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NAVAL POSTGRADUATE SCHOOL

Monterey, California

DEPARTMENT OF THE NAVY
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OPERATIONAL DATA TESTS WITH A TROPICAL CYCLONE MODEL

Russell L. Elsberry

March 1977

Technical Report Period July 1976 - March 1977

NAVAL POSTGRADUATE SCHOOL
Monterey, California

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ABSTRACT

The coarse-grid version of the tropical cyclone prediction model described by Ley and Elsberry (1976) has been used to evaluate the effect of using operationally-analyzed rather than hand-analyzed data. A series of 41 cases from the 1975 typhoon season resulted in larger errors than the official forecasts. In most of the cases the track was forecast well, but the translation speed was slow. Tests with a fourth-order advection scheme did not lead to significant improvements over the second-order advection. Based on a subjective classification of the initial fields, it was concluded the most likely source of error was due to data deficiencies in the western Pacific region.

Wind direction estimates based on the Defense Meteorological Satellite Program (DMSP) photographs were compared to the Joint Typhoon Warning Center (JTWC) hand-analyzed streamlines. About 65-70% of the DMSP direction estimates at the gradient and 250-mb level were with ± 10° of the hand-analyzed fields. A comparison of the initial wind direction from the operationally-analyzed fields used in the tropical cyclone model and the JTWC directions resulted in large differences. Consequently the new data source of DMSP direction estimates should be used in the operational analysis.

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

(14) 1. ~~REPORT NUMBER~~ NPS-63Es77031

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER (9)

(6) 4. TITLE (*and Subtitle*) OPERATIONAL DATA TESTS WITH A TROPICAL CYCLONE MODEL,

5. TYPE OF REPORT & PERIOD COVERED Technical Report, Jul[redacted]976-Mar[redacted]977,

6. PERFORMING ORG. REPORT NUMBER

(10) 7. AUTHOR(s) Russell L./Elsberry

8. CONTRACT OR GRANT NUMBER(s) N6685677WR00036

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Postgraduate School
Monterey, California 93940

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS (12) 32p.

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Environmental Prediction Research Facility
Monterey, California 93940

12. REPORT DATE (11) Mar[redacted]77

13. NUMBER OF PAGES 28

14. MONITORING AGENCY NAME & ADDRESS(*if different from Controlling Office*)
Naval Environmental Prediction Research Facility
Monterey, California 93940

15. SECURITY CLASS. (*of this report*) Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)

Approved for public release; distribution unlimited

DDC
MAY 10 1977
C

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Tropical cyclone
Satellite wind estimates
Numerical weather prediction

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

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S/N 0102-014-6601

UNCLASSIFIED

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The author concludes that

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LIST OF FIGURES

LIST OF TABLES

1. Introduction

Based on the recent developments in numerical simulation of tropical cyclones and in limited-area, fine-mesh modeling (see Elsberry, 1975), several U.S. Navy agencies are cooperating in the development of an operational model for predicting tropical cyclone motion in the western Pacific region. Ley and Elsberry (1976) have tested a three-layer, triply-nested tropical cyclone forecast model using hand-analyzed data. The technique for initializing the nested-grid model was described by Elsberry and Ley (1976). The case selected for the feasibility study was a late-season typhoon that had been forecast to recurve in advance of a middle-latitude trough. Both the nested-grid model and a coarse-mesh version predicted correctly the non-recurvature of Irma and the subsequent westerly track. Consequently, the coarse grid model was selected for efficient evaluation with a large number of operationally-analyzed cases.

One of the important problems in the application of a model with operational data is the separation of errors that are caused by shortcomings in the numerical model from those due to data deficiencies. A total of 41 cases during the 1975 season were selected for the operational data tests. A large number of typhoons during 1975 tracked from south-to-north, which resulted in higher forecast errors than in previous seasons (Annual Typhoon Report, 1975). The initial fields for the 2° latitude coarse-mesh model were interpolated from the Fleet Numerical Weather Central (FNWC) global band upper air analyses (GBUA). The only modifications to these operationally-analyzed fields were in bogusing the typhoon circulation. In the GBUA fields the only bogus is at the gradient level. Although this circulation will tend to be reflected in the upper levels due to the variational procedure used in creating the GBUA (Lewis, 1972), the circulation will be considerably weaker than at the surface. Because the gradient-level bogus was primarily for "cosmetic purposes", the storm was located somewhat arbitrarily on the relatively coarse global band grid (Numerical Environment Products Manual, 1975). The first modification of the bogus procedure was to locate the center as precisely as possible within the coarse grid model. This was done by repeated smoothing of the wind fields in the region of the storm center, and then inserting a symmetric bogused storm based on the warning messages. This method uses only the information that would be available on an operational basis, rather than using the best track or post-season analyses, which are presumably more accurate. In the second procedure the cyclonic circulation was also bogused at the middle and upper layers with percentage reductions of 75% and 25% respectively. A small warm area centered on the typhoon location was also added to the 850-mb temperature field. The model results to be summarized below were initialized with the second procedure. Although exceptional cases occurred, the proper placement of the storm center was a more important feature than the vertical structure of the bogus.

