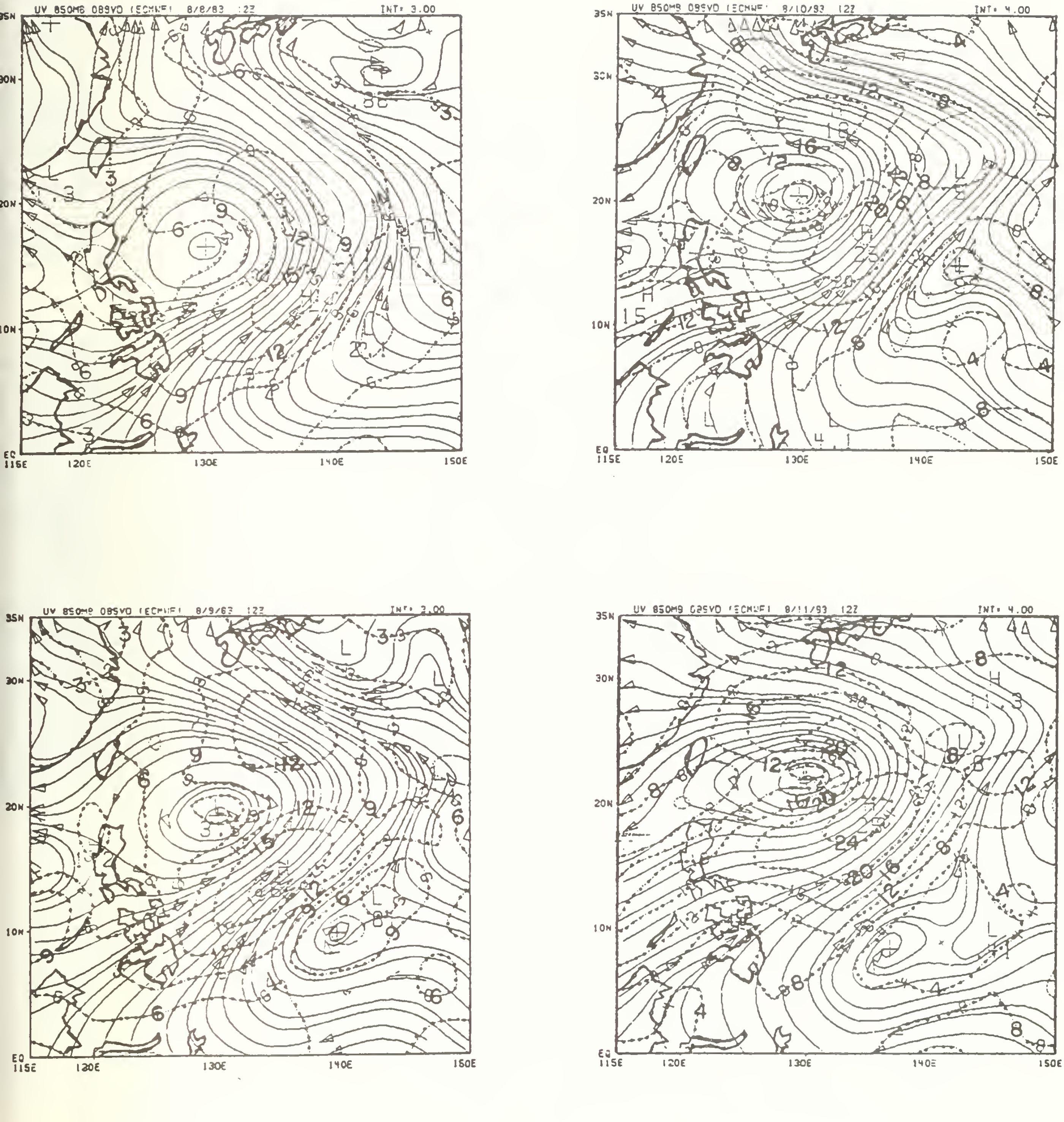
150°E

Fig. 5


UV 850MB OBSVD (ECMWF) 8/8/93 12Z INT= 3.00
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UV 850MB OBSVD (ECMWF) 8/9/93 12Z INT= 3.00
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35N
30N
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H

Fig. 6

FORECAST WINDS FOR TYPHOON ABBY (1983)

