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A stepwise screening discriminant analysis is used to develop an algorithm for forecasting tropical cyclone intensification. Some potential predictors used in the analysis are derived from FNOC (Fleet Numerical Oceanography Center) zonal wind analyses. Other potential predictors considered are simple climatological parameters and persistence of intensification. The potential predictors are screened by a stepwise discriminant analysis program to determine which significantly discriminate between three (intensifying, filling, and neither) intensification categories. The best discriminators are then used as predictors in an intensification forecasting algorithm.

The algorithm is developed and tested on Western Pacific tropical cyclone data from the years 1974-82. In addition to the independent test, stability of the algorithm is investigated and a test is conducted to compare forecasts produced by the algorithm with forecasts made by JTWC (Joint Typhoon Warning Center) and with forecasts of persistence

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AN APPLICATION OF DISCRIMINANT ANALYSIS TO A TROPICAL CYCLONE INTENSIFICATION FORECASTING ALGORITHM

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JULY 1985

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TABLE OF CONTENTS

1. INTRODUCTION

One of the major tasks facing the Joint Typhoon Warning Center (JTWC) is to produce consistent and accurate forecasts of tropical cyclone movement and intensity[1]. The area of responsibility of JTWC extends from 180° longitude westward to the east coast of Africa; however, the emphasis for accurate forecasts is placed in the western North Pacific region. This area experiences, on average, three times as many tropical cyclones as the North Indian Ocean region and includes concentrated areas of DoD assets (U.S. Naval Oceanography Command Center/JTWC, 1983).

Because of the great importance of the forecasts, new techniques and forecasting aids are continually being tested. However, in contrast to improvements made in recent years in predicting the movement of tropical cyclones, the skill in forecasting their intensity has improved very little (U.S. Dept. of Commerce/NOAA, 1982). A reason for the lack of improvement is that the intensity forecasts prepared at JTWC are primarily based on: 1) a climatological pressure/intensity relationship implemented by extrapolating the cyclone's pressure tendency from a recent observation, and 2) satellite interpretation using the Dvorak (1975) model. The purpose of this study is to develop an objective forecast aid to assist JTWC in producing better quality intensity forecasts.

Dropco (1981) has shown for the Gulf of Mexico that the large-scale wind fields contain sufficient information to be able to differentiate between environments favorable for tropical cyclone intensification and decay. The most useful information was found to be contained in the zonal wind fields over the region approximately 6° - 11° latitude radius from the cyclone center. Gray (1979) has shown that this region surrounding the cyclone is important for synoptic scale interaction and feedback influences on cyclone intensity over time scales of approximately 12-48 h.

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[1] Defined as the maximum sustained surface wind speed.

Harr (1982) tested the predictive ability of the dynamic portion of Dropco's algorithm using JTWC hand analyzed charts for the western North Pacific Ocean region. Using Student's t-test, Harr showed that these data also exhibit significant differences between intensifying and filling cyclones and developed an improved version of Dropco's algorithm with the additional data.

Based on the findings of Dropco and Harr, we decided to develop a similar algorithm to forecast Western Pacific tropical cyclone intensification from operationally available data. To develop the forecast algorithm, variables suggested by Dropco and Harr were extracted from Fleet Numerical Oceanography Center (FNOC) archived data fields. The variables were screened by a stepwise discriminant analysis program to determine which variables significantly discriminated between three intensification categories. The selected variables were then used to develop an algorithm to forecast cyclone intensification. Besides an independent test, the stability of the algorithm was investigated and it was compared to the official JTWC forecasts and to forecasts of persistence of intensification.

2. DATA

The intensification forecast algorithm was developed and tested on Western Pacific tropical cyclone data from the years 1974-82. Archived FNOC Global Band analyses of the 700, 400, and 250 mb zonal wind fields were available and provided some of the data from which the potential predictors were determined; some simple climatological parameters and persistence of intensification were also included as potential predictors.

The Global Band analyses are performed twice daily on a 2.5^{o} longitude and latitude mercator grid that is global in longitude and banded between 60^{o}N and 40^{o}S. Wind analyses are performed at the surface, 700, 400, 200, and 250 mb and are vertically coupled by using temperature analyses at intermediate levels. For this study, only the archived 700, 400, and 250 mb wind analyses were available. The input for the upper-air analyses include the 12 h old analysis as a first guess, the current mid-latitude wind analyses, observations from satellites, rawinsondes, aircraft and pibals, and the current Global Band surface pressure and surface wind analyses. The surface analyses include wind and pressure climatologies due to sparse data coverage. In addition, when there is a tropical cyclone present, there are eight surface wind vectors bogused symmetrically at an 80 km radius around the cyclone center (U.S. Naval Weather Service, 1975). For this study, no attempt was made to evaluate the impact of the bogusing on the derived algorithm.

The dynamical potential predictors were derived from a semi-circular grid centered on the cyclone at its current position. As seen in Figure 1, each grid consists of 114 data points extending from 6° to 11° latitude from the cyclone center. The fields were interpolated from the archived FNOC analyses to the grid using a double Bessel interpolation. Approximately 70 Global Band grid points are included in the influence radius associated with each grid. The potential predictors were computed as the mean values of the parameters over the grid and were derived with the grid in two orientations; they were interpolated to the grid when it was oriented to the north, along the longitude of the cyclone center, and when the grid was oriented along the direction of motion of the cyclone (see Figure 1). The direction of the cyclone's motion was calculated using the current and previous 6 h position. All of the positions were extracted from the JTWC post-analyzed best track data file at the Naval Environmental Prediction Research Facility (NEPRF). Figure 1 also shows the relationship of the semicircular grid to the Colorado State University (CSU) compositing grid. The compositing grid is a cylindrical grid, centered about the cyclone's position, and is divided horizontally into octants and eight radial belts of two degrees latitude spacing (Dropco, 1981).

