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An Evaluation of the DVORAK Technique for Estimating Tropical Cyclone Intensities from Satellite Imagery

by

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CONTENTS

ABSTRACT

This paper investigates the accuracy of tropical cyclone intensity estimates as derived from the Dvorak technique. Estimates of current intensity and 24-hour forecast intensities were verified against JTWC official best track data. Results from a 396-case sample indicate overall absolute and bias errors of less than one CI number, even though forecast intensity errors were twice that of the current intensity estimates. Comparison of Dvorak and JTWC intensity errors indicate that they are essentially equal. The Dvorak 24-hour forecast intensities are also superior to all objective forecast aids available to the JTWC. Dvorak forecast data were also evaluated as a function of the tropical cyclone's life cycle. Results show a tendency of the Dvorak technique to over-forecast developing and weakening trends. Verification of cases which included a PLUS or MINUS symbol indicated no improvement over cases with no symbols. However, the use of the symbols is believed to reduce forecast intensity error.

AN EVALUATION OF THE DVORAK TECHNIQUE FOR ESTIMATING TROPICAL CYCLONE INTENSITIES FROM SATELLITE IMAGERY

1. INTRODUCTION

The meteorological satellite is a principal source of reconnaissance data for estimating the intensity of tropical cyclones. Several methods have been developed for obtaining intensity information from satellite imagery (WMO, 1977). Dvorak (1973 and 1975) developed a successful technique for determining the intensity of tropical cyclones (Table I)

TABLE I

The empirical relationship between the current intensity (CI) number, the maximum wind speed (MWS), and the minimum sea-level pressure (MSLP) (Dvorak, 1975).

CI Number	MWS (kt)	MWS (ms^{-1})	MSLP (NW Pacific) (mb)
1	25	13	-
1.5	25	13	-
2	30	15	1003
2.5	35	18	999
3	45	23	994
3.5	55	28	988
4	65	34	981
4.5	77	40	973
5	90	46	964
5.5	102	52	954
6	115	59	942
6.5	127	65	929
7	140	72	915
7.5	155	80	900
8	170	87	884

using daytime visual imagery from polar-orbiting satellites. This technique estimates a tropical cyclone's current intensity[1] (CI) and provides a 24-hour forecast intensity[2] (FI). To date, the Dvorak technique appears to show the most skill in comparison with other methods. It is currently used extensively on an operational basis by both civilian and military agencies. The Naval Oceanography Command Center/Joint Typhoon Warning Center (NOCC/JTWC), Guam, uses intensity data, derived from the Dvorak technique, on a routine basis to analyze and forecast tropical cyclone intensities. The Dvorak technique offers one of the few objective techniques to forecast tropical cyclone intensity. However, at present, the JTWC places more reliability on estimates of current intensity than on forecast intensity.

The purpose of this study is to evaluate both the current intensity and, especially, the 24-hour forecast intensity derived from the Dvorak (1975) technique. Comparisons are made between the Dvorak estimates, JTWC official forecasts, and climatology. Dvorak forecast intensities are also correlated to the tropical cyclone's life cycle to determine the accuracy of the Dvorak technique during different stages of tropical cyclone development. Finally, the authors recommend changes to the interpretation of Dvorak data and emphasize the importance of applying the entire Dvorak technique to produce the best possible forecast intensities.

1 The CI number is derived from the tropical cyclone's T-number, as modified by observed conditions (see Dvorak, 1975). The Dvorak T-number represents a numerical classification of a tropical cyclone based on its current cloud features. The classification of the cyclone according to its T-number is the heart of the Dvorak technique.

2 The FI number is determined from the CI number and the past trend (see Dvorak, 1975), with modifications for any significant present or anticipated changes (see Section 4.3). The FI and T-numbers use the same numerical scale as the CI numbers.

2. REVIEW OF PRIOR STUDIES

There have been very few studies that review the accuracy of the Dvorak technique. The U.S. Air Force and Navy have a high degree of interest in this technique because DoD resources in and around the tropical oceanic regions are often threatened by destructive tropical cyclones. Detachment 1, 1st Weather Wing (1WW), routinely positions and estimates intensities of tropical cyclones using satellite imagery from Defense Meteorological Satellite Program (DMSP) and national satellites. Detachment 1 made a few but significant changes to Dvorak's technique because of the high resolution of DMSP data and experience gained from operational evaluation. These evaluations are based on JTWC post-analysis track and intensity data (see Section 3). Results indicated a current intensity mean error of 8 kt (4 ms^{-1}) with an RMS error of 12 kt (6 ms^{-1}). The forecast intensity mean error was 13 kt (7 ms^{-1}) with an RMS error of 18 kt (9 ms^{-1}). These evaluations are documented in the 1st Weather Wing Pamphlet (1WWP) 105-10 (1974), which is currently being updated for 1980.

Independent evaluations performed at Detachment 1, at the National Environmental Satellite Service (NESS) in Washington, and by Dvorak have demonstrated that consistent results are obtained between analysts and that intensity estimates have a high correlation with conventional intensity estimates. The most recent evaluation by Sheets and Grieman (1975) tested three groups of skilled analysts, each making many classifications of North Atlantic and North Pacific cyclones using imagery from polar-orbiting and the earlier geostationary (ATS-3) satellites. Results of this study also show that skilled analysts usually obtain consistent and accurate intensity estimates. The average error of satellite analysts was approximately 0.5 T-number[1]. From Table I, this translates into an estimated average MWS error of 5 to 15 kt (3 to 8 ms^{-1}), depending on location on the CI scale.

1 The CI/T-numbers have intervals of 0.5 T-numbers (see Table I).

3. DATA AND METHODOLOGY

This study used tropical cyclone data from the 1978-79 time period. A total of 51 tropical cyclones in the western North Pacific, including tropical depressions[1] through super typhoons[2], were used.

Satellite intensity estimates and forecasts received operationally at JTWC for issuing tropical cyclone warnings were used for this study. These fixes[3] were made by a network of tactical DMSP sites which supports JTWC's tropical cyclone reconnaissance requirements. This network includes Det 1, 1WW Nimitz Hill, Guam; Det 5, 1WW Clark AB, Philippines; Det 8, 30WS Kadena AB, Japan; Det 15, 30WS Osan AB, Korea; and Det 4, 1WW Hickam AFB, Hawaii. All fixes were made from DMSP visual imagery using techniques described in 1WWP 105-10 (1974) and, although all fixes were made independent of the other sites, each had access to JTWC's warnings. This obviously introduced feedback of intensity information to the analysts. This feedback was unavoidable and unmeasureable, yet an integral part of the warning system. Due to the operational nature of these data, the results of this study are applicable to similar tropical cyclone warning systems in other regions.

