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An objective determination of tropical cyclone warning positions.

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NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

AN OBJECTIVE DETERMINATION OF TROPICAL CYCLONE WARNING POSITION

by

William Thomas Curry

June 1985

Thesis Advisor: R. L. Elsberry
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An Objective Determination of Tropical Cyclone Warning Positions

by

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Lieutenant Commander, United States Navy
B.S., University of Utah, 1977

Submitted in partial fulfillment of the
requirements for the degree of

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June 1985

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A technique has been developed to determine objectively the location of a tropical cyclone at warning time and reduce the short-term forecast errors due to errors in the warning position. The western North Pacific CLIPER (CLImatology and PERsistence) forecast scheme is used to generate a potential track from each fix, and a smooth curve is fit to the future and past positions. When multiple fixes are available, weighting functions are applied to account for fix platform accuracy and time of receipt. A set of 836 cases from 30 storms during 1981-1983 was evaluated. Using the objective scheme, 16 of the 30 tropical cyclones had reduced warning position errors compared to the Joint Typhoon Warning Center official warning position. For 11 of the 30 storms, the objective warning positions resulted in more accurate 24-h forecasts with the CLIPER technique than the official warning positions. This technique appears to provide an efficient, interactive tool to the forecaster to use in establishing the warning position.

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I. INTRODUCTION

Studies in the western North Pacific (Jarrell, et al., 1978) and the eastern North Pacific (Thompson, et al., 1981) link short-term tropical cyclone track forecast errors, in part, to an incorrect initial position. Prior to requesting any of the various objective forecast aids (persistence, climatology, analog, statistic or dynamic), a current "warning position" must be determined. Initial positioning error is defined as the distance between an initial warning position and the corresponding post-season Best Track (BT) position. Neumann and Pelissier (1981) eliminated the effect of this initial position error in their evaluation of forecast errors by shifting the forecast tracks of the various objective aids so that the initial position was coincident with the BT position.

Efforts continue to be made to reduce this initial positioning error. Prior to 1983, the Joint Typhoon Warning Center (JTWC), Guam, used the speed and movement based on the latest fix information to extrapolate a 6-h warning position. This extrapolated position was used as the "current warning position" when requesting forecast aids. The extrapolation procedure introduces uncertainty in this critical short-term forecast variable. Since 1983, the JTWC minimizes this uncertainty by using the most recent "working best track" position as the initial warning position for the purpose of requesting objective aids. The "working best track" (WBT) is the adjustment of the previous warning positions during each warning cycle to better approximate the recent storm track based on the accumulated information. In most cases, positions 36 to 48 hours prior to the most recent position are not significantly altered. This procedure is similar to the approach in determining the "official best track" after completion of the storm. WBT positions at -6 h, -12 h, -18 h, and -30 h are sent to the Fleet Numerical Oceanography Center (FNOC) to generate the various climatological and dynamic forecast aids that are used in preparing the warning position and future warning track. The +6-h forecast positions from the objective aids are blended with the most recent fix positions to determine the "current warning position". Greater confidence should result since extrapolated tracks from each fix are not the only information utilized to establish the warning position. Rather, the forecast tracks from the various aids provide a kind of hindsight for judging the likely accuracy of each fix. Subjectivity still enters the procedure during the blending process. The Typhoon Duty Officer (TDO) must consider the likely accuracy of the fixes from the various platforms (satellite, aircraft, radar or synoptic) in determining the optimal warning position based on his experience and recent platform performance, i.e. which platform has given the best indication of recent storm movement. The TDO has available one to 15 fix positions during the six hours since the previous warning.

The goal of this thesis is to develop an objective procedure for the TDO to use in determining the initial warning position. The strategy for the objective warning position determination proposed here is based on the idea that it is often easier to determine which of the storm center fixes to accept if the forecaster knows the future track. That is, hindsight often allows the forecaster to select more intelligently from a number of possible fix positions. The TDO might then use the warning position from the objective scheme as a "first-guess" position. This position is then adjusted to reflect consistency with the synoptic reasoning that forms the basis for the forecast track. It is hoped that this objective warning position could be used as a "tool" by the tropical cyclone forecaster to provide a more consistent initial warning position and a more accurate short-term forecast.

In this thesis, a detailed description of the objective technique procedures and weighting functions applied to the individual fixes will first be given, followed by a summary of the sensitivity tests applied to the dependent data sample. Results from both dependent and independent samples will then be discussed.