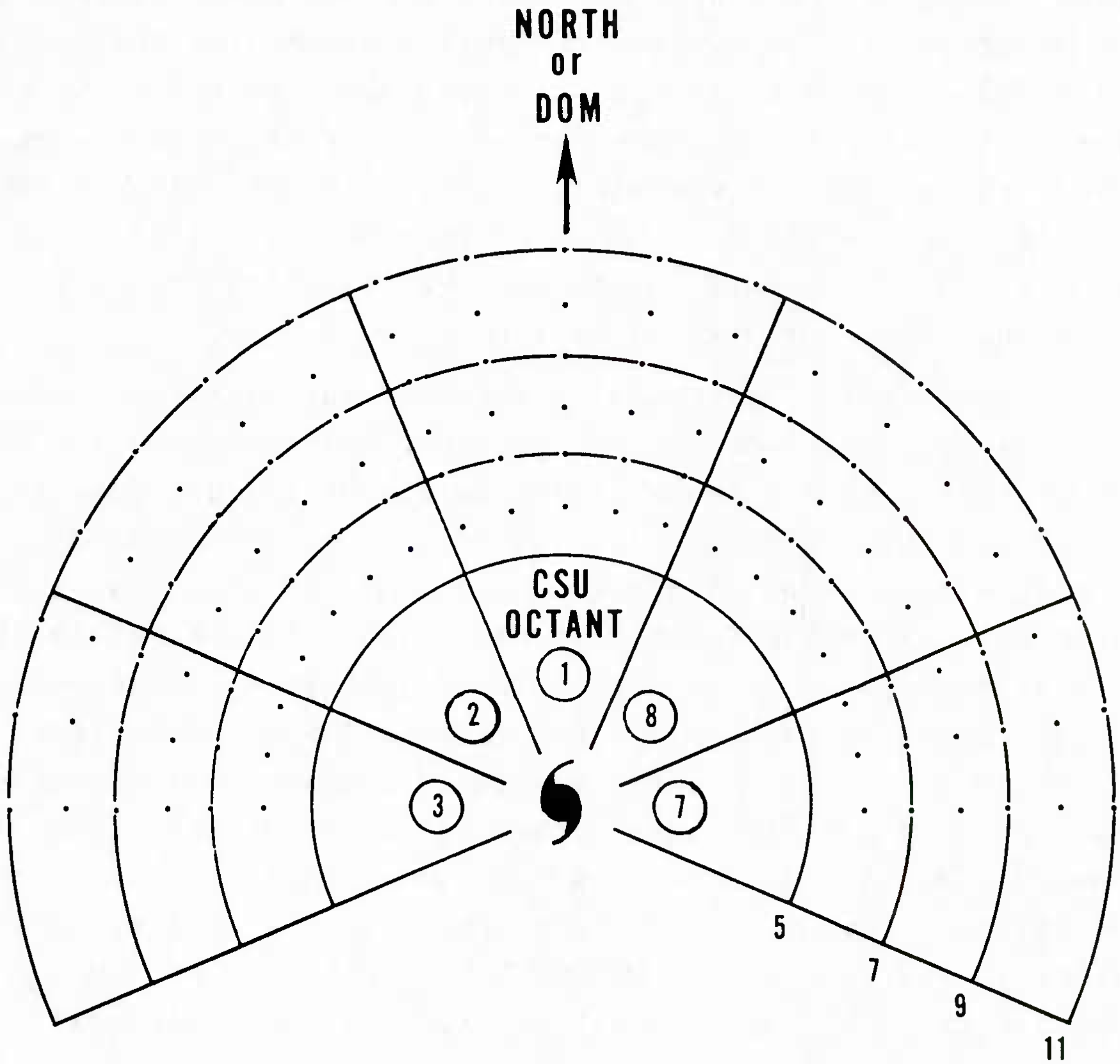


Figure 1. Diagram showing the relationship between the cyclone centered grid used in this study (114 dots) and the CSU compositing grid. Arrow shows the orientation of the grid: north, or in the Direction Of the cyclone's Motion (DOM). Radial increments are in degrees of latitude.

The predictive ability of the parameter variances over the grid was not investigated. Although the variances possess considerable information, the purpose of this study was to extend the CSU algorithm development to the Western Pacific. The CSU compositing philosophy has been to use mean parameter values, although they are not sufficient to completely describe the fields. Future efforts should include investigating the contribution of the parameter variances to the prediction scheme.

The data set used to derive and test the forecast algorithm consists of 6451 best track reports from which 2371 complete cases were available. A complete case was defined as a 0000 or 1200 GMT observation which included all three wind analyses and which had the current, -24 h, and +24 h best track intensities. The mean and standard deviation zonal wind fields for the 2371 cases are shown in the Appendix. The 700, 400, and 250 mb zonal wind data are shown over both the north oriented grid and the grid oriented along the cyclone's direction of motion. Also shown are the difference fields representing the wind shear between levels. Of the 2371 complete cases, a 877 case developmental data set was extracted by using the criterion of a 36 h separation between two consecutive cases from the same cyclone. The remaining 1494 complete cases were reserved for testing.

As shown in Table 1, the 20 potential predictors were grouped according to their physical representation to facilitate their inclusion or exclusion in each experiment of the algorithm development. The experiments are described in the following sections.

Table 1. Potential predictors used in this study.

REPRESENTATION	SYMBOL	DESCRIPTION
AVERAGE ZONAL WIND	$\overline{U}_{700}, \overline{U}_{400}, \overline{U}_{250}$	700, 400, 250 mb zonal wind averaged over the north oriented grid (ms^{-1}).
	$\widetilde{U}_{700}, \widetilde{U}_{400}, \widetilde{U}_{250}$	700, 400, 250 mb zonal wind averaged over the DOM oriented grid (ms^{-1}).
VERTICAL WIND SHEAR	$\Delta\overline{U}_{400-700}$ $\Delta\overline{U}_{250-400}$ $\Delta\overline{U}_{250-700}$	Vertical shear of the average zonal wind for the 400-700, 250-400, and 250-700 mb layers for the north oriented grid (ms^{-1}).
	$\Delta\widetilde{U}_{400-700}$ $\Delta\widetilde{U}_{250-400}$ $\Delta\widetilde{U}_{250-700}$	Vertical shear of the average zonal wind for the 400-700, 250-400, and 250-700 mb layers for the DOM oriented grid (ms^{-1}).
	$\Delta\overline{U}_{250-700}+\overline{U}_{250}+\Delta\overline{U}_{400-700}$ $\Delta\widetilde{U}_{250-700}+\widetilde{U}_{250}+\Delta\widetilde{U}_{400-700}$	Dropco (1981) IP parameter for the north and DOM oriented grid (ms^{-1}).
	$\Delta\overline{U}_{400-700}+\overline{U}_{400}-\Delta\overline{U}_{250-400}$ $\Delta\widetilde{U}_{400-700}+\widetilde{U}_{400}-\Delta\widetilde{U}_{250-400}$	Harr (1982) IP parameter for the north and DOM oriented grid (ms^{-1}).
CLIMATOLOGY	Vo	Current intensity of the cyclone (ms^{-1}).
	ϕ	Latitude of the cyclone center (Deg.).
	θ	Longitude of the cyclone center (Deg.).
PERSISTENCE	INTENSIFY NEITHER FILLING	Intensity change classification for the previous 24 h (no units).

3. ALGORITHM DEVELOPMENT

To classify the development and decay of tropical cyclones three categories were defined: 1) Intensifying - cyclones having an increase of at least 5 ms^{-1} in their reported maximum wind speed over the 24 h period after an observation (0000 or 1200 GMT); 2) Filling - cyclones having at least a 5 ms^{-1} decrease in their reported maximum wind speed over the same period; 3) Neither - cyclones whose intensity varied less than ± 5 ms^{-1} over the 24 h period. For the best track developmental data set 321 cases (37%) were classified as intensifying, 248 cases (28%) were classified as filling, and the remaining 308 cases (35%) were classified as neither. The three categories are shown schematically in Figure 2 and were defined to include approximately equal numbers of cases and to maximize the utility to the forecaster. An objective procedure to classify cyclones into well separated intensifying and filling groups can enhance the decision making process by providing forecaster guidance. A two group classification scheme with a cut point of zero (no change) does not differentiate enough between cyclone intensification and decay to be of practical use as a decision making aid.

In this study, discriminant analysis is used to classify an observation of a tropical cyclone into its proper intensification category. The problem of discriminant analysis is to assign an observation of an unknown individual into a group on the basis of its predictor characteristics. The objective is to make the assignment with as low an error rate as possible. We assume that when the groups are defined there exist some combination of predictors which will allow us to classify the developmental data into their correct groups. The linear discriminant function used here is optimal if the observations are multivariate normal; moderate departures from normality are not serious and are not addressed. However, an additional simplifying assumption used in the analysis is that the covariance matrices for each group are equal. The classification procedure derived is satisfactory if the covariance matrices are not too different; otherwise a quadratic discriminant function is optimal (Lachenbruch, 1975).