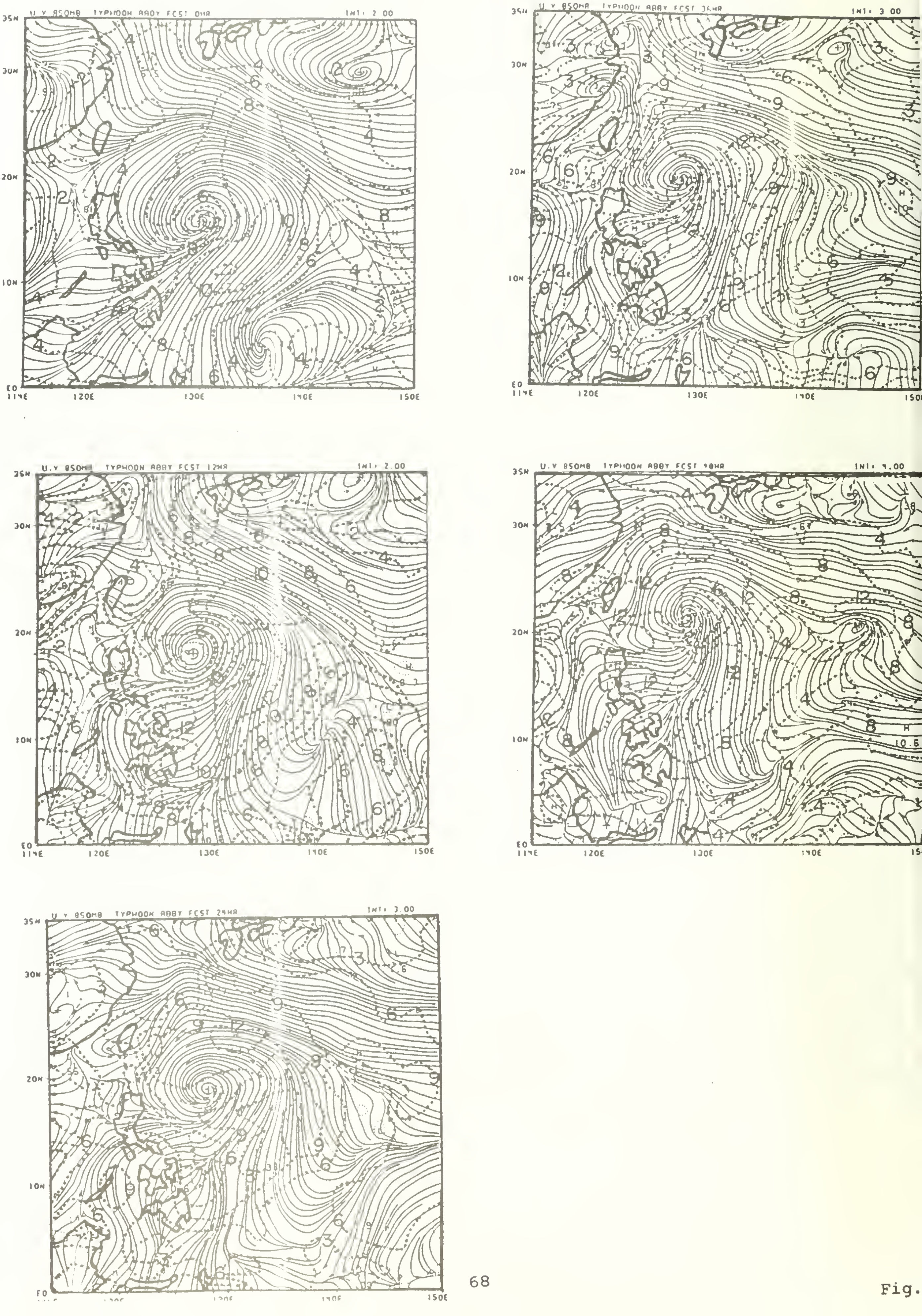