The verification of the Dvorak intensities were based on JTWC official best track data. Best track data are derived by JTWC forecast personnel using a combination of objective and subjective post-analysis methods. Each best track is a smoothed path, versus a precise and very erratic fix-to-fix path, of a tropical cyclone's position and intensity history. All fix information, including aircraft,

1 Tropical depression: a tropical cyclone in which the maximum sustained surface wind (1-minute mean) is 33 kt (17 ms^{-1}) or less.

2 Super typhoon: a tropical cyclone in which the maximum sustained surface wind (1-minute mean) is 130 kt (67 ms^{-1}) or greater.

3 For the purpose of this paper, the term fix will only refer to cyclone intensity estimates and forecasts, not cyclone position.

satellite, radar and synoptic, are evaluated during the best tracking process. Best track data are generated at 6-hour intervals for each tropical cyclone. Intensity data are rounded to 5-knot intervals. Verification intensities were linearly interpolated between the 6-hourly best track data.

Each satellite fix was checked for reliability. That is, each fix had to meet two criteria. First, only fixes which provided a current intensity (CI) and a 24-hour forecast intensity (FI) were selected. These FI were further checked to insure that they were not greater than 1.5 from their corresponding CI number (an acceptable range of the Dvorak technique). This check eliminated possible errors in the fix data base.

A second criterion assured that only those satellite fixes which were within 24 hours of an aircraft fix were selected for study. Additionally, the verifying time of the FI (24 hours after CI time) also had to be within 24 hours of an aircraft fix. These time restrictions increase verification validity because of the greater accuracy of the aircraft's position and derived intensity data. An aircraft intensity is derived from the combined evaluation of the aircraft's measured sea-level pressure (by dropsonde), measured flight-level height (by aircraft instrumentation), measured flight-level winds (by doppler radar), and observed surface winds (by trained ARWO[1]). Greater weight is given to the measured data in the best track process. Also, the tropical cyclone's central pressure/height data are a better measure of intensity compared to averaging or estimating sustained winds around the entire vortex. Pressure/height data are directly converted to a maximum sustained surface wind using the Atkinson and Holliday (1977) relationship (Fig. 1). This relationship is used operationally at JTWC and has recently been reevaluated and verified with independent data (Lubeck and Shewchuk, 1980). Therefore, the increased accuracy of best track intensities, which were significantly influenced by nearby aircraft data, provided the best source of verification data available to the authors. These data/verification constraints produced a data sample of 396 satellite fixes. Most of these data are in the 1978 and 1979 Annual Typhoon Reports (ATRs). Complete listings are available from the NOCC/JTWC, Guam.

1 ARWO: Aerial Reconnaissance Weather Officer.

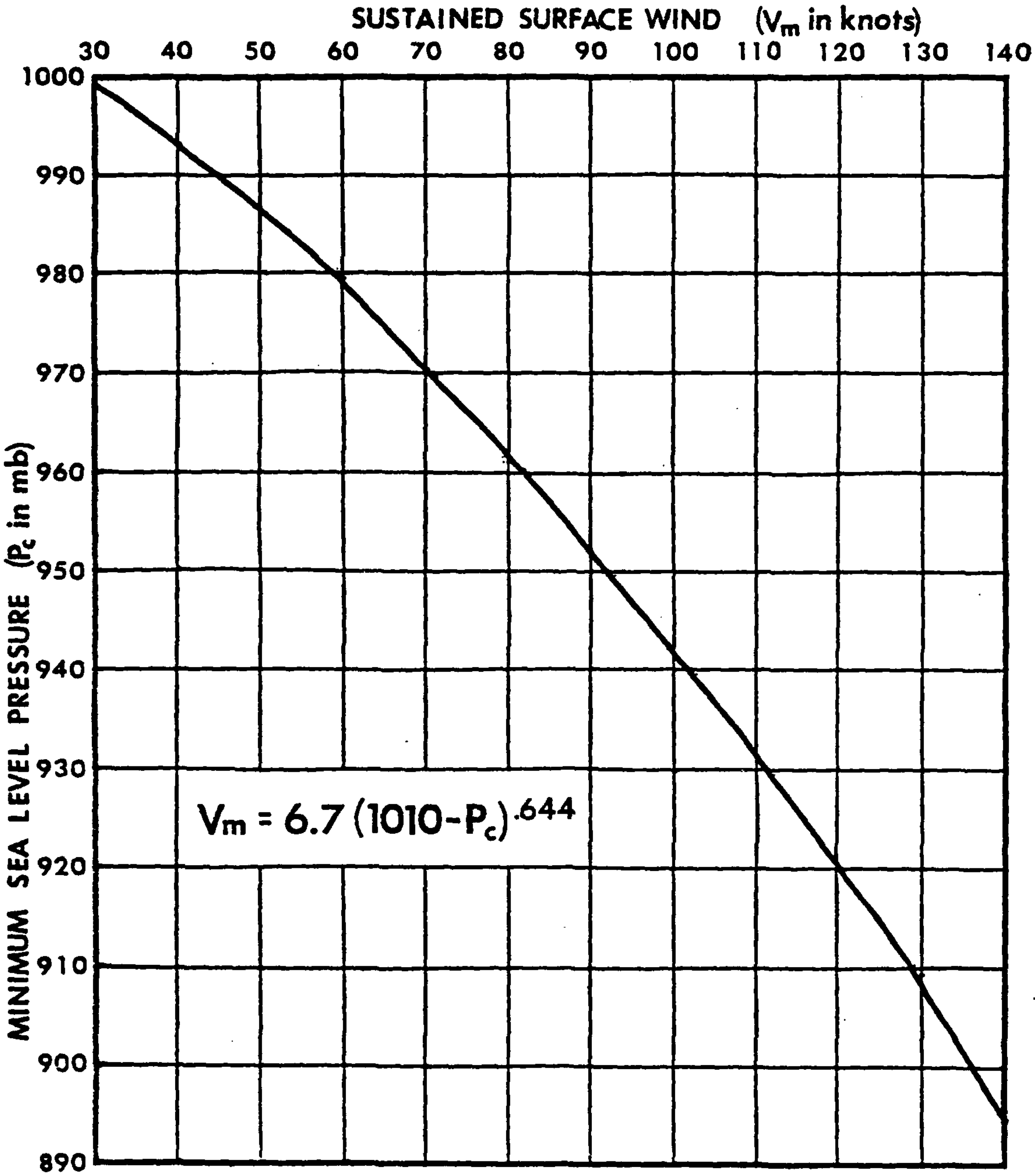


FIGURE 1. Atkinson and Holliday (1977) maximum sustained surface wind speed - minimum sea level pressure relationship for NW Pacific tropical cyclones.