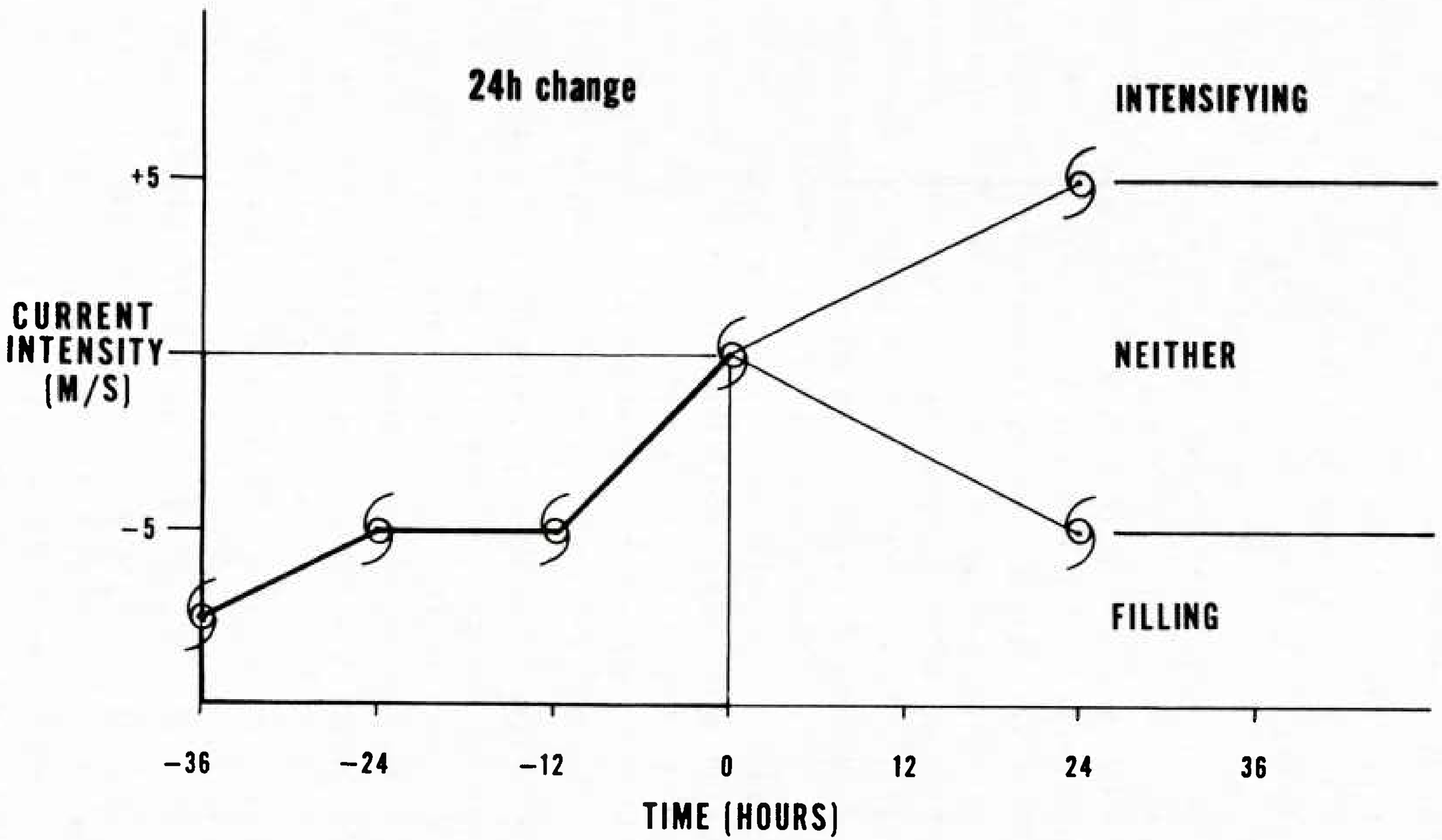


Figure 2. A schematic representation of the tropical cyclone intensification forecasting algorithm. At the current time (=0) the cyclone is classified as intensifying, filling or neither intensifying nor filling, over the next 24 h, based on environmental and climatological parameters.

Future efforts should include comparisons between linear and quadratic discriminant functions.

To predict the intensity classification of an unknown cyclone, the potential predictors shown in Table 1 were entered as variables into the BMDP7M stepwise discriminant analysis program (Dixon, 1981). The variables were screened by the program in a stepwise manner and those which best discriminated between the three categories were included in a forecast algorithm. Because the classification boundaries were defined by user preference and not by equal probabilities, the frequency distribution described above was used by the program as a set of a priori probabilities for the classification of the intensity forecasts.

Briefly, the program proceeds as follows: at each step the variable that adds most to the separation of the categories (as measured by a one-way analysis of variance F statistic on the residuals of the variable) is entered into the algorithm. The stepping continues until no additional variables significantly contribute to the discrimination between the categories. Thus, the best discriminators are deduced.

When the screening of the variables is complete, BMDP7M produces linear discriminant functions composed of the best discriminators. For this study, three discriminant functions were produced, one for each of the three categories. To apply the algorithm to intensity forecasting, the functions are evaluated using the observed values of the discriminators. The function with the largest sum is then the category of the forecast for that particular case. Posterior probabilities of correct classification, which define the sharpness of the forecast technique, were not computed because of the unavailability of computer resources needed for the large data set.

The great asset of the BMDP programs is that they can be run repeatedly and efficiently with only minor control language changes. This capability was exploited in this study by running the BMDP7M program for six experiments. The experiments were conducted to quantify the contribution of each of the variables to the skill of the forecasts. For each experiment certain variables were systematically included or excluded from the potential predictors based on their representation in Table 1. The results of the discriminant analysis experiments using the developmental data are summarized in Table 2. The EXPERIMENT INCLUDES column in Table 2 lists potential predictors used in the experiment and the VARIABLES SELECTED column lists predictors which were selected that best discriminated between the three categories. The relative significance of predictors decreases from left to right.

Perusing the VARIABLES SELECTED column for six experiments in Table 2, we find that variables representing climatology, persistence, and mean zonal flow at 400 mb are the most frequently selected predictors. The inclusion of the current intensity is reasonable because, in general, incipient cyclones tend to intensify slowly and mature cyclones tend to decay rapidly (e.g., Dvorak, 1975). Since tropical cyclones generally move westward during their life cycles, their current longitude also seems to be a reasonable predictor. The latitude predictor possibly reflects a condition for recurvature and weakening. This condition is also evident in the $\overline{U}_{400}$ predictor. Tropical cyclones moving north into a stronger westerly flow are generally expected to weaken as they interact with the cooler polar air mass associated with the baroclinic zone (Anthes, 1982).

The $\overline{U}_{400}$ predictor could also be representing a neglected climatological component: time of year. The zonal wind fluctuates on an annual scale in the tropics, reaching a minimum near August. Perhaps a more sophisticated treatment of climatology, including nonlinear effects, would raise its skill level beyond the other techniques.

In experiment #4, Harr's (1982) IP statistic was selected in preference to Dropco's (1981) IP statistic. This was expected since Dropco's statistic was derived using a data set consisting of Atlantic tropical cyclones while Harr's data set was composed

Table 2. Results of discriminant analysis experiments using developmental data.