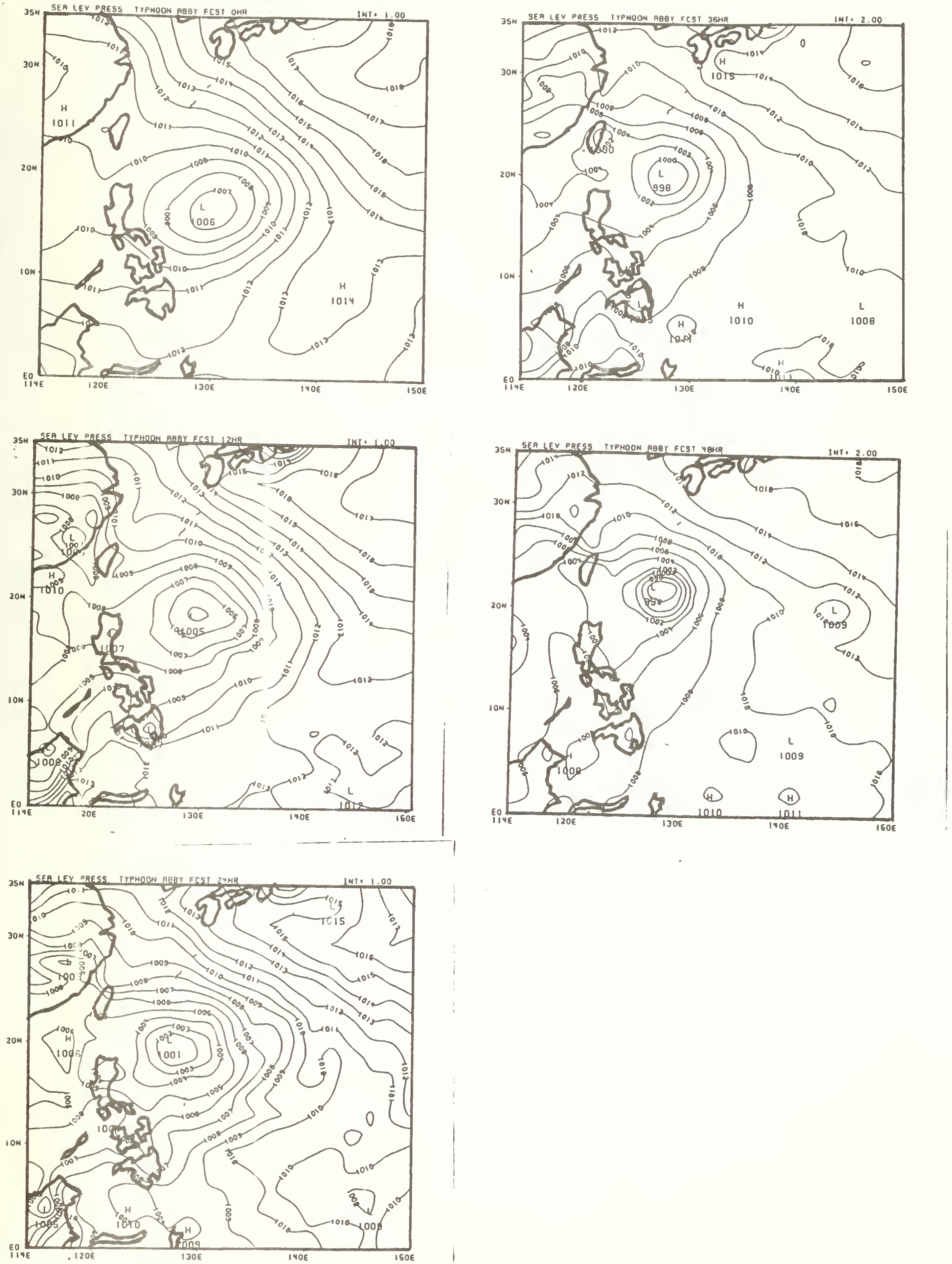