A number of model modifications were programmed by R. Perry of NEPRF in adapting the coarse-mesh model to run in an operational environment. Numerous utility programs were necessary to provide data and constants on a relocatable grid. One of the major changes was to incorporate a direct solver (Rosmond and Faulkner, 1976) for the Poisson equations in the initialization. It was convenient at the same time to expand the grid from 28 (east-west) by 20 points to 32 by 24 points. Modifications to the numerical scheme include provision for a fourth-order advection scheme, a Robert time filter and some additional smoothing to reduce noise. Various routines were optimized to reduce the running time to nearly the same time required by the Ley and Elsberry (1976) version on the smaller grid.

It should be noted that a similar model was adapted for quasi-operational predictions at FNWC by LT D. Hinsman. One of the products of this work was an objective scheme for tracking the maximum vorticity center associated with the typhoon.

The purpose of this report is to evaluate the model results with operationally-analyzed data for selected typhoons during 1975, and to evaluate a new data source for improving the specification of the initial fields for the tropical cyclone model. Wind direction estimates at both lower and upper levels were derived by personnel at Anderson Air Force Base from the high-resolution, Defense Meteorological Satellite Program (DMSP) photographs. These direction estimates were made available to the Joint Typhoon Warning Center (JTWC) during the 1975 season, but were not used in the GBUA at FNWC.

2. Evaluation of 1975 Tropical Cyclone Model Predictions

The primary objective of the tests with the coarse-mesh model was to evaluate the problems associated with the use of operationally-analyzed data. One might anticipate more serious data deficiencies in the western Pacific than in the western Atlantic or eastern Pacific regions where cloud motion vectors are routinely available from the geostationary satellites. A second objective was to determine whether a very crude dynamical model would provide guidance for forecasting recurving storms. Forecast schemes based on climatology and extrapolation of the present movement tend to give excellent results for periods up to a day. By contrast, the difficulty of placing the storm center at the reported initial location and of tracking the subsequent movement on a grid with only 2° latitude resolution contributes to dynamical model errors that are large compared to the 24-h displacements. However, the non-dynamical forecast techniques are less reliable in situations involving interaction with surrounding systems. Such an interaction was presumably the cause of the large number of south-to-north displacements during the 1975 season, and it was therefore decided to test the tropical cyclone model with cases selected from that period.

One of the primary results of the 41 cases from the 1975 season was that the track was forecast better than the rate of displacement. A similar result has been reported by Hovermale et al. (1976) for predictions of Atlantic hurricanes made with a more complex numerical model. Three sample forecasts of Typhoon Ida are shown in Fig. 1. This storm was difficult to forecast because of the predominately northward track from initial detection near 10N. Each forecast was initiated at 00 GMT on the date shown along the track. Predicted 24-, 48- and 72-hr displacements were consistently smaller than the corresponding observations. Except for the first 24-h movement on each day, the predicted tracks tended to parallel the observed tracks. A second sample of forecasts of Typhoon Elsie is shown in Fig. 2. One can note that the initial storm locations on the 2°latitude grid did not always coincide with the actual location of the center. The 24-, 48-, and 72-h movement predictions were again slow compared to the observed displacements, except for the 14 October forecast. One particularly successful storm track prediction was the forecast for a predominately westward movement beginning 00 GMT October 10, since it followed a northward track during the preceding 6-12 h. By contrast, a prediction of recurvature based on the forecast initiated 13 October 1975, would have been very misleading.

The question is then what causes the slow displacements and the occasional poor track directions in the model predictions. One explanation is that the slow displacement is due to the typical phase speed errors associated with small-scale features that are inadequately resolved with

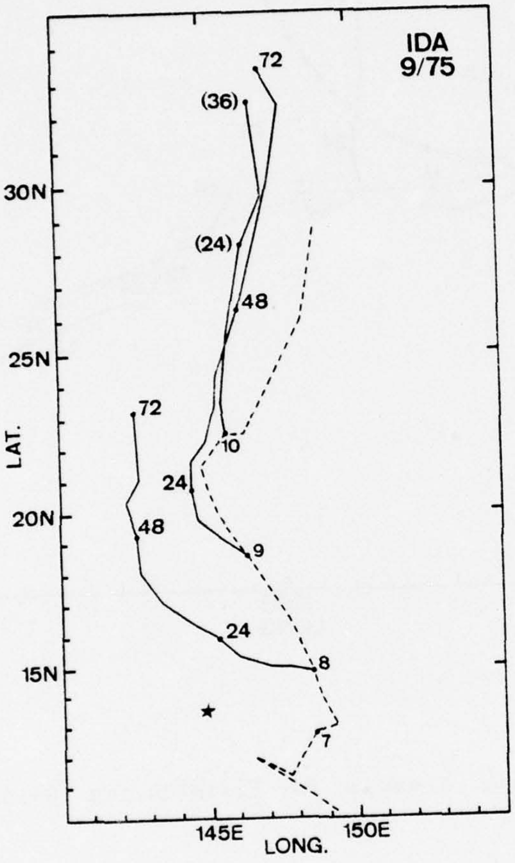

Fig. 1. Warning positions (dashed) and 24-, 48- and 72-h tropical cyclone model predictions for tropical cyclone Ida during the period 7-10 September 1975.