4. RESULTS

4.1 CI and FI Verification

Results from verifying the 396-case data sample were encouraging. Figure 2 depicts the Dvorak current intensity (CI) and forecast intensity (FI) errors in terms of CI numbers from 1.0 to 8.0. CI numbers with less than 3 verifying cases were not depicted. (Tables of all verification data can be found in the Appendices.) The mean absolute and bias errors are shown. M is the mean absolute error for all CI numbers and B is the corresponding bias error. The CI data verified very well. The mean absolute error was less than one CI number with a zero overall bias. The largest errors were encountered when tropical cyclones were less than tropical storm strength[1], CI 2.0. The FI data verified with a mean absolute error twice the CI error, but still less than one CI number. The bias was very small and positive, indicating a slight tendency to over-forecast. It is interesting to note that the FI errors had a definite and opposite bias relative to CI 3.0. That is, application of the Dvorak technique produced data which under-forecast when FI was less than 3.0 and over-forecast when greater than 3.0.

The accuracy of error statistics presented in this paper are limited by the intensity intervals of the original data. Dvorak intensities are obtained from generally larger intensity intervals than JTWC forecasts. Dvorak intensities range from 5 to 15 knots and JTWC issues forecasts at 5-knot intervals. Climatology intensity forecasts are generated from past tropical cyclone best tracks. Therefore, error differences of less than 5 knots between forecast methods are considered essentially equivalent and within the noise limits of their data samples. It should also be noted that, because JTWC forecasts to the nearest 5 knots and Dvorak resolution is less precise, the Dvorak technique does not provide data which fully meets JTWC's data requirements, especially at the larger intensities. For example, the CI numbers increase by 15-knot intervals above CI 7.0 (140 knots).

1 Tropical storm: a tropical cyclone with maximum sustained surface winds (1-minute mean) in the range of 34 to 63 kt (18 to 32 ms^{-1}), inclusive.

FIGURE -2-

ALL FIXES (396 CASES)

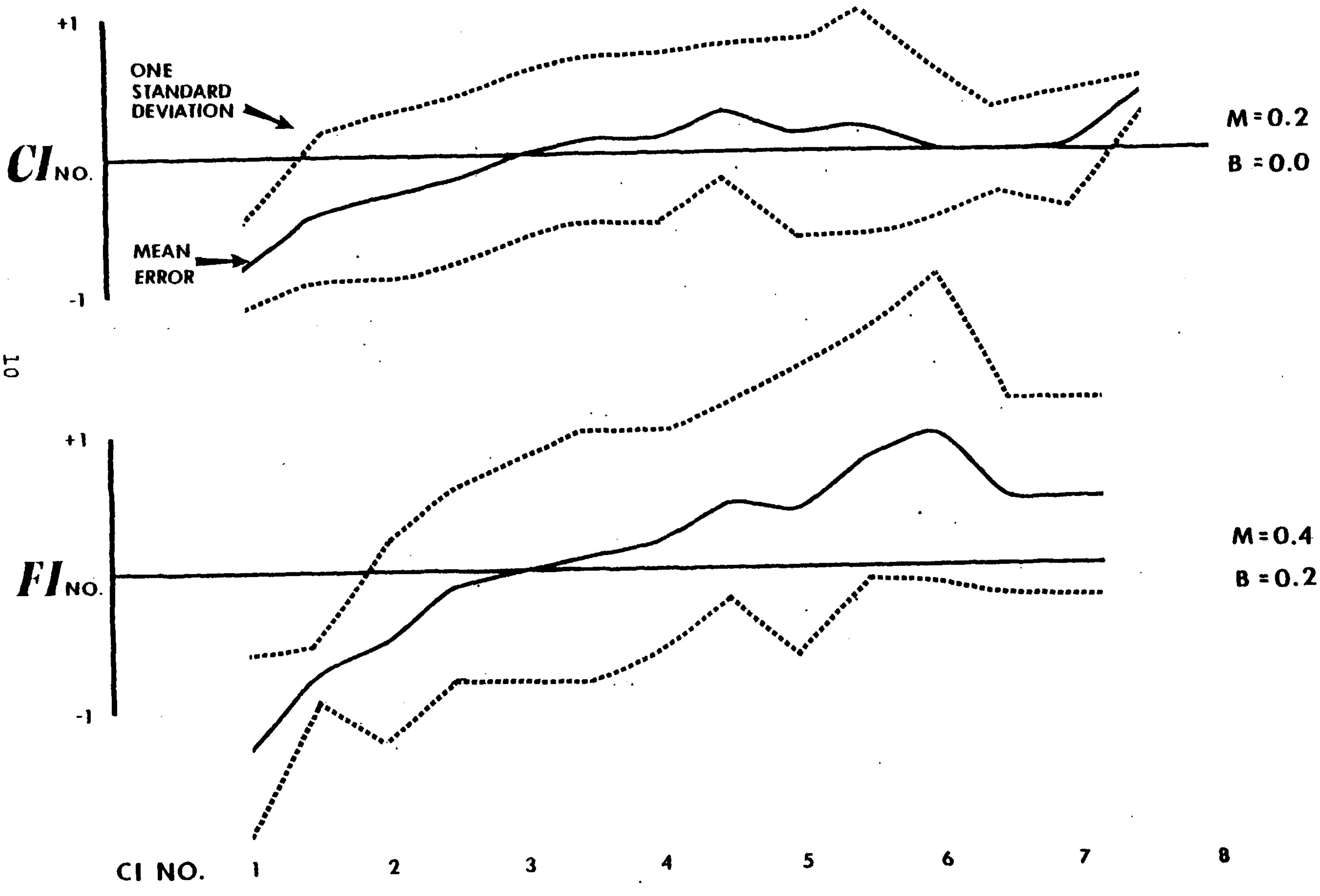


Table II compares the results of Figure 2 to official JTWC intensity errors and climatological intensity forecast errors. The Dvorak and JTWC current intensity errors were nearly equal, but more importantly, the mean error for the Dvorak forecasts was superior to the official JTWC 24-hour intensity forecasts. Notice, however, that the Dvorak technique produced a larger bias. As previously discussed, these error statistics are essentially equivalent, because the intensity data and errors are within their respective data intervals.