Fig.


SEA LEV PRESS TYPHOON ABBY FCST 0HR
INT= 1.00
H 1011
L 1006
H 1014
SEA LEV PRESS TYPHOON ABBY FCST 12HR
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L 1005
H 1010
L 1012
SEA LEV PRESS TYPHOON ABBY FCST 24HR
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L 1001
H 1015
H 1010
SEA LEV PRESS TYPHOON ABBY FCST 36HR
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H 1015
L 998
H 1010
L 1008
SEA LEV PRESS TYPHOON ABBY FCST 48HR
INT= 2.00
L 1009
H 1010
H 1011
35N
30N
20N
10N
EQ
114E
120E
130E
140E
150E

Fig. 8

THEORY OF TROPICAL CYCLONE MOTION

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In this research the motion of tropical cyclones is investigated with a non-divergent barotropic model. We have shown (Chan and Williams, 1987) that a vortex can move when there is no basic flow as a result of the beta effect. The interaction between the planetary Rossby wave dispersion and the vorticity advection induces an asymmetric circulation which causes the vortex motion. Fiorino (1987) has shown that the vortex moves very nearly with the asymmetric flow across the center, and that the speed is principally dependent on the outer wind structure of the vortex. Our work and especially that of Fiorino shows that the asymmetry is dominated by wavenumber one around the vortex, at least in the inner region. Willoughby (1988) has formulated a shallow water analytical model based on a linearization with respect to the vortex. He includes friction and looks for solutions which are steady in the frame of reference moving with the storm. Willoughby finds a number of solutions for each case in which the vortex moves with different speeds and directions, and he uses a minimization of the Lagrangian of the system which picks the most likely direction and speed. When Willoughby applies this theory to the beta drift problem, he obtains the right direction of propagation, but the speed is an order of magnitude too large. One of our objectives is to develop a simple model similar to Willoughby's which can explain the numerical solutions.

In order to discuss the various physical effects it is useful to breakup the streamfunctions as follows:

$\tilde{\psi}(r)$ = symmetric vortex, $\bar{\psi}(r \cos \theta)$ = zonal current which is a function of latitude, ψ' = asymmetric perturbation. The vorticity equation in cylindrical coordinates can be written:

$$\frac{\partial \zeta'}{\partial t} + \frac{\tilde{v}'}{r} \frac{\partial \zeta'}{\partial \theta} + u' \frac{\partial \tilde{\zeta}}{\partial r} + V' \cdot \nabla \zeta'$$

$$+ \bar{u} \, (r \sin \theta) (\cos \theta \, (\frac{\partial \tilde{\zeta}}{\partial r} + \frac{\partial \zeta'}{\partial r}) - \frac{\sin \theta}{r} \frac{\partial \zeta'}{\partial \theta} \,]$$

$$+ [\cos \theta \, (\tilde{v} + v') + \sin \theta \, u'] \, (\beta + \frac{\partial \bar{\zeta}}{\partial r} \,] = - K \zeta', \qquad (1)$$

where K is a linear function coefficient. If we set the zonal mean flow to zero and linearize following Willoughby (1988) we obtain:

$$\frac{\partial \zeta'}{\partial t} + \tilde{v} \frac{1}{r} \frac{\partial \zeta'}{\partial r} + u' \frac{\partial \tilde{\zeta}}{\partial r} = - \cos\theta \tilde{v} - K\zeta'. \qquad (2)$$

If the vortex moves with speed C in the direction ϕ, the linearized time tendency becomes

$$\frac{\partial \zeta'}{\partial t} = - C \cos \, (\phi - \theta) \, \frac{\partial \tilde{\zeta}}{\partial r} \quad . \qquad (3)$$

In Willoughby's study he assumed a steady state in the moving coordinate system which corresponds to eliminating $\partial \zeta'/\partial t$ between (2) and (3). In our study we did not want to make the steady state assumption so we treat the following equation in the moving coordinate system:

$$\frac{\partial \zeta'}{\partial t'} = C \cos(\phi - \theta) \frac{\partial \tilde{\zeta}}{\partial r} - \tilde{v} \frac{1}{r} \frac{\partial \zeta'}{\partial \theta} - u' \frac{\partial \tilde{\zeta}}{\partial r} - \cos\theta \tilde{v} - K\zeta' \quad (4)$$

Here t′ indicates the moving coordinate system. We took the wave number one component of (4) and then wrote it in complex form. The resulting equation was then solved with time implicit finite difference scheme. The equations were integrated with friction from an initial condition of zero amplitude for wave number one. The solutions approached a steady state most rapidly for vortices which moved toward the northwest and the approach was much slower for some other directions of movement. Also for a fixed speed C, the vortices which moved to the northwest tended to have the smallest wavenumber one amplitude.