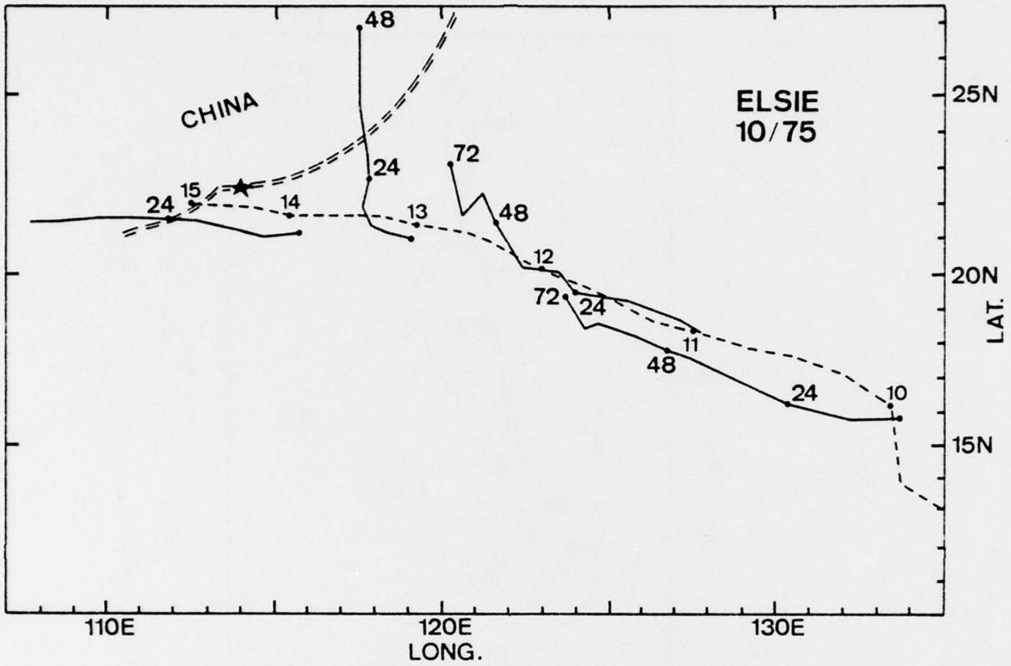

Fig. 2. Same as Fig. 1 except for Elsie during 10-15 October 1975.

a coarse-grid model. Indeed, one justification for developing a nested grid model is to improve the resolution. Another possible explanation lies in the poor vertical resolution in the present models. With only three layers the interaction between the hurricane and the basic flow may not be well represented, especially in the outflow layer. A third possibility is that there is an incorrect specification of the large-scale flow. The sparsity and the irregular distribution of the data could produce a bias in the initial fields. In addition, there may be inadequate physics in the coarse-mesh model to properly simulate the evolution of the large-scale features during the forecast interval. As a poor specification of the initial fields could explain both the slow displacements and the occasional poor track prediction, this factor was examined first.

Each initial flow field derived from the operational wind analysis (GBUA) was examined and characterized subjectively in terms of the representativeness of the synoptic features. As might be expected, there was a wide variety of situations depending on the size and intensity of the typhoon, and on the placement of the grid relative to the rawinsonde station network. Consequently, the classification of the initial fields was somewhat arbitrary. Two examples of 850-mb height fields that were derived from the analyzed wind fields (see Ley and Elsberry, 1976, for a description of the reverse balancing approach) will be shown to illustrate the classification. The height field shown in Fig. 3 was given a classification of I because the typhoon and adjacent anticyclones seem to provide a good definition of the basic flow. By contrast, the example of an initial height field shown in Fig. 4 shows a very poor definition of the large-scale features and was given a classification of (V). These poorly defined cases tended to occur when the storm was weak, or when the storm was well-removed from the Asian

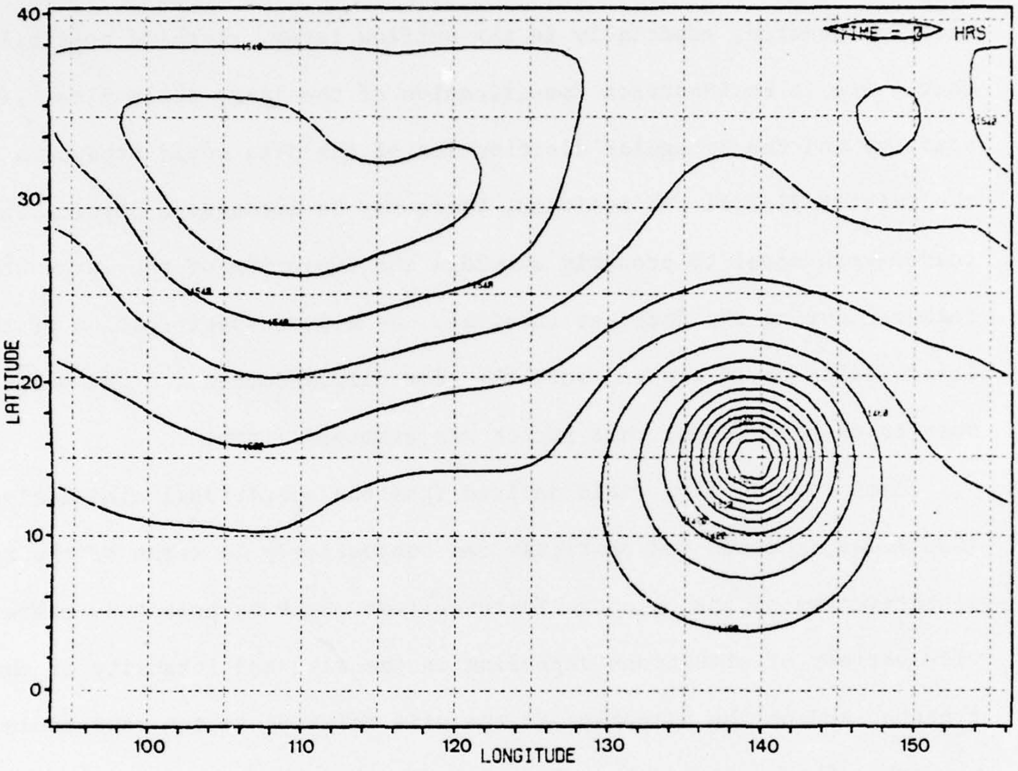

Fig. 3. Example of initial 850-mb height field given a classification of I (see text). The contour interval is 20m.