Experiment number	Experiment includes	Variables selected	Number forecast correctly	Number of forecasts	F Statistic	Degrees of freedom	F Confidence level
1	Average zonal wind, vertical wind shear, climatology, and persistence	Vo, $\overline{U}_{400}$, θ, Φ	494	877	91	4, 872	99.9%
2	Average zonal wind, vertical wind shear, and persistence	$\overline{U}_{400}$, Persistence	438	877	43	2, 874	99.9%
3	Average zonal wind and vertical wind shear	$\overline{U}_{400}$	413	877	58	1, 875	99.9%
4	Vertical wind shear	IP	396	877	110	1, 875	99.9%
5	Climatology and persistence	Vo, Φ, θ	470	877	61	3, 873	99.9%
6	Persistence	Persistence	447	877	59	1, 875	99.9%

Vo = Current intensity (ms^{-1})

$\overline{U}_{400}$ = 400 mb zonal wind averaged over the north grid (ms^{-1})

θ = Current longitude (°East)

Φ = Current latitude (°North)

IP = $3\overline{U}_{400} - \overline{U}_{700} - \overline{U}_{250}$ (Harr (1982) IP statistic for north grid; ms^{-1})

Persistence = Persistence of intensity change of Western Pacific tropical cyclones. In addition, only those variables computed for the north oriented grid were selected. The flow fields to the north and to the south of the cyclones tend to offset each other when averaged over the grid oriented easterly or westerly, in the direction of the cyclone's motion.

4. DEVELOPMENTAL DATA VERIFICATION

To determine the experiment which performed most accurately in forecasting tropical cyclone intensification, several standard forecast verification scores were computed from contingency tables calculated from the developmental data (see Figure 3). The verification scores which were computed are the percent correct, skill score, threat score, adjusted threat score, bias, false alarm ratio, and probability of detection. The skill score is a simple measure of the model's skill against the skill of a forecast of persistence. The skill score SK is defined as

$$SK = \frac{CF - P}{TO - P} \tag{1}$$

where P is the number of correct forecasts by persistence, CF is the number of correct forecasts by the model, and TO is the total number of forecasts. The skill score for persistence is zero by definition.

The threat score is an arbitrary measure of how well the model can forecast the event (intensification) itself (Godfrey, 1982). Using the contingency table in Figure 3 as an example, the threat score TS for the INTENSIFY category is

$$TS = \frac{R}{X + U + R + S + T} \; . \tag{2}$$

An adjusted threat score AT is defined as

$$AT = \frac{(\text{THREAT SCORE}) - (\frac{A}{D})}{1 - (\frac{A}{D})} \tag{3}$$

FORECAST

OBSERVED		INTENSIFY	NEITHER	FILL	OBSERVED TOTALS
	INTENSIFY	R	S	T	A
	NEITHER	U	V	W	B
	FILL	X	Y	Z	C
	FORECAST TOTALS	G	F	E	D

Figure 3. An example of the contingency tables used to construct the forecast verification scores described in the text. The letters in the table represent category counts.

is the threat score normalized with respect to the climatological frequency ($\frac{A}{D}$) of observed periods of intensification, and gives the percent improvement of the scheme over climatology (Lowe, 1985).

The false alarm ratio FAR and the probability of detection POD are verification scores discussed by Donaldson et al. (1975). The FAR is the proportion of incorrect forecasts, and for the INTENSIFY category is

$$FAR = \frac{U + X}{G} \quad . \tag{4}$$

The corresponding POD is the proportion of intensifying events forecast correctly and is given by

$$POD = \frac{R}{A} \quad . \tag{5}$$

The bias in forecasting cyclone intensification is

$$BIAS = \frac{G}{A} \quad . \tag{6}$$

The verification scores are shown in Table 3 for each of the six experiments. The percent correct and skill score apply to all three forecast categories and the remaining verification scores apply only to the model's performance in the INTENSIFY forecast category, as defined above. All of the scores presented were calculated from contingency tables similar to Figure 3, which were generated by the stepwise discriminant analysis program using a leaving-one-out procedure. This procedure was used to reduce the bias in the group classifications.

The significance of the differences between some of the verification scores were tested using the procedure described in Lowe (1985). The differences between the percent correct, threat scores, false alarm ratios, and probabilities of detection were

Table 3. Verification scores for the experiments using the developmental data with the leaving-one-out validation procedure.

All categories				Intensifying category				
Experiment number	Variables selected	Percent correct	Skill Score	Threat score	Adjusted threat score	Bias	False alarm ratio	Probability of detection
1	Vo, $\overline{U}_{400}$, θ, Φ	56.32	.11	.42	.09	1.11	.43	.63
2	$\overline{U}_{400}$, Persistence	49.94	-.02	.42	.09	1.43	.50	.72
3	$\overline{U}_{400}$	46.98	-.08	.40	.05	1.62	.53	.75
4	IP	45.15	-.12	.38	.02	1.50	.54	.69
5	Vo, Φ, θ	53.59	.05	.35	-.03	.92	.46	.50
6	Persistence	50.97	.00	.37	.01	1.09	.48	.56

tested by computing their Z-statistics and associated probabilities. The skill score, adjusted threat score, and bias cannot be interpreted as probabilities, therefore, their differences were not tested for significance. The Z-statistics were computed by estimating the score variances by approximating their binomial distributions by normal distributions. Lowe (1985) has shown this is a valid procedure provided the sample size is large and the data are independent. Because of the large sample size used and the 36 h separation between consecutive cases from the same cyclone, the data are assumed to meet the constraint of independence. Significance is based on a two-tailed test at the 0.05 and 0.01 significance levels; we cannot reject the null hypothesis (must assume the non-zero differences have arisen by chance) if the Z values are less than 1.96 and 2.58, respectively.

One can see that experiment #1 and experiment #5 are the only experiments that have more skill than persistence (experiment #6). The verification scores for experiment #5 are not as favorable as those for experiment #1, however, the differences are significant only for the threat score (0.05 level) and probability of detection (0.01 level). Experiments #2, #3, and #4 have large probabilities of detection but have unacceptably large biases; events were detected more often because of the excessive over-forecasting by the models. As expected, a forecast of persistence of intensification performs well (experiment #6). The 50.97 percent correct is the third largest value of the six experiments and is significantly different from experiment #1 at the 0.05 level. Persistence is a good short range prediction technique because the methods used operationally for intensity forecasting rely heavily on the assumption that the intensity of tropical cyclones varies slowly and smoothly over time (e.g., Dvorak, 1975). In practice, deviations from the smooth intensification curve occur only when they are based on overwhelming evidence from satellite or aircraft reconnaissance data.

In summary, the algorithm from experiment #1 has the most desirable verification scores of the six experiments. Except for the percent correct and false alarm ratio, all the scores for experiment #1 are significantly better than those for experiment #5. Experiments #2, #3, and #4 show negative forecasting skill compared to persistence; therefore, experiment #1 is chosen as the model to be used for further testing. Because most of the scores for persistence do not significantly differ from the scores for experiment #1, forecasts of persistence (experiment #6) will also be included in the testing and verification. The estimated linear discriminant function coefficients and constant for each of the three forecast categories computed from experiment #1 are shown in Table 4. Table 5 lists some statistics computed for each of the four selected variables. The differences between the means of the variables within each of the forecast categories were tested for significance using BMDP3D, a program for the comparison of two groups (Dixon, 1981). The results show that differences between the means of variables, as measured by Student's t-test, are all significant at the 0.05 level and most of the differences are significant at the 0.001 level. The mean values of variables for each group are consistent with the discussion in Section 3.

Table 4. The estimated linear discriminant function coefficients and constants for each category. The algorithm are from experiment #1. The units for the predictors are listed in Table 2.

Category	V_o	$\overline{U}_{400}$	θ	ϕ	Constant
Intensifying	.11723	-.42276	.67027	.43510	-52.30736
Neither	.10254	-.37817	.65444	.44781	-50.07278
Filling	.19958	-.31949	.62391	.51129	-50.49353

Table 5. Comparison of experiment #1 predictors for each group: Intensifying vs. Neither, Neither vs. Filling, and Filling vs. Intensifying.