In order to consider the steady motion problem in more detail, set $\partial/\partial t = 0$ in (2) and divide by $\partial\tilde{\zeta}/\partial r$ which yields

$$C \cos(\phi-\theta) - \frac{\tilde{v}}{r\partial\tilde{\zeta}/\partial r} \frac{\partial \zeta'}{\partial \theta} - u' - \cos\theta \frac{\tilde{v}}{\partial\tilde{\zeta}/\partial r} - \frac{K\zeta'}{\partial\tilde{\zeta}/\partial r} = 0. \quad (5)$$

Since the numerical experiments used no friction, it is reasonable to neglect the last term in (5). With K = 0 this equation is independent of the overall strength of the vortex since the terms involving $\tilde{v}$ do not change if a given wind profile is multiplied by a constant. This indicates that the speed C cannot be determined by the Eq (5) since our numerical experiments show that the speed increases when the overall vortex strength is increased. We have solved both (4) and (5) with $K = 0$. The solution from (4) showed extremely slow convergence to the steady state, although an approximate balance developed within a moderate period of time. The steady state solutions to (5) had very large amplitudes. In order to obtain an orientation which corresponded to the motions of the vortex, it was necessary to choose a value of C which was at least 10 times too large, which agrees with Willoughby's results. We suggest that the motion may depend on the outer flow which has more the character of planetary Rossby waves. This is consistent with analyses carried out by Fiorino which demonstrates the importance of the outer part of the vortex on the movement.

We also studied vortex motion in non-uniform basic currents by integrating the barotropic vorticity equation directly. The first case treated was the linear shear field

$$\bar{u}(y) = u_o + \alpha y, \tag{6}$$

where u_o and α are constants. For interpretation we substitute (6) into (1) which yields

$$\frac{\partial \zeta'}{\partial t} + \left(\frac{\tilde{v}}{r} - \frac{\alpha}{2}\right) \frac{\partial \zeta'}{\partial \theta} + u' \frac{\partial \tilde{\zeta}}{\partial r} + V \cdot \nabla \zeta' + u_o\left[\cos\theta \left(\frac{\partial \tilde{\zeta}}{\partial r} + \frac{\partial \zeta'}{\partial r}\right)\right.$$

$$\left. \frac{\sin\theta}{r} \frac{\partial \zeta'}{\partial \theta}\ \right] + \frac{\alpha r}{2}\left[\sin 2\theta \frac{\partial \tilde{\zeta}}{\partial r} + \sin 2\theta \frac{\partial \zeta'}{\partial r} + \frac{\cos 2\theta}{r} \frac{\partial \zeta'}{\partial \theta}\right]$$

$$+ (\cos\theta\ \tilde{v} + \cos\theta\ v' + \sin\theta\ u')\ \beta = 0. \tag{7}$$

The experiments with $\beta = 0$ showed no net motion, but a small wavenumber two perturbation did develop. The forcing of wavenumber two comes from the term $(\alpha r/2) \sin 2\theta \ \partial\tilde{\zeta}/\partial r$.

The experiments with $\beta \neq 0$ showed significant motion. For $\alpha > 0$ the vortex moved to the right of the no shear track and for $\alpha < 0$ it moved to the left. As the vortex moves northwest because of the beta drift it was advected by the westerly ($\alpha > 0$) or easterly ($\alpha < 0$) winds. For $\alpha > 0$, the vortex moved farther to the north than for $\alpha < 0$. This apparently occurs because the orientation of the wavenumber one gyres is affected by the shear contribution to the term $(\tilde{v}/r - \alpha/2) \ \partial\zeta'/\partial\theta$. This change in orientation changes the direction of motion.

Other numerical experiments were carried out with a parabolic jet. This profile leads to a modification of the beta drift and also some advective effects.

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Linear Motion of a Shallow-Water, Barotropic Vortex

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A barotropic model of tropical-cyclone motion follows from calculation of linear wavenumber one perturbations on a moving, axisymmetric, maintained vortex. The perturbations are Rossby waves that depend upon the radial gradient of axisymmetric relative vorticity. The vortex has normal modes at zero frequency and at the most anticyclonic orbital frequency; the latter is barotropically unstable. The structure of the perturbations is calculable for arbitrary motion of the vortex, but one can select the actual motion in a particular situation because that motion minimizes the Lagrangian of the system.