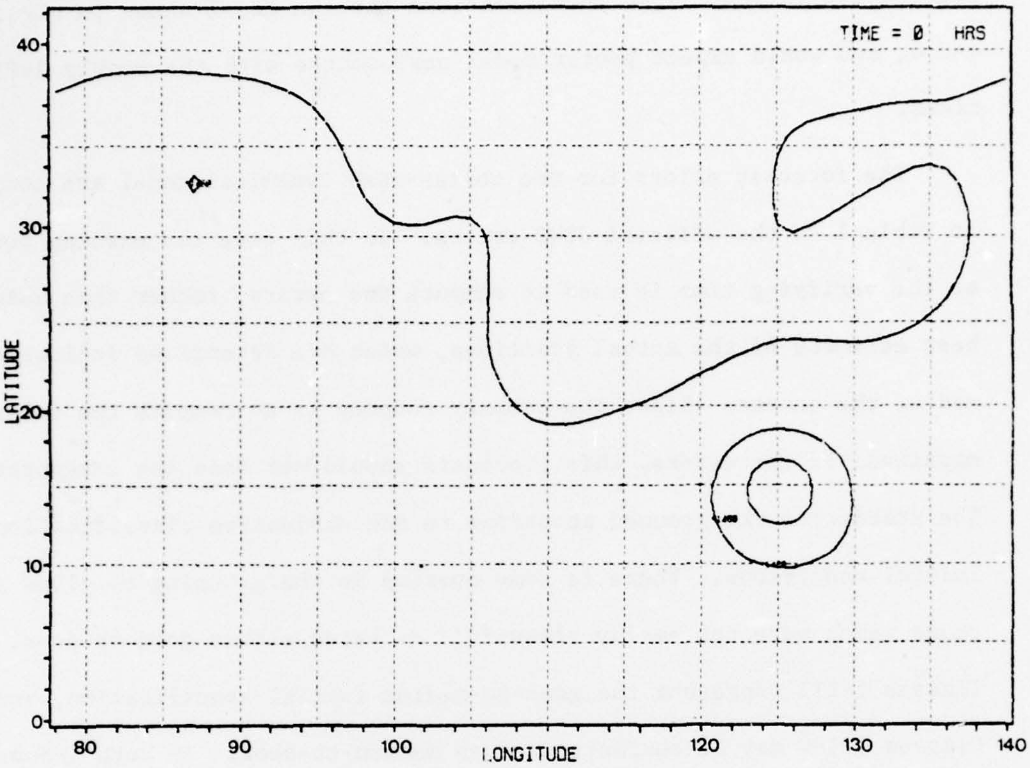

Fig. 4. Same as Fig. 3 except for classification of V.

continent, and thus was in a region of poor rawinsonde data coverage. Although the judgment was subjective, most analysts would distinguish between the initial field specifications for the model shown in Figs. 3 and 4, and would expect poorer model performance with the poorly defined cases.

The forecast errors for the coarse-mesh dynamical model are compared in Table 1 to the official JTWC errors. In this case the warning position at the verifying time is used to compute the errors, rather than using the best estimate of the actual positions, which are determined following the end of the season. Since the primary purpose is to compare the relative magnitude of the errors, this procedure should not bias the interpretation. The statistics are grouped according to the subjective classification of the initial conditions. There is some overlap in the grouping to allow for cases which were not easily classified as being either good or poor. Classes I-III represent the good-to-medium initial specification, and Classes III-V may be characterized as medium-to-poor. In both groups the forecasts error are larger and grow more rapidly with forecast interval than for previous seasons (Annual Typhoon Report, 1975). It is somewhat encouraging that this relatively crude model resulted in 72-hr forecast errors in Classes I-III that were not much greater than the official forecasts (note that this is a very small sample). As expected, the group with poorly defined initial fields resulted in larger forecast errors than the group with better-defined synoptic conditions. It is interesting to note that the official forecast errors were also larger for the poorly-defined group, at least through the 48-hr forecast period.

Table 1. COMPARISON OF OFFICIAL AND DYNAMICAL MODEL TRACK FORECAST ERRORS (KM)

		CLASSES I-III		CLASSES III-V	
		OFFICIAL	DYNAMIC	OFFICIAL	DYNAMIC
24 Hour	N	24		17	
	A	181	259	205	329
48 Hour	N	15		15	
	A	422	546	545	600
72 Hour	N	7		10	
	A	728	768	737	881

N - SAMPLE SIZE A - AVERAGE

Table 2. COMPARISON OF TRACK FORECAST ERRORS (KM) FOR SECOND ORDER AND FOURTH ORDER ADVECTION

		CLASSES I-III		CLASSES III-V	
		SECOND	FOURTH	SECOND	FOURTH
24 Hour	N	21		17	
	A	269	260	329	334
48 Hour	N	14		15	
	A	558	534	600	635
72 Hour	N	6		11	
	A	855	923	854	889