TABLE II

Comparison between current and forecast intensity errors (knots) derived from Dvorak, JTWC and climatology. Dvorak and JTWC verification is based on 1978-79 data, while climatology is based only on 1979 data. Climatology (Clim) only provides forecast information. Errors represent all available verification data, and therefore, are not equivalent cases.

		Mean	Bias
Current Intensity	Dvorak	3	+1
	JTWC	4	0
24-Hour Forecast	Dvorak	8	+5
	JTWC	11	-1
	Clim	15	-1

4.2 FI Trend Comparisons

In this section, the Dvorak intensity forecasts are evaluated during the life cycle of tropical cyclones. Figure 3 depicts FI errors as a function of the time history of all verifying cyclones. The point in time history of a particular FI was determined by dividing the life of each cyclone into 10 time intervals. The first 5 intervals and the last 5 intervals were separately, but equally, divided about the cyclone's maximum (peak) intensity. Intervals 1 through 5 represent cyclone development, 6 through 10 represent weakening, and the cyclone's peak intensity (or last peak for multi-modal cases) is represented by 5.5. The time history graphs depict the average errors for all verifying FI cases between 1.0 and 8.0 on the Dvorak scale that fell within their respective time intervals. Time intervals with less than 3 verifying cases were not depicted.

Figure 3 indicates that FI errors are smaller for the developing stage than for the weakening stage of tropical cyclones. Similarily, the variance of the forecasts gradually becomes larger as the cyclone matures and finally decays. There is no apparent forecast bias during the developing stage. The positive bias for the weakening stage indicates that the Dvorak technique forecast development after the cyclone reached peak intensity. This result was expected, because the Dvorak technique uses a built-in lag effect[1] where the CI number is usually not lowered until the T-number has shown weakening for 12 hours or more.

Figures 4 and 5 depict FI errors only when developing or weakening was forecast, respectively. Each figure depicts the FI errors as a function of CI number and cyclone time history. Figure 4 depicts FI errors only during cases when FI was greater than CI; i.e., intensification was forecast. A total of 204 development forecasts

1 The CI number is the same as the T-number during the development stages of a tropical cyclone, but is held higher than the T-number while a cyclone is weakening. This is done because a lag is often observed between the time a storm pattern indicates weakening has begun and the time when the storm's intensity decreases (from Dvorak, 1979).

FIGURE-3- ALL FIXES (396 CASES)

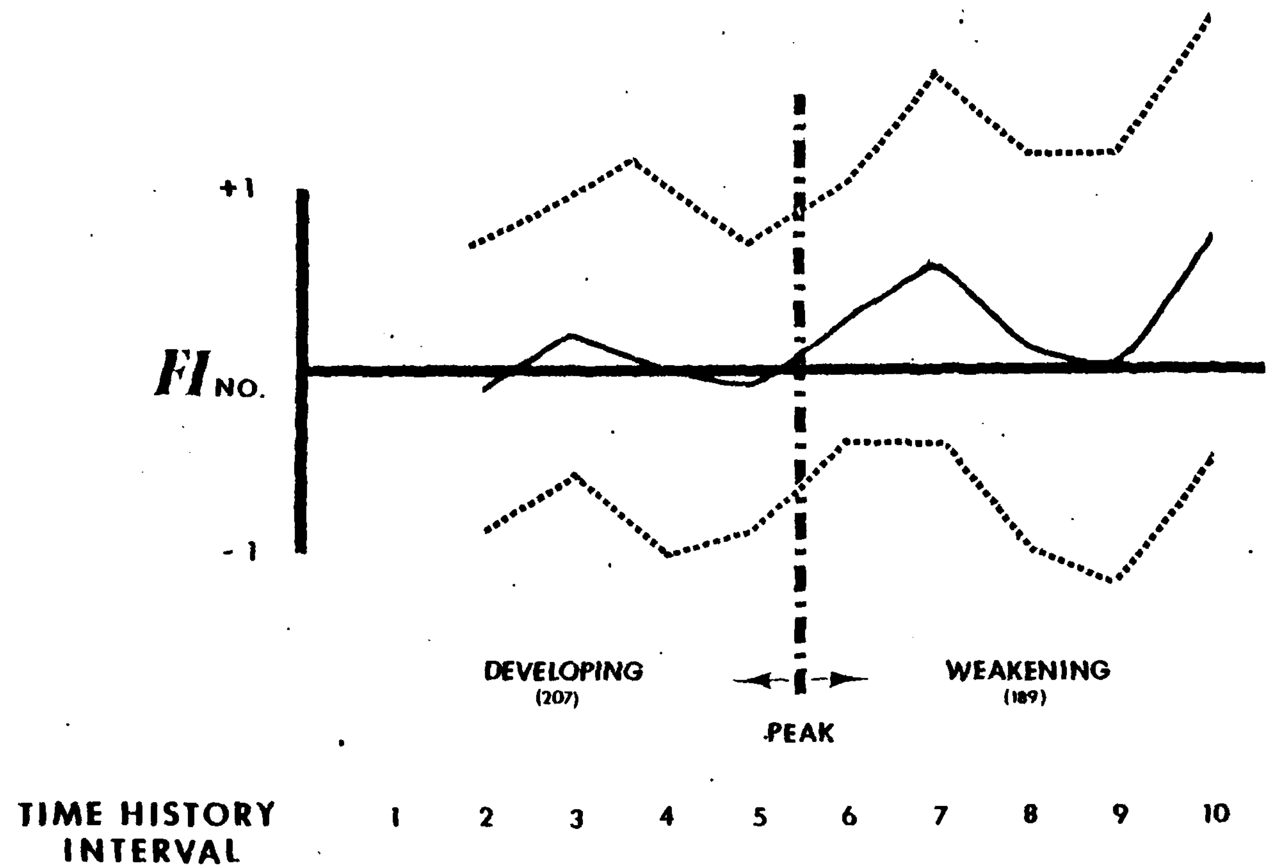


FIGURE -4- FORECAST DEVELOPMENT, FI>CI (204 CASES)