Motion of tropical cyclones may arise from environmental currents, convection, or the beta effect. In an environmental current that turns as time passes, the motion is nearly the same as the current, except when the frequency matches a normal mode. The effect of convection is simulated by an imposed, rotating mass source-sink pair which excites both the normal modes and a perturbation that depends upon forcing at Rossby-wave critical radii. The latter response seems to correspond to the trochoidal motion of real tropical cyclones. It has fastest vortex motion when its frequency is the same as the orbital frequency of the axisymmetric flow where the forcing is imposed. On a beta plane, the vortex motion is poleward with speed proportional to the total relative angular momentum of the vortex. Because of the normal mode at zero frequency, the poleward motion is much too fast when the vortex has cyclonic circulation throughout. This physically unreasonable result highlights the importance of nonlinear processes in tropical cyclone motion.

Last Year Research Accomplishments on ONR Sponsored Tropical Cyclone Motion Initiative

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The following research was accomplished on the author's Colorado State University research project as related to the ONR Tropical Cyclone Motion initiative. The author is currently writing a research report to summarize this recent project research which will hopefully be available by the time of the ONR TC Motion workshop in Australia in late June.

1) TC motion as related to aircraft measured 700 mb 0-2 1/2° radius composite wind fields in 6 coordinate systems (NAT, MOT, ROT, MOTROT, MOTROT-VORT, and NAT-VORT) for various motion categories. This research is directed to the question of the cyclone's core responses to various outer wind conditions. How different are core circulation wind fields before, during, and after motion changes? A number of these results are contained in the Ph.D. thesis of C. Weatherford that is about to be circulated. The 700 mb wind field in the NW Pacific (with cyclone vortex removed) is typically through the TC from front to back. This gives a somewhat stronger tangential wind field on the left as opposed to the right quadrant. These NW Pacific conditions are opposite to those of the Atlantic where vortex removed tangential wind asymmetry is stronger on the right quadrant. These asymmetrical differences are a result of differences in tropospheric vertical wind conditions in the NW Pacific as opposed to the Atlantic. Cyclones south of the subtropical ridge in the Pacific typically have increasing zonal winds with height while in the Atlantic tropospheric zonal winds south of the subtropical

ridge typically decrease with height.

2) Our major ONR project efforts over the last year have been directed to the physical processes associated with the questions of TC recurvature vs. non-recurvature. We are analyzing recurvature and non-recurvature with our 21-year NW Pacific rawinsonde data set and also with our project's 5-year reconnaissance data sets. This involves a massive observational analysis of inner core and environmental wind-height-temperature conditions. Data is being portrayed in 4 different coordinate systems.

There are special poleward wind-height changes which occur 24-36 hours prior to recurvature which do not occur with non-recurvature. Differences are greatest in the upper troposphere at levels of 100-300 mb. This may be beneficial for the future use of satellite sounder systems to help predict recurvature. The question of how and on what time scale surrounding cyclone environmental wind-height changes are transmitted to the cyclone center to cause it to change its direction and speed of motion is being better sorted out. This subject is believed to be very important because recurvature is considered to be the major operational forecast problems of the NW Pacific. There are also a number of basic vortex motion physical questions associated with recurvature. A forthcoming project report by S. Hodanish and W. Gray (1988) is being prepared.

3) We have analyzed initial TC position error as related to 24-48-72 hour TC motion prediction by JTWC, OTCM, CLIPPER, etc. for the period of 1979-1986. When initial positions relative to post-analysis best tracks are significantly in error, 24-hr. forecasts are influenced by about a like amount. There are, however, not so many errors relative

to 48-72-hr forecast positions except in recurvature situations where initial fix position errors are carried well out to 72 hours. These results will be reported upon in a forthcoming CSU project report by J. Martin (1988).

4) Chan and Williams (1987) have reported TC motion-environmental influences associated with TC vortex outer-core wind strength differences. We have been documenting the wide variety of different TC outer-core wind strengths which can occur with NW Pacific tropical cyclones as measured by reconnaissance data out to 2 1/2° to 4° radius. These results are being published in two papers in the March 1988 Monthly Weather Review by C. Weatherford and W. Gray. This research has been partially supported by ONR sponsorship to the author's project.

5) Our project's association with Vonder Haar's CSU satellite systems and with Raymond Zehr and his NOAA/NESDIS/RAMM satellite products is enabling us to quantitatively explore in more detail the possible association of TC motion with deep cumulus convection. There may be some degree of TC deep convection and motion association. Whether related or not this topic is, with the development of the new SMS satellite systems, a very important one for full exploration. We have begun research on this topic but as yet do not have results to report. These results should be available next year.

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