N - SAMPLE SIZE A - AVERAGE SIZE

The nested-grid model described by Ley and Elsberry (1976) has not been run for the 1975 typhoon cases. Although one would expect some improvement, the amount may not be large if the major source of error is due to the specification of the initial fields from the operational data. An indcation of the potential improvement due to a better handling of the advection in a nested-grid model may be gained in a comparison of the coarse-grid model with higher order advection (Table 2). Numerous authors have demonstrated the improved phase propagation of fourth-order rather than second-order advection schemes. The forecast errors in Table 2 are again grouped as in Table 1, with some small changes in the averages where there is a difference in sample size. In classes I-III with the better defined initial fields, the improvement due to the fourth order advection is quite small for 24- and 48-h forecasts. Likewise for the poorly defined fields, the changes are so small as to be insignificant compared with the errors in locating the center on a 2^{o}-latitude grid. In fact, the model with fourth-order advection resulted in larger errors with the poorly specified fields.

These statistics indicate the shortcomings of the numerical model, and that a nested model may not have resulted in a significant improvement in forecast error. But more importantly, the conclusion must be that the specification of the initial fields from the operationally-analyzed data is inadequate. In addition to the problem of sparsity of data in the western Pacific, one must also consider the analysis technique, including the specification of the first-guess field. In the next section we consider the potential usefulness of a new data source --- the DMSP satellite-derived wind directions.

3. Evaluation of a new data source.

Procedure. The DMSP direction estimates are based on a particular orientation of the low-level cloud clusters in relation to the wind direction. Potential cloud clusters are numerous in the region surrounding the tropical cyclone center; however, in many cases the upper-level cirrus obscures the low-level clouds. The upper-level wind direction is estimated from the orientation of the cirrus streamers. The outflow from the tropical cyclone circulation provides a number of direction estimates. To evaluate the potential usefulness of the DMSP-based direction estimates, the ground-truth was assumed to be the JTWC hand-analyzed streamlines at the gradient and 250-mb levels. These direction estimates were available to the analyst, but were regarded as experimental. The analysts apparently attempted to fit the synoptic circulation patterns to all sources of data. However, in regions of rawinsonde or aircraft reports the analyst would generally disregard any contrary satellite-derived direction.

Wind directions from the GBUA fields were estimated at the same locations as the randomly spaced DMSP-direction estimates. Comparison of the DMSP data and the JTWC analysis indicates the reliability of the DMSP data, and comparison of the GBUA and JTWC directions is a measure of initial fields provided the tropical cyclone model for those locations. This is only indirectly an indication of the improvement of the GBUA fields if all the DMSP direction estimates were available, because it presumes an optimal objective analysis scheme that takes into account the reliability of the estimates and rejects correctly all poor estimates. One must also assign a wind speed to use these direction estimates in the objective analysis. When these direction estimates were inserted into the operational analysis at FNWC during 1976, a speed estimate at the location was interpolated from the first-guess wind field.

It should be noted that the wind directions were estimated to the nearest 10 degrees and were located to the nearest degree latitude and longitude. DMSP-based directions (especially at the gradient level) were not available for all days that the tropical cyclone model was run. As shown in Table 3 the number of estimates that fell within the domain of the TCM averaged 16 per day at the gradient level and 20 at the upper level, with maximum values of 39 and 37, respectively.

The distribution of DMSP-derived wind directions estimates at the 250-mb level is summarized by one degree latitude/longitude squares in Fig. 5. As many as five of the 34 days in this sample had a direction estimate within some of the squares at this level, and three was the maximum number at the gradient level. Generally the estimates lie in the over-water region surrounding the tropical cyclone, rather than over the land. Consequently these data tend to supplement the data coverage in the region of most interest. Good data in the near-environment of the tropical cyclone center is crucial for the 24- to 72-h forecast period.

Results. A total of 481 gradient-level direction estimates were available. The difference between the hand-analyzed streamline direction and the DMSP-derived direction is shown in the top portion of the histogram in Fig. 6. About 48% of the DMSP-derived directions were the same as the "ground-truth". This indicates that the JTWC analysts had considerable confidence in the direction estimates and attempted to fit the circulation pattern to this data. The cluster of the data about the

Table 3. Number of DMSP-Derived wind direction estimates within the domain of the tropical cyclone model.

Storm	Day	Gradient Level	250 -mb	Storm	Day	Gradient Level	250 -mb
NINA	8/2	0	22	CORA	10/2	12	37
	8/3	8	17		10/3	0	34
ORA	8/11	0	18		10/4	0	21
PHYLLIS	8/14	22	27		10/5	0	0
	8/15	13	13	ELSIE	10/10	20	30
	8/16	0	19		10/11	1	33
RITA	8/21	23	11		10/12	13	22
	8/22	13	7		10/13	10	9
TESS	9/3	34	32		10/14	1	0
	9/4	0	0	FLOSSIE	10/21	8	9
	9/5	21	16		10/22	16	18
	9/6	0	0	IDA	11/8	20	25
	9/7	0	0		11/9	0	0
WINNIE	9/10	16	19		11/10	0	0
ALICE	9/17	11	12	JUNE	11/17	22	14
	9/18	19	18		11/18	39	33
	9/19	13	7		11/19	24	18
BETTY	9/20	10	15		11/20	25	16
	9/21	22	27		11/21	5	12
	9/22	16	22		11/22	10	19
					11/23	14	19