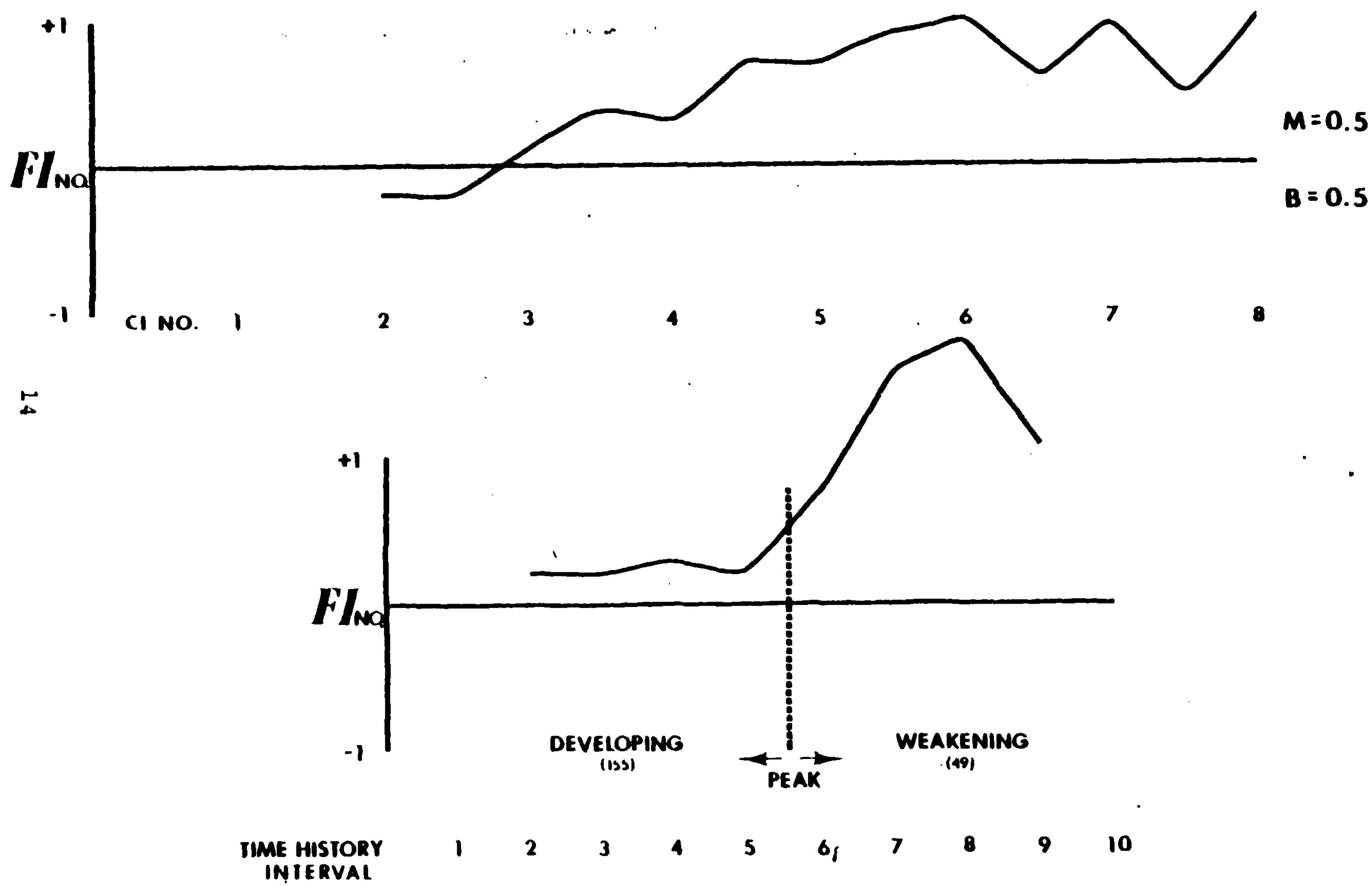
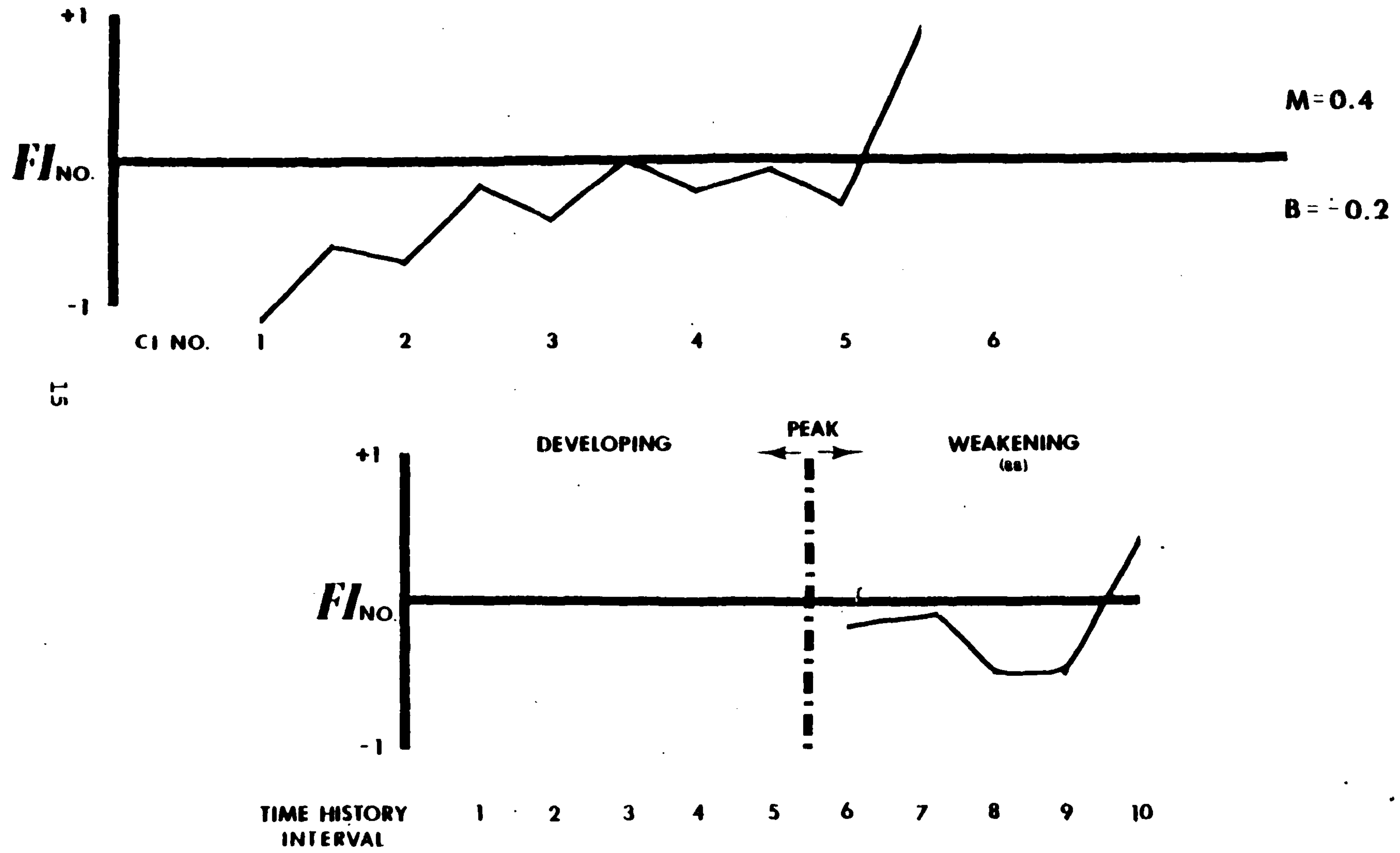