	INTENSIFYING		vs			NEITHER		vs			FILLING		vs			INTENSIFYING	
	$\overline{X}$	σ	T	DF	α	$\overline{X}$	σ	T	DF	α	$\overline{X}$	σ	T	DF	α	$\overline{X}$	σ
τ_{400}	-1.15	5.50	4.54	627	.001	1.16	7.15	-6.18	554	.001	5.36	8.87	-10.74	567	.001	-1.15	5.50
ϕ	15.91	5.89	2.75	627	.006	17.43	7.87	-7.08	554	.001	22.02	7.27	-11.08	567	.001	15.91	5.89
θ	137.94	14.11	-2.27	627	.023	135.28	15.24	3.70	554	.001	130.62	14.12	6.14	567	.001	137.94	14.11
Vo	45.42	21.81	-2.52	627	.012	40.78	24.29	-13.83	554	.001	72.26	29.36	-12.51	567	.001	45.42	21.81

$\overline{X}$ = Group mean
σ = Standard deviation
T = T-test (pooled variances)
DF = Degrees of freedom
α = Significance level

Figure 4 is a comparison of the observed vertical profile of the zonal wind for the intensifying and filling cyclones from the developmental data set with comparable values from Harr's (1982) study and Dropco's (1981) study. The results presented are for many cases (see inset in Figure 4) and show that the filling (or non-intensifying) cyclones tend to match Harr's vertical profile and intensifying cyclones tend to match Dropco's vertical profile. The filling cyclones used in this study are, on average, embedded in a deep layer of winds with strong westerly components. The vertical shear in the lower layer of the environment of filling cyclones is slightly larger than the shear in the upper layer. The environments of intensifying cyclones used in this study tend to exhibit a smaller overall vertical shear than filling cyclones, and the shear is almost equal between both layers. The major difference between the layer shears for cyclones used in this study is in the lower layer, where the difference is almost three times as large as the difference between shears in the upper layer (3.4 vs 1.2 ms^{-1}). The The 400-700 mb shear, however, was not found to significantly discriminate between categories. It is possible this is due to the effect of the presence of the third (NEITHER) group on the screening procedure.

The small vertical wind shear in the lower troposphere supports the intensification of tropical cyclones by allowing the divergent upper-level flow to couple with the lower- and middle-level convection. The enhanced lifting increases the convection and the lower-level convergence necessary to produce hurricane vorticity values.

The environments of the filling cyclones are deep baroclinic regions which can be responsible for cyclone decay by injecting cool air into their circulations. The large upper tropospheric wind speeds, indicated by the $\overline{U}_{400}$ predictor, can ventilate the system by advecting the upper-level temperature and moisture anomalies away from the disturbance (Anthes, 1982).

STUDY	LINE CODE	700 MB	400 MB	250 MB	# CASES
DEVELOPMENTAL DATA	○—○	-0.8	5.3	9.5	248
	○- - -○	-3.8	-1.1	1.9	321
HARR (1982) "MIDDLE" DATA SET	△—△	1.5	7.4	10.0	11
	△- - -△	-8.0	-6.1	2.1	8
DROPCO (1981) 42 H BEFORE LANDFALL	□—□	-2.5	5.0	16.0	9
	□- - -□	-3.5	0.0	5.5	18

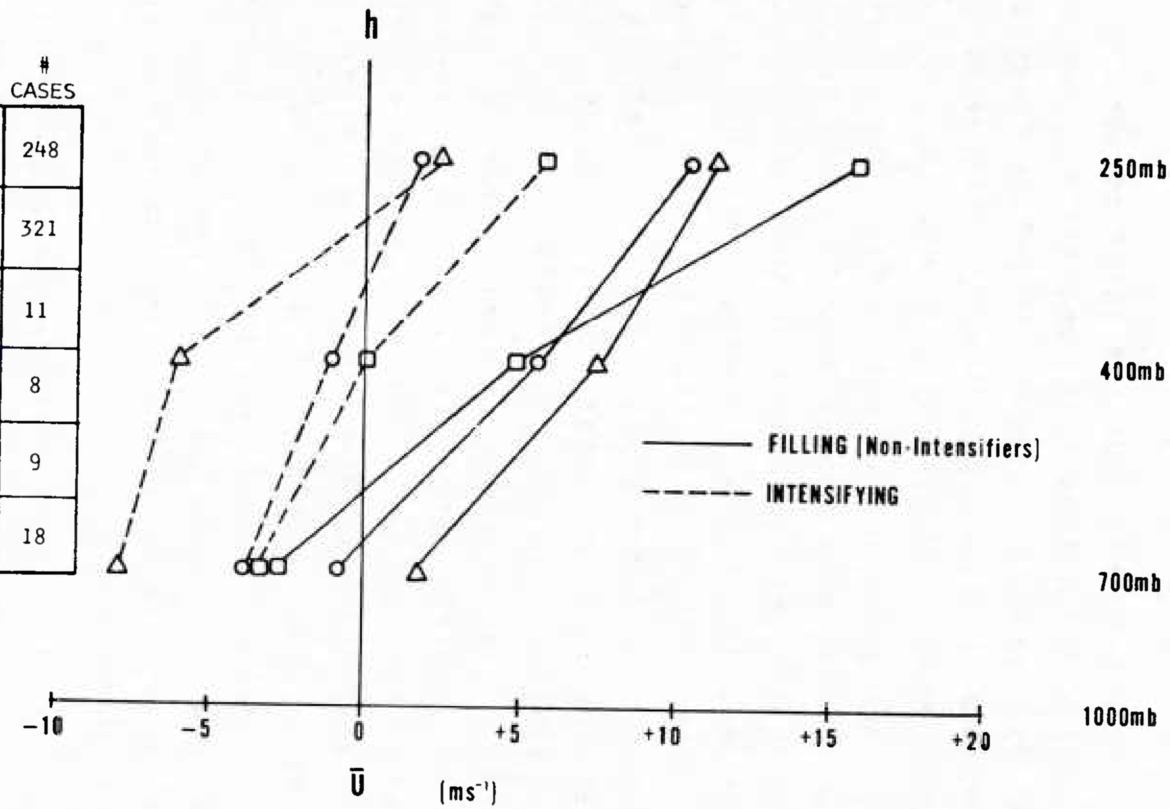


Figure 4. Comparison of observed vertical profile of average zonal wind for cyclone centered 6° to 11° north radial grid. Dropco (1981) used 5° to 11°.

5. INDEPENDENT DATA VERIFICATION

The algorithm developed using experiment #1 was independently tested using the 1494 cases that remained after the 877 developmental cases were extracted from the complete data set. A jackknife-,or bootstrap-type repetitive subsampling method was used to test the algorithm. The procedure consisted of randomly selecting a subset of 100 cases from the 1494 case data set and computing the forecast verification scores. This was done 30 times for each run and was repeated five times, for a total of 15000 forecasts or 150 tests. The score means and standard deviations were computed for each run of 30 scores and the results are presented in the bottom two rows of Table 6. The score means and the means of the standard deviation (computed for the 5 runs) are shown. For comparison purposes, one run using the same procedure was performed with the developmental data set and the results are shown in the two center rows of Table 6. The verification scores for the developmental data (from Table 3) are also reproduced as the top row of Table 6 for comparison with the jackknife results. The performance of the algorithm is compared to the performance of persistence in each of the experiments.

The algorithm performed well on the independent data. For every score except the probability of detection the algorithm performed better than persistence, as evinced by the positive skill score, although none of the differences between the scores are significant.

The stability of the algorithm was investigated by comparing the verification scores from the independent data to the scores from the developmental data. Except for the skill score, all the verification scores are consistent between data sets. The degradation of the skill score, and the slight degradation of the percent correct, is to be expected when the algorithm is applied to independent data that have slightly different statistical characteristics than the developmental data. The differences,

Table 6. Summary table of verification scores for experimental results. Standard deviation (σ) computed per 30 * 100 24-hour forecasts.