LEVEL	DAYS	NUMBER	AVERAGE
Gradient	30	481	16
250-mb	34	671	20

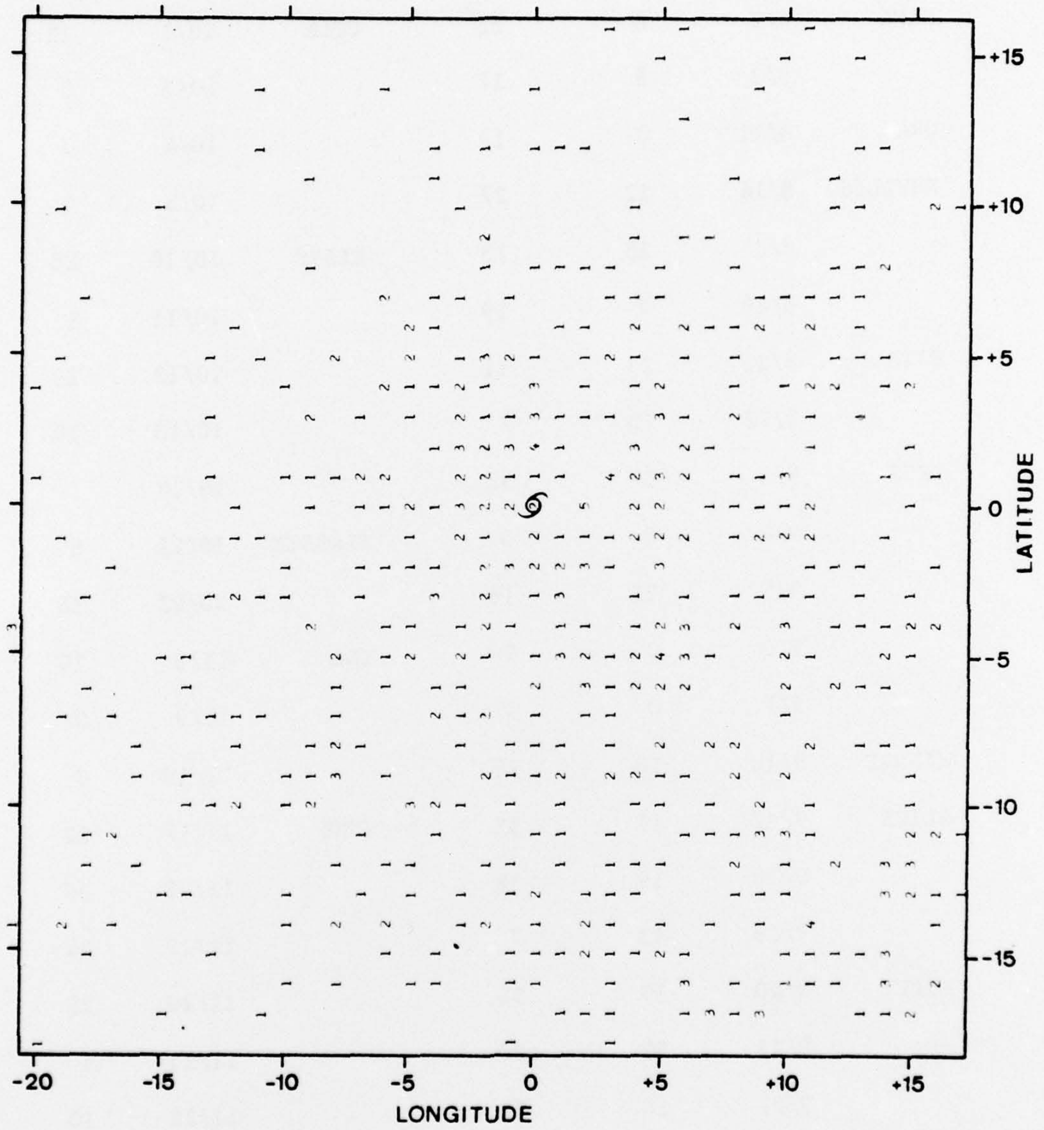

Fig. 5. Number of 250-mb DMSP direction estimates within 1° lat/long squares during 34-day period. All but 37 of the 671 reports are included.

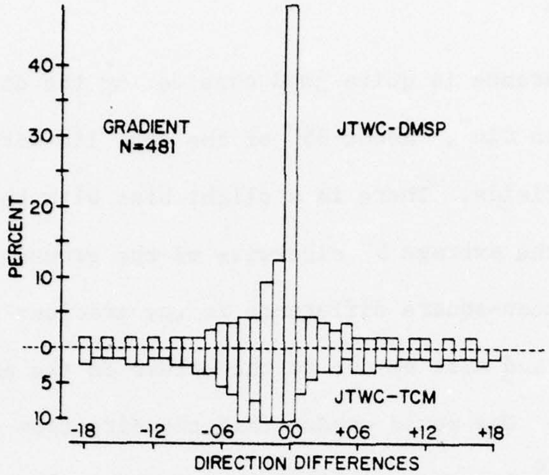

Fig. 6. Histogram of gradient-level direction differences (tens of degrees) for JTWC-DMSP (top) and JTWC-TCM (bottom).