FIGURE -5- FORECAST WEAKENING, FI < CI (96 CASES)



had a mean and bias error of 0.5 CI number. Development forecasts verified well when cyclone development actually occurred. However, the cyclone actually weakened for 49 development forecasts. These latter cases increased the errors considerably.

Figure 5 depicts FI errors only during cases when FI was less than CI; i.e., weakening was forecast. The weakening forecasts verified slightly better than the development cases, especially the bias error. Only 18 of 96 weakening forecasts were verified when cyclone intensification occurred. A comparison of Figures 4 and 5 shows that there is a tendency to over-forecast developing and weakening trends. Overall, there is no significant difference between developing and weakening forecast errors.

4.3 PLUS and MINUS Verification

The Dvorak technique allows for rapid changes in cyclone intensity at the time of the latest satellite picture. These changes (PLUS and MINUS)[1] are used only when the apparent existing or anticipated change in intensity is significantly different from the past change. This permits the satellite analyst to deviate from the forecast model[2] when determining the FI. This requires a qualitative judgment based on experience. Atmospheric or terrain conditions affecting the cyclone will usually influence the analyst to use these changes. A total of 141 fixes of all available (verified and non-verified) fixes included a PLUS or MINUS symbol in the Dvorak code. Figure 6 depicts the geographic distribution of these fixes. The majority of these fixes were made when the cyclones were near large land masses. Weakening over land and development over water after crossing

1 PLUS denotes more rapid intensification (or less rapid weakening) than the observed past change. MINUS denotes less rapid intensification (or more rapid weakening).

2 The Dvorak forecast model determines the expected FI from intensity change curves depicting typical, rapid and slow development/weakening curves (Dvorak, 1975).