Experiment		All categories				Intensifying category									
		Percent correct		Skill score		Threat score		Adjusted threat score		Bias		False alarm ratio		Probability of detection	
		A	P	A	P	A	P	A	P	A	P	A	P	A	P
Developmental data. 877 forecasts	X	56.32	50.96	.11	.00	.42	.37	.09	.01	1.11	1.09	.43	.48	.63	.56
Developmental data. Jackknife 30 * 100 forecasts	$\bar{X}$	55.70	51.07	.09	.00	.40	.35	.06	-.02	1.01	1.04	.44	.49	.57	.52
	σ	4.08	3.97	.11	.00	.06	.06	.10	.09	.10	.15	.07	.08	.08	.08
Independent test data. Jackknife 5 * 30 * 100 forecasts	$\bar{X}$	54.45	52.52	.03	.00	.39	.36	.09	.06	1.12	1.22	.47	.51	.58	.59
	$\bar{\sigma}$	4.66	4.36	.13	.00	.07	.06	.09	.08	.20	.21	.08	.08	.08	.08

A = Algorithm
P = Persistence
Algorithm developed from experiment #1.

however, between the developmental and independent test data are not significant, therefore, we conclude that the algorithm is stable.

6. COMPARISON TEST VERIFICATION

The algorithm was also compared to some of the official JTWC forecasts from the years 1979-81. Of the 877 case developmental data set, 232 cases coincided with entries in a data file consisting of official warnings. The 232 comparison cases were extracted, and the forecast categories corresponding to the official warnings, the algorithm, and persistence were computed. The verification scores are summarized in Table 7.

The algorithm also performed quite well on the comparison data. The overall percent correct for the algorithm was 57.76 compared to 59.48 for the official forecasts and 50.43 for persistence, although only the difference between the official forecasts and persistence is significant (0.05 level). The skill score and threat score for the algorithm are higher than the corresponding score for persistence and are slightly lower than the scores for the official forecasts, however, these differences are not significant. Neither JTWC nor the algorithm have threat scores significantly better than persistence. From the high bias and false alarm ratio for persistence we conclude that it tends to excessively overforecast intensification. Therefore, we find that both the algorithm forecasts and the official forecasts are superior to forecasts made by using only persistence, but the improvement is not significant. We cannot reject the possibility that the better scores appeared by chance.

The ability of the algorithm to compare favorably with the official forecasts supports the validity of the discriminant analysis approach used in this problem. However, the dynamic potential predictors screened were only a few of the variables available from the archived FNOC fields. As Dropco (1981) has indicated, if additional dynamic variables were included in the analysis, along with thermodynamic variables, the algorithm

Table 7. Comparison of model results to official JTWC warnings for 232 24-hour forecasts.

	All categories		Intensifying category				
1979 - 1981 Developmental data subset. 232 forecasts	Percent correct	Skill score	Threat score	Adjusted threat score	Bias	False alarm ratio	Probability of detection
Algorithm	57.76	.15	.48	.17	1.10	.39	.68
JTWC official warnings	59.48	.18	.54	.26	1.14	.34	.75
Persistence	50.43	.00	.44	.10	1.26	.45	.69

Algorithm developed from experiment #1.

should improve. It should be remembered, however, that the official forecasts were placed in categories based on a simple difference between the 24 h forecast intensity and the warning intensity. The forecasters did not make categorical forecasts which could have been verified directly and which could have had statistical properties different than those of the comparison data set presented.

7. SUMMARY AND CONCLUSIONS

A stepwise discriminant analysis was used to develop an algorithm for forecasting one of three categories of the intensification of tropical cyclones. The data used to develop the algorithm were derived from JTWC best track reports and archived FNOC analyzed fields for 0000 and 1200 GMT from the years 1974-82. The potential predictors included dynamic variables extracted from FNOC wind analyses using a 6° - 11° radial storm centered grid, climatological parameters, and persistence of intensification. The dynamic variables used were in agreement with the results of Dropco (1981) and Harr (1982), who showed that sufficient information exists in the analyzed wind fields to be able to define differences between the environments of intensifying and non-intensifying tropical cyclones. The test results, however, showed that the 400 mb zonal wind was the only Global Band field examined that had significant predictive ability; none of the other dynamic variables, or combinations suggested by the previous studies, significantly discriminated between the three forecast categories. The other predictors selected were the current intensity and position of the cyclone and showed just about as good discrimination as the 400 mb zonal wind.

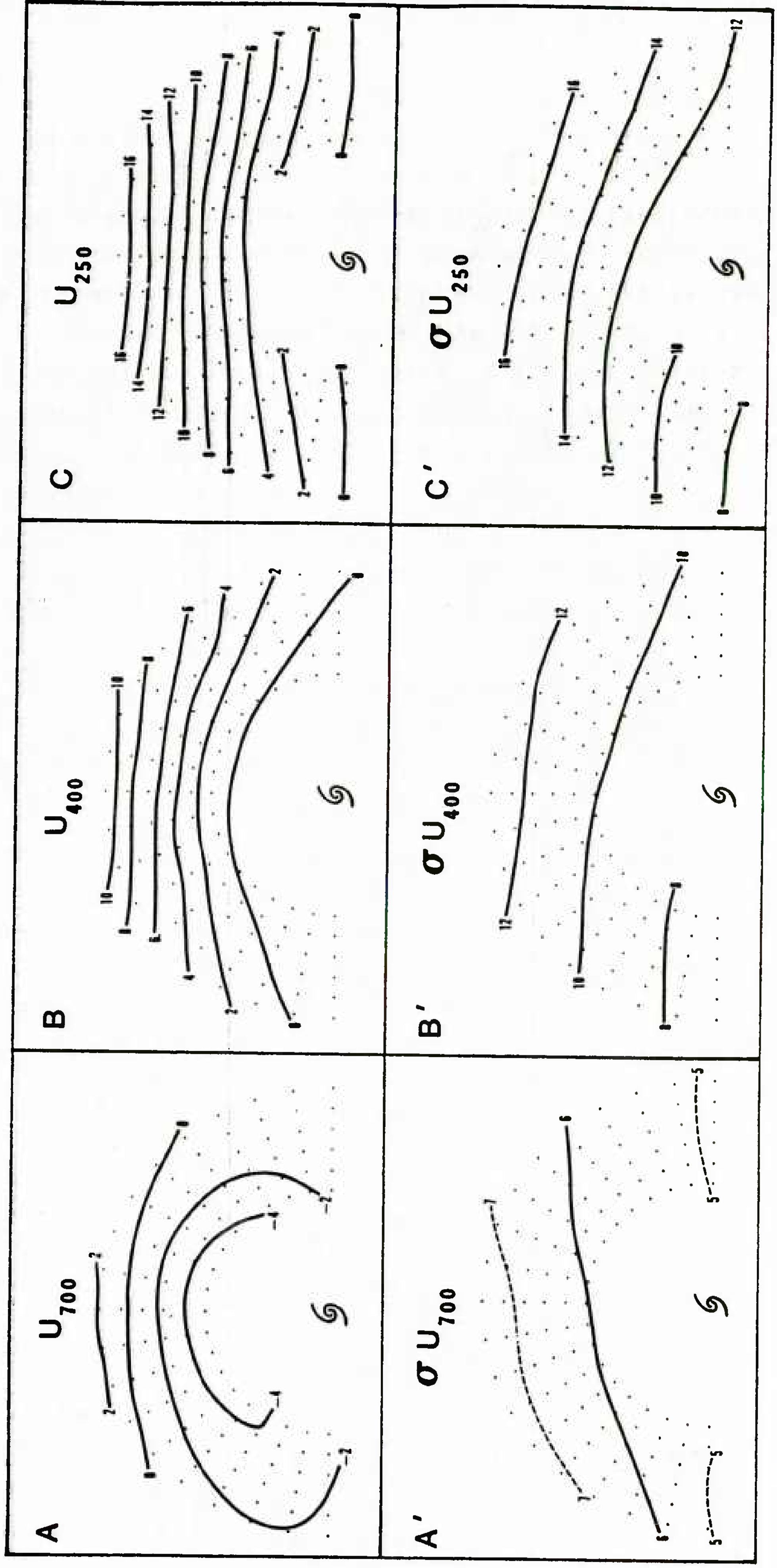
The algorithm developed was tested using a repetitive subsampling technique and was found to perform better than persistence in all cases, although not significantly better. The algorithm was also found to be stable and to compare favorably to forecasts from the official JTWC warnings; however, neither the algorithm nor JTWC performed significantly better than persistence. Except for the difference between the percent correct for JTWC and persistence, none of the differences between the scores were significant. For this data set, JTWC did not forecast tropical cyclone intensification significantly better than the algorithm or persistence. The algorithm, however, does give quantitative guidance for the parameters which were found to be important to tropical cyclone intensification.