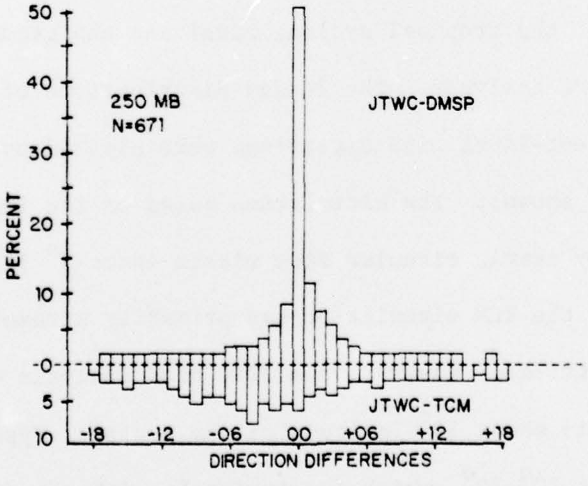

Fig. 7. Same as Fig. 6 except at 250-mb level.

zero difference is quite good considering the difficulty in reading the data to ±10°. About 65% of the data lie within ±10° of the hand-analyzed fields. There is a slight bias with the satellite directions being on the average 5° clockwise of the ground truth (see Table 4). The root-mean-square difference at the gradient level of 36° is relatively large, and must be due to the values on the extreme wings of the distribution. One would expect that the direction estimates which were nearly 180° in error would tend to occur in locations with light winds or in regions of rapidly changing directions.

The lower portion of the histogram in Fig. 6 is a comparison of the GBUA directions and the hand-analyzed streamline direction. A much broader distribution resulted with an average bias of 13° clockwise from the hand-analyzed directions. The median value was 20° clockwise, and the root-mean-square difference was 67°. This is indicative of the numerous large differences in direction between the gradient-level input fields for the tropical cyclone model and the ground truth represented by the JTWC analyses. The 30-day distributions of the JTWC and of the TCM gradient-level wind directions were plotted on a latitude/longitude grid (not shown). The circulation based on the TCM winds was characterized by nearly circular flow within about 6° latitude of the typhoon. Evidently the TCM circulation was primarily a result of the bogus, which was symmetrical. However, the JTWC hand analysis was strongly convergent within about 10° latitude of the center. Typical inflow angles were about 10°-30°, which is consistent with the differences in the histogram in Fig. 6. For example, directly east of the typhoon center the JTWC directions were typically from 160° whereas the TCM direction was 180°. Therefore, the JTWC gradient-level winds tend to be repre-

Table 4. Summary of wind direction differences (degrees) from hand-analyzed JTWC streamlines for the DMSP-derived direction estimates and the global band upper air (GBUA) directions at the same locations.

	SAMPLE		DIRECTION DIFFERENCES		
LEVEL	SIZE		MEAN	MEDIAN	RMS
GRAD	481	DMSP	-5	0	36
		GBUA	-13	-20	67
UPPER	671	DMSP	-1	0	37
		GBUA	-18	-30	87

sentative of the planetary boundary layer, whereas the TCM winds represent the more symmetric flow above the frictional layer. The average DMSP-derived directions fell between the JTWC and TCM winds, but were much closer to the JTWC directions (Table 4). This suggests that the low-level clouds viewed in the DMSP photographs were representative of the planetary boundary flow and included a significant inflow component.

The histogram of direction differences for the 250-mb level is shown in Fig. 7. About 50% of the DMSP-desired directions are identical to the hand-analyzed JTWC streamlines, which indicates the high reliability given to the DMSP data by the analysts. As may be seen in Table 4, the mean direction difference (-1°) is nearly equal to the median (zero difference), with about 70% of the values lying within ±10%. As at the gradient level, the root-mean-square difference was about 36°. One may conclude from these statistics that the DMSP direction estimates provide useful estimates of the circulation in the region of the tropical cyclone.

Comparisons of the GBUA directions and the JTWC directions are summarized in the lower histogram in Fig. 7 and in Table 4. There is a large bias (average, 18°; median, 30°) in the GBUA directions relative to the assumed ground truth. Furthermore, the RMS difference of 87° indicates that in many cases the wind direction implied in the upper level GBUA may even be from the wrong quadrant. Streamline analyses of the overall (34-day) distribution of JTWC and TCM 250-mb wind directions (not shown) did reveal significant differences. The

JTWC winds resulted in a well-defined anticyclonic outflow relative to the mean typhoon location. The outflow appeared to be concentrated in two branches. A channel of northward flow to the west of the typhoon center continued into the westerlies in advance of a middle-latitude trough. The remainder of the outflow formed a broad anticyclonic flow with a predominate branch of southward winds continuing toward the equator. By contrast, the TCM flow at 250 mb was constrained by the southern boundary. Although there was some semblance of the northward flowing branch of the outflow, the southward flowing branch was not well represented in the TCM. It was in this domain that the largest wind direction differences occurred. It should be emphasized that the anticyclonic outflow was sufficiently large to be resolved on the 2.5° longitude grid of the GBUA, if the data had been available for the operational analysis. The small region of cyclonic outflow above a mature typhoon will not be resolved on such a coarse grid and will have to be bogused.

4. Conclusions.

As expected, the evaluation of the coarse-mesh Tropical Cyclone Model for a series of 41 cases from the 1975 typhoon season showed significantly larger errors than the official forecasts. There was some indication that the track forecasts were better than the storm speed along the track. Thus, even the coarse-mesh model may provide useful guidance for the typhoon forecaster in recurvature situations. The occasional poor track predictions and the bias toward slow displacements leads one to question whether numerical errors or data deficiencies contribute more to the dynamical model forecast errors. A subjective classification of the initial fields provided the Tropical Cyclone Model suggested that the poorly defined initial fields resulted in larger forecast errors. Model forecasts with a fourth order advection scheme showed negligible improvement over the second-order advection results. Consequently, it was concluded that the principal source of error was related to data deficiencies.