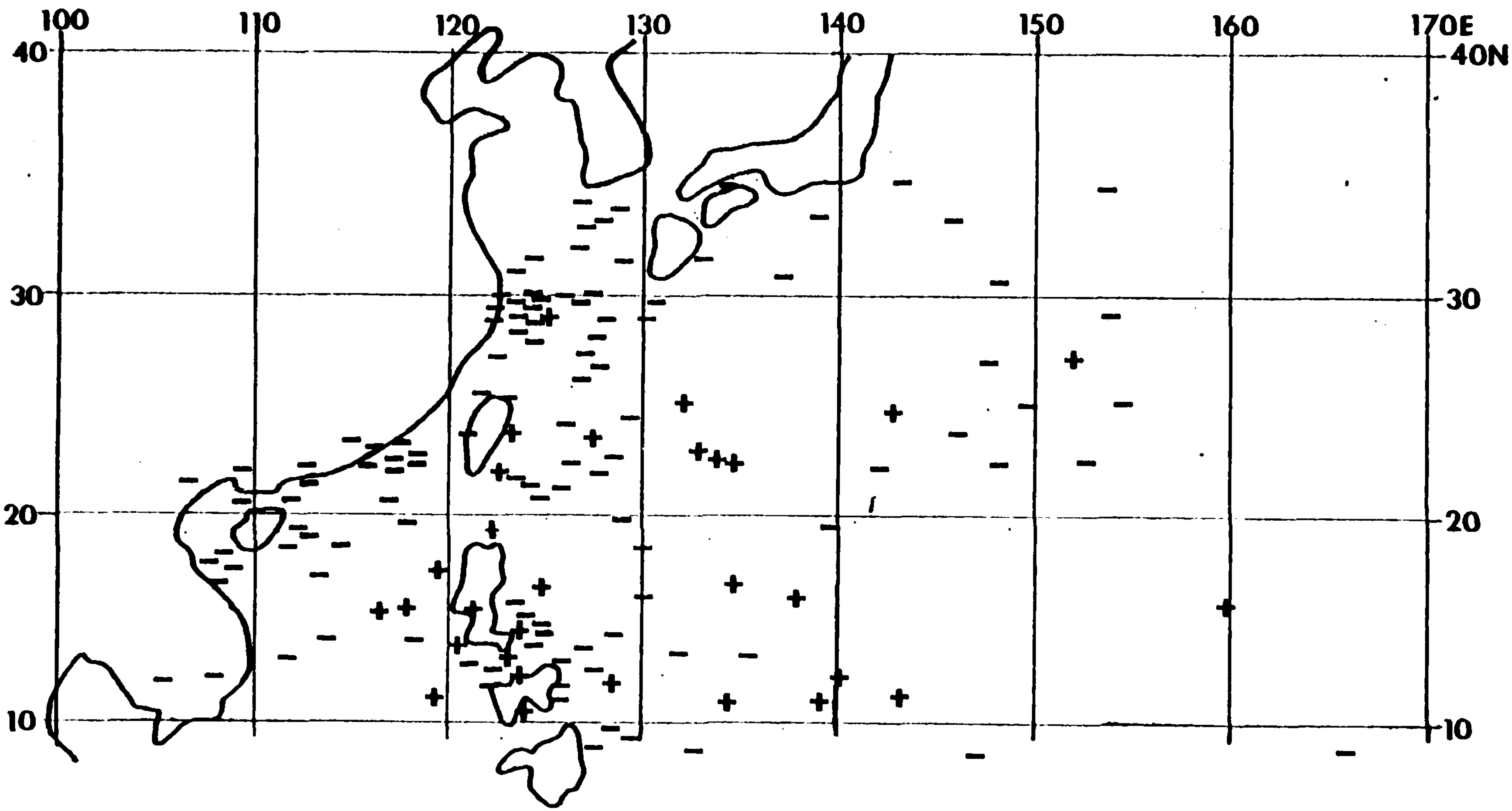


FIGURE 6. Locations of all satellite fixes which used a PLUS (+) or MINUS (-) symbol in the Dvorak code to determine the forecast intensity (FI).

the Phlippines were the probable reasons which influenced the analysts. Seventy-nine out of the 396-case sample observed or anticipated significant change; 30 were PLUS and 49 were MINUS. These 79 cases were verified to determine if the use of the PLUS and MINUS modifications led to improved forecasts. Figure 7 depicts these errors as a function of CI number. The results show that there was no improvement in the mean or bias errors, or a reduction of variance. But, because these cases usually represent greater than average amounts of 24-hour intensity change, the use of the symbols may have had value in reducing possible greater errors.

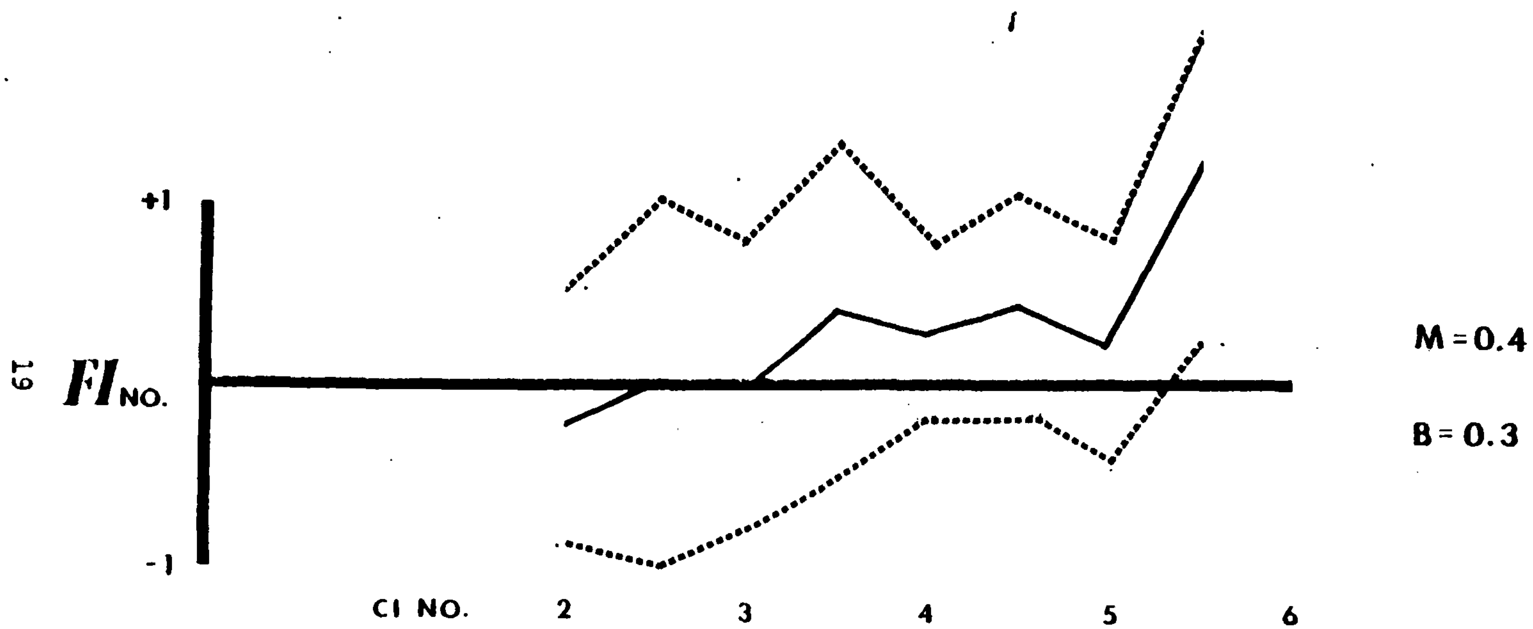
5. CONCLUSIONS

5.1 Summary

This study evaluated tropical cyclone current intensity (CI) and 24-hour forecast intensity (FI) fix information based on the Dvorak technique. The mean absolute CI error from the 396-case data sample was less than one CI number. The corresponding mean absolute FI error was twice the mean absolute CI error, but still less than one CI number. Both the CI and FI errors slowly increased above and below 3.0 on the CI scale. These CI and FI errors are relatively small when compared to JTWC official errors. In fact, the 24-hour Dvorak forecast intensities were superior to all other objective forecast aids used by JTWC. The Dvorak errors were also superior to JTWC's current and 24-hour forecast intensity errors, however, the Dvorak technique always produced larger variance. It is important to note that, because the intensity data and their errors are within their data intervals, Dvorak and JTWC errors are comparatively similar.

When Dvorak forecasts were verified with respect to the life cycle of tropical cyclones, it was found that the Dvorak technique works better for the developing stage than for the weakening stage. The mean absolute error and variance increased once the cyclone's peak intensity occurred. This result was expected due to a lag effect within the Dvorak technique. Verification of only developing and

FIGURE-7- FIXES WITH PLUS OR MINUS (79 CASES)



weakening forecasts resulted in errors similar to the 396-case data sample. There were also no significant differences between developing and weakening forecast errors. However, comparison of these errors show that there is a tendency to over-forecast developing and weakening trends. This result is also attributed to the Dvorak technique's lag effect.