Generally, the 400-700 mb layer vertical wind shears exhibited a greater difference between intensity categories than did the 250-400 mb layer shears. And the intensifying cyclones were generally found to be embedded in an environmental flow which had a weaker vertical wind shear than the flow surrounding the non-intensifying cyclones. With small vertical shears tropical cyclones can develop when the divergent upper-level flow supports the lower-level convergence and convection. High zonal wind speeds and large vertical wind shears can be responsible for cyclone decay by advection of upper-level temperature and moisture anomalies away from the cyclone and by injection of cool air into its circulation.

The approach used in the present study to develop an intensification algorithm is a general one and could conceivably be used to develop other tropical cyclone forecasting procedures. Besides the current analyses, forecast fields could also be used for a Model Output Statistics (MOS) approach (Glahn and Lowry, 1972) to tropical cyclone prediction. Future efforts, however, should include a more comprehensive comparison between the data used and the assumptions and constraints attendant to the application of discriminant analysis.

APPENDIX

The Global Band field data, and their differences, used in the analysis are presented as Figures A-F and A'-F' for the north oriented grid and as Figures G-L and G'-L' for the grid oriented along the direction of the cyclone's motion. The fields represent the means and standard deviations (σ) for the 2371 case data set. Approximately 70 Global Band grid points are included in the influence radius associated with each grid.