The wind direction estimates derived from the DMSP satellite that fell within the boundaries of the Tropical Cyclone Model were compared to the JTWC hand-analyzed streamline directions. At the same points the initial wind direction for the Tropical Cyclone Model was extracted for comparison with the JTWC analysis. The average number of direction estimates available at the gradient and 250-mb levels was 16 and 20, respectively. At both levels about 65-70% of the DMSP estimates were within ±10° of the hand-analyzed fields. However, the directions from the operationally analyzed fields were quite different than the hand-analyzed values. Not only were there large root-mean-square differences of 67° and 87° at the gradient and 250-mb levels, but there was an average clockwise bias of about 15° in the Tropical Cyclone Model directions at the two levels. One must conclude that the DMSP direction estimates would be a useful data source for the operational analysis.

5. Recommendations.

In these 1975 cases the grid was always positioned in approximately the same orientation with respect to the typhoon center given in the warning message. The typhoon was located to the east and south of the center in expectation of a predominately northwestward track. As noted above, many of the 1975 storms tracked northward and recurved. Thus the predicted storm motion would bring the center into a region influenced by the artificial buffer zone along the eastern boundary that was used to make the fields cyclic east-west. The storms which tracked rapidly northward also tended to be influenced by the northern channel boundary. Some of these effects could be reduced by simply varying the grid location relative to a typhoon which had a recent history of northward movement. A second improvement could be made by replacing the isolated channel used here with an open-boundary model that is provided boundary values from a global model. Such a global model is presently being evaluated for possible operational use at FNWC. In addition to providing boundary values, it is anticipated that an operational global model would have another important effect. The present GBUA fields only have a dynamically-influenced first guess north of about 20°N, because that is the southern boundary of the hemispheric prediction model. The first guess for the remainder of the field is based on persistence with a slow reversion to climatology. Consequently, the regions with sparse data coverage could contain erroneous or unrepresentative fields. A forecast-analysis-forecast cycle with the dynamical model providing the first guess for the analysis would produce dynamically balanced fields throughout the region. Thus, an operational global model would be expected to provide more consistent fields for initialization of a dynamical tropical cyclone model. One could get an indication of the effect of dynamically balanced fields by initializing the Tropical Cyclone Model with the FNWC hemispheric analyses for the 1975 cases that occurred north of about 20°N. Another improvement may result from initializing the Tropical Cyclone Model with a tailored analysis package. The special objective analysis scheme that has been developed for the nested grid model (Langland et al., 1977) should be tested with the coarse-mesh model as well. If the dynamically balanced fields from the hemispheric model were shown to improve the forecasts, the special analysis scheme could also use the hemispheric fields rather than the global band upper air fields as a first-guess on the coarse-mesh grid.

Efforts should be made to assure that the wind direction estimates based on DMSP photographs are continued, and expanded if possible, as these estimates are a useful data source. The reliability of both the low-level and upper level DMSP-derived wind directions appears to be quite good, if one accepts the JTWC hand analysis as ground truth. The median direction difference was found to be zero for both levels, with a root-mean-square difference of about 35°. Eventually these data may be replaced by direction <u>and</u> <u>speed</u> estimates from the Japanese geostationary satellite. Until that time the DMSP-derived direction estimates are useful in the data-void regions of the western Pacific. Wind direction estimates from the DMSP should be considered as an additional data source for the global band upper air (GBUA) analysis at FNWC. Wind directions that were extracted from the GBUA at selected points within the domain of the tropical cyclone model had a significant bias and large root-mean-square errors at both upper and lower levels. Some DMSP direction data were incorporated in the GBUA analysis during the 1976 typhoon season. Similar statistics should be prepared for the 1976 tropical cyclone cases to determine whether the objective analysis scheme properly handled the data, and led to the observed improvement in the 1976 forecast errors compared to the 1975 season. It should be noted that the horizontal scale of the outflow circulation of a mature typhoon may not be resolvable on the scale of the present GBUA. As suggested above, it may be necessary to do the analysis on a higher resolution grid in the region of the typhoon. Finally, the streamline fields analyzed routinely at JTWC should be considered as a potential source of bogus winds for the tropical western Pacific. With the advent of a global prediction model at FNWC, the input of realistic wind fields over the tropical oceans becomes more important. Previous studies with hand-analyzed data have indicated an improvement in tropical cyclone motion forecasts. More extensive tests of the dynamical models with and without the hand-analyzed data would be possible if an adequate distribution of bogus winds was extracted from the JTWC analyses.

Acknowledgements. This research was supported by the Naval Environmental Prediction Research Facility. R. Perry of NEPRF reprogrammed the coarse-mesh model for use with operational data and provided the data for evaluating the 1975 results discussed in Section 2. Data for the study of DMSP wind direction estimates were provided by the Joint Typhoon Warning Center with the help of LCDR Dave Sokol. A preliminary set of direction comparison was prepared by CAPT John Shewchuk (USAF). Additional data extraction was done by AG Oniel Estela and the histograms were prepared by Tanya Servaas. Professor G.J. Haltiner reviewed the manuscript, which was typed by Miss M.G. Nichols.

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