The satellite analyst has the option to use a PLUS or MINUS symbol to develop the FI during periods of rapid change in cyclone intensity. The forecasts which included a PLUS or MINUS symbol were separately verified to determine if the use of the symbols led to improved forecasts. Errors from these cases were similar to those cases which had no symbols. However, if the symbols had not been used for these cases, errors may have been greater.

5.2 Recommendations

The authors' recommendations are directed to the users of the Dvorak technique. This study found that the most consistent errors occurred as a result of over-forecasting developing and weakening trends, while the greatest errors occurred after the tropical cyclone's peak intensity was reached. These errors are a direct result of the Dvorak forecast model and built-in lag effect used to determine the FI. These constraints were designed to give the Dvorak technique stability and consistency. Even though this study has shown that the Dvorak technique produces excellent 24-hour forecasts, the constraints limit the forecasting of intensity trend changes and rapid intensity changes. The Dvorak technique accommodates these changes through the use of the PLUS and MINUS symbols. The application of these symbols are probably the most subjective aspect of the forecast procedure, yet they are very important, because these symbols denote significant intensity changes. The authors believe that the use of PLUS and MINUS symbols reduce intensity errors and recommend that all satellite analysts be fully aware of their use and potential. The successful application of these symbols requires the satellite analyst to be knowledgeable of the cyclone's history and, most importantly, the synoptic-scale cyclone environment, including the multitude of environmental (land, sea, and air) factors which can significantly alter a cyclone's intensity.

Finally, the authors recommend that the empirical MWS/MSLP relationship (shown in Table I) be modified to better reflect NW Pacific tropical cyclone characteristics. This relationship produces MSLP values which are consistently higher than typically observed for their corresponding MWS values. The Atkinson and Holliday (1977) relationship (Fig. 1) is the most reliable and tested MWS/MSLP relationship in use at the JTWC. Therefore, Table III is a recommended revision of Table I and lists lower MSLP values as derived from the Atkinson and Holliday relationship.

TABLE III

Recommended change to MWS/MSLP relationship from Table I with revised minimum sea-level pressure (MSLP) as derived from the Atkinson and Holliday (1977) relationship.

CI Number	MWS (kt)	MWS (ms^{-1})	MSLP (NW Pacific) (mb)
1	25	13	-
1.5	25	13	-
2	30	15	1000
2.5	35	18	997
3	45	23	991
3.5	55	28	984
4	65	34	976
4.5	77	40	966
5	90	46	954
5.5	102	52	941
6	115	59	927
6.5	127	65	914
7	140	72	898
7.5	155	80	879
8	170	87	858

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APPENDIX A; CI/FI Errors as a Function of CI Number

		CI Scale														
		1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
ALL FIXES	Mean Error	-0.8	-0.4	-0.3	-0.2	0.0	0.1	0.1	0.3	0.1	0.2	0.0	0.0	0.0	0.4	-
CI ERRORS	Standard Dev.	0.3	0.5	0.6	0.6	0.6	0.6	0.6	0.5	0.7	0.8	0.5	0.3	0.4	0.1	-
	# Cases	25	14	41	23	53	45	61	40	53	12	14	4	7	4	-
ALL FIXES	Mean Error	-1.3	0.7	-0.5	-0.1	0.0	0.1	0.2	0.5	0.4	0.8	1.0	0.5	0.5	0.5	1.0
FI ERRORS	Standard Dev.	0.7	0.2	0.7	0.7	0.8	0.9	0.8	0.7	1.0	0.9	1.1	0.7	0.7	0.1	0.1
	# Cases	22	5	21	20	60	44	63	39	55	28	21	7	5	2	2
FORECAST	Mean Error	-	-	-0.2	-0.2	0.1	0.4	0.3	0.7	0.7	0.8	1.0	0.6	1.0	0.4	1.0
DEVELOP-	Standard Dev.	-	-	0.6	0.6	0.7	0.7	0.7	0.5	1.0	0.9	1.1	0.9	0.6	0.0	0.1
MENT	# Cases	-	-	11	9	32	16	32	23	30	23	19	4	2	1	2
FORECAST	Mean Error	-1.1	-0.6	-0.7	-0.2	-0.4	0.0	-0.2	-0.1	0.3	0.9	0.5	0.1	-	-	-
WEAKEN-	Standard Dev.	0.7	0.1	0.6	0.8	0.7	0.9	0.7	0.5	1.1	1.1	0.9	0.1	-	-	-
ING	# Cases	8	3	6	8	14	15	14	9	8	5	2	2	-	-	-
PLUS	Mean Error	-0.5	-0.5	-0.2	0.0	0.0	0.4	0.3	0.4	0.2	1.2	1.3	0.2	-	-	-
or	Standard Dev.	0.0	0.0	0.7	1.0	0.8	0.9	0.5	0.6	0.6	0.9	0.0	0.5	-	-	-
MINUS	# Cases	1	1	4	5	12	9	12	12	9	11	1	2	-	-	-

APPENDIX B: FI Errors as a Function of Tropical Cyclone Time History

		Time History Intervals									
		1	2	3	4	5	6	7	8	9	10
ALL FIXES	Mean Error	-	-0.1	0.2	0.0	-0.1	0.3	0.6	0.1	0.0	0.7
	Standard Dev.	-	0.8	0.8	1.0	0.8	0.7	1.0	1.1	1.2	1.2
	# Cases	-	18	50	64	75	40	57	44	32	16
FORECAST DEVELOP-MENT	Mean Error	-	0.2	0.2	0.3	0.2	0.8	1.6	1.8	1.1	3.5
	Standard Dev.	-	0.7	0.6	0.9	0.6	0.6	0.8	0.8	0.4	0.0
	# Cases	-	13	38	51	53	18	17	8	5	1
FORECAST WEAKEN-ING	Mean Error	-	-	-0.7	-1.3	-1.4	-0.2	-0.1	-0.5	-0.5	0.4
	Standard Dev.	-	-	1.2	1.6	0.0	0.5	0.7	0.7	1.0	1.0
	# Cases	-	-	4	3	1	10	22	25	17	14

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