A
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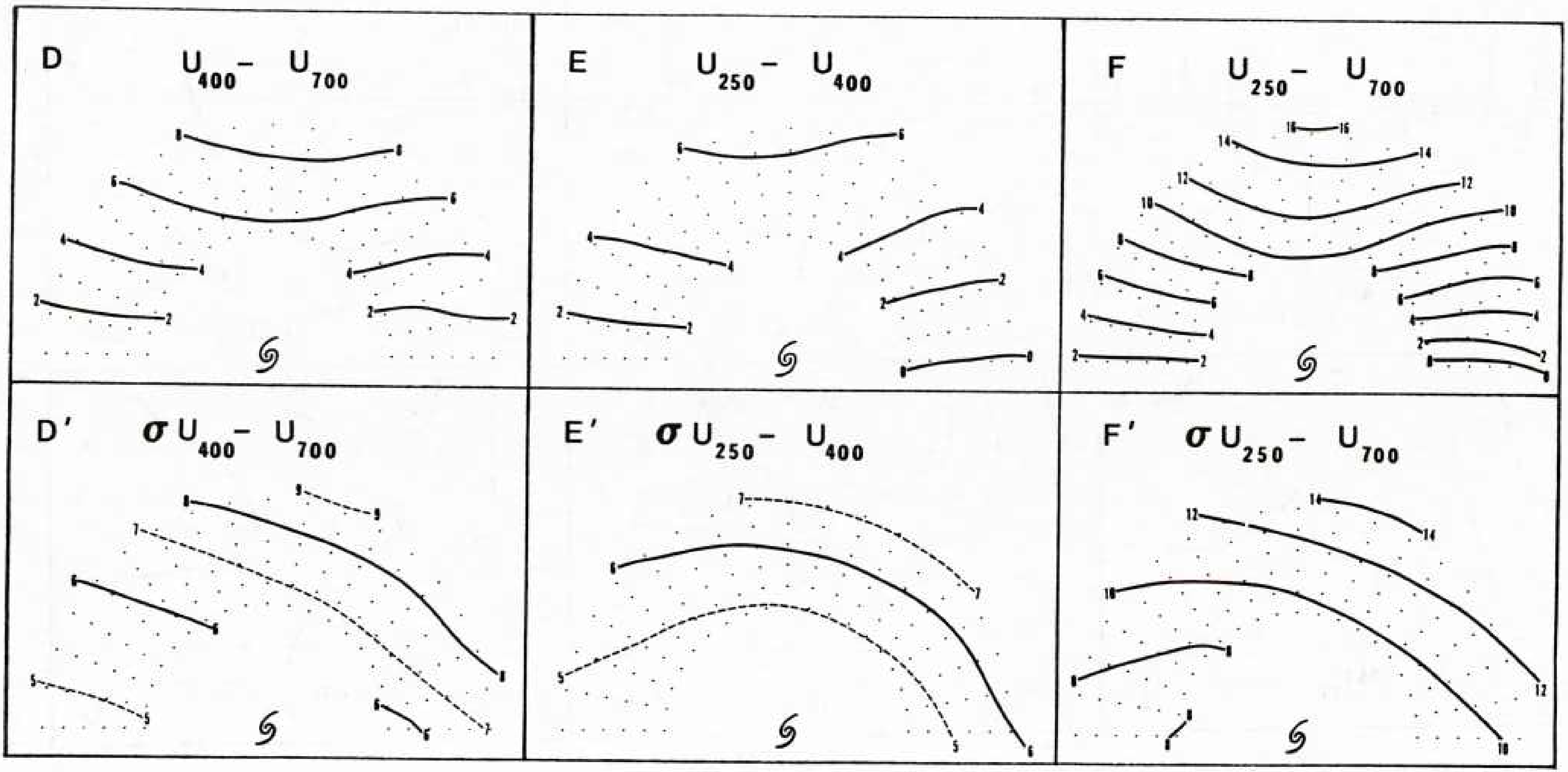
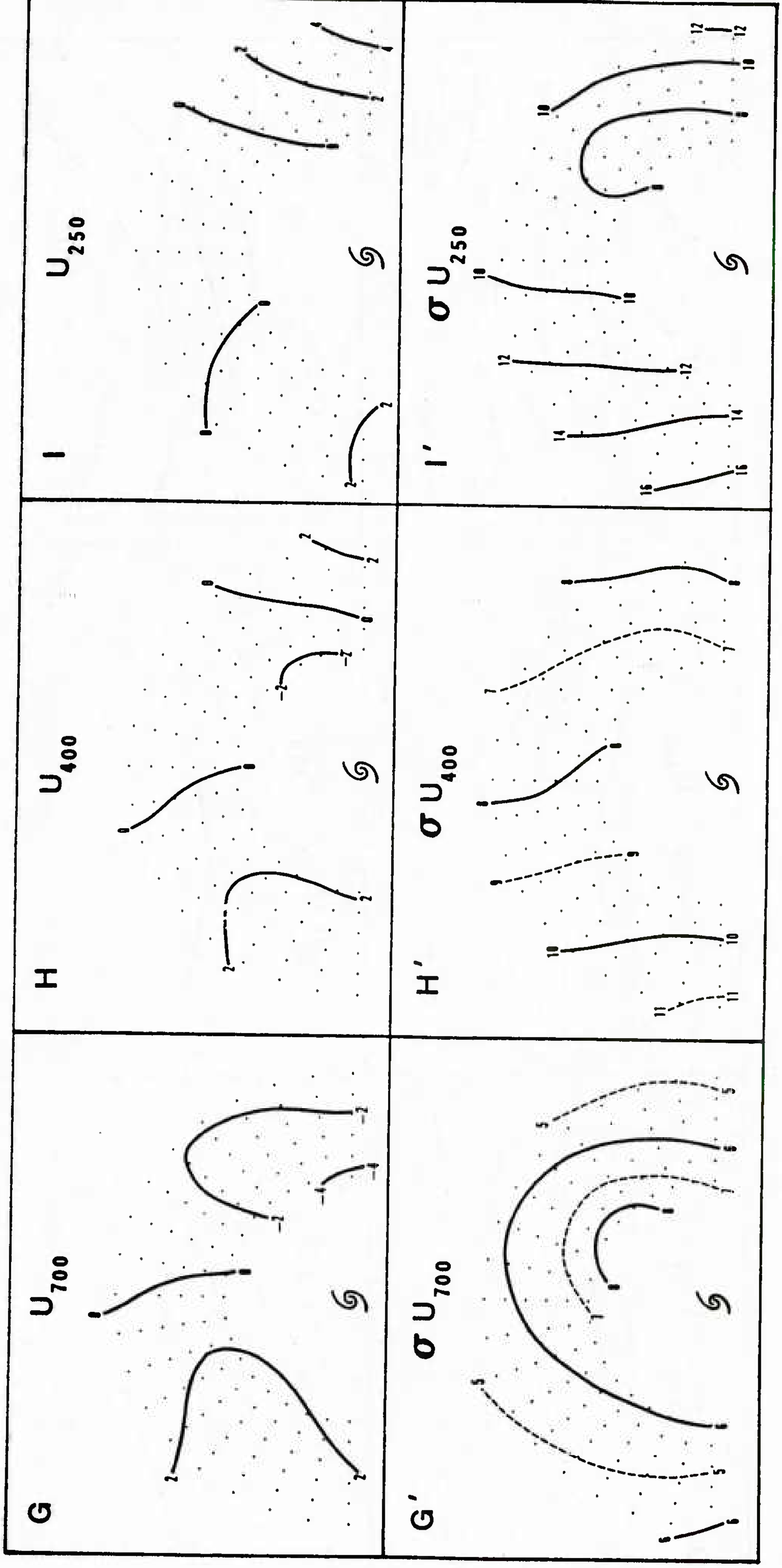
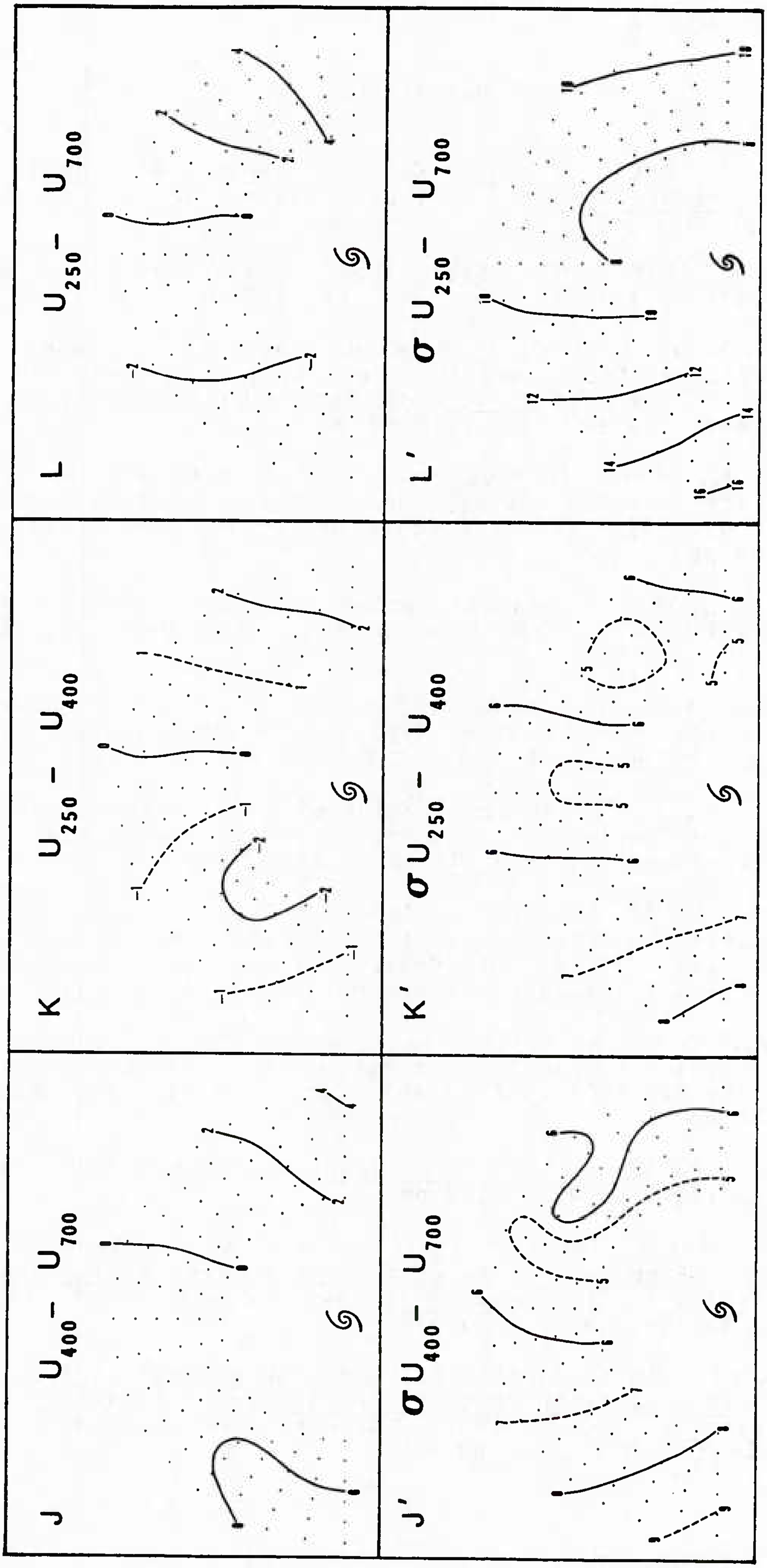
B
U_{400}
C
U_{250}
A′
σU_{700}
B′
σU_{400}
C′
σU_{250}


D $U_{400} - U_{700}$
E $U_{250} - U_{400}$
F $U_{250} - U_{700}$
D′ $\sigma U_{400} - U_{700}$
E′ $\sigma U_{250} - U_{400}$
F′ $\sigma U_{250} - U_{700}$


G
U_{700}
H
U_{400}
I
U_{250}
G′
σU_{700}
H′
σU_{400}
I′
σU_{250}


J
$U_{400} - U_{700}$
K
$U_{250} - U_{400}$
L
$U_{250} - U_{700}$
J′
$\sigma U_{400} - U_{700}$
K′
$\sigma U_{250} - U_{400}$
L′
$\sigma U_{250} - U_{700}$

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