II. PROCEDURES OF THE OBJECTIVE TECHNIQUE

Objective initial positioning has been proposed by Morford (1979) as an essential step in improving the short-term (less than 24-h) forecasts at JTWC. Simpson (1971) had earlier proposed a decision-tree format for establishing the initial warning position. This decision-tree approach attempted to use objective aids and similar reasoning in each forecast cycle to insure consistency. However, Simpson's technique was subjective rather than objective. The objective scheme proposed here simulates hindsight by estimating the future positions associated with each fix through an economical and viable short-term forecast technique, the western North Pacific CLIPER, described below.

The western North Pacific CLIPER (CLImatology and PERsistence), which was developed by Xue and Neumann (1984) at the National Hurricane Center (NHC), uses regression equations to relate future storm displacement (DISP) to eight basic environmental predictors:

$$DISP = f(Xo, Yo, U_{-12}, U_{-24}, V_{-12}, V_{-24}, W, D)$$

Xo = Initial longitude

Yo = Initial latitude

U_{-12} = Previous 12-h east-to-west translation

U_{-24} = Previous 24-h east-to-west translation

V_{-12} = Previous 12-h south-to-north translation

V_{-24} = Previous 24-h south-to-north translation

W = Initial maximum wind speed (kt)

D = Julian date.

Note that westward and northward translations are defined to be positive as the typical cyclone track is toward the northwest in the western North Pacific.

Because storm track forecasts to 24 h rely heavily on persistence, the primary input to CLIPER is the past 12 and 24 hour movement. However, higher order (up to third-order) terms can also serve as predictors in the regression equations. When all eight basic parameters are included, there are 165 possible products and cross-products as potential predictors in the regression equations. The applicable regression coefficients were derived for storms south of 35°N and west of 150°E during the months of May through December (see Xue and Neumann, 1984, for details).

A. INTERPOLATION TECHNIQUE

Upon receipt of a fix position, past positions at fix-time minus 12 hours (F-12) and fix-time minus 24 (F-24) hours must be derived to provide the required input to CLIPER (see Fig. 2.1). Rather than linearly interpolating between the -12 and -24 h WBT positions, a smooth WBT is determined from which the desired positions (F-12, F-24) can be interpolated. A third-order polynomial is fitted to the latest warning position and the -6, -12, -18 and -24 h WBT positions. As stated above, the TDO will adjust the WBT as far back as 36 to 48 hours to better reflect the latest information. As the greatest confidence can be placed on the "earlier" positions, higher weighting factors are given to the -12, -18 and -24 h positions (Table 1). The polynomial coefficients derived from this fitting routine allow the determination of interpolated positions at any time along the smooth WBT. For example, if fix A (Fig. 2.1) was received at 0430 GMT, position B at 1630 GMT (F-12) and C at 0430 GMT (F-24) would be interpolated using the third-order polynomial coefficients. These three positions, the current maximum wind speed (taken from the most recent warning or from the fix if it is from aircraft reconnaissance) and the current Julian date/time are input to CLIPER to generate a 72-h forecast. Since the goal is an improved initial warning position, only the 12-h and 24-h forecast positions are calculated. However, the 36-h through 72-h track is available if the complete forecast is desired. Linear interpolation is used to derive CLIPER forecast positions at +6 h and +18 h from fix time.

TABLE 1

Empirically-derived weighting factors applied when determining a smooth working best track

	Time (Hours)				
	-24	-18	-12	-06	00
Weight:	20	15	15	10	10

A fourth-order polynomial fit of the future CLIPER warning positions (W+6 to W+24) and prior (00 to W-24) WBT positions is used to determine a smooth estimate of the storm movement. The polynomial routine allows for user-specified weights at each fitted position. Different order polynomial fitting will be included as an option to be selected by the TDO in the interactive version of the scheme. Larger weighting factors (Table 2) are given to the prior positions to assure a smooth evolution from these relatively well-known positions. Separate polynomial fitting of the latitude and longitude positions with time was adopted as an alternative to fitting the time sequence of latitude/longitude pairs. These time-dependent, fourth-order polynomial coefficients are used to determine the tentative warning position (the +6-h position in Fig. 2.1). Notice that the fix position (A) is not included in the polynomial routine. If the fix is close to the previous warning time or an erroneous fix is encountered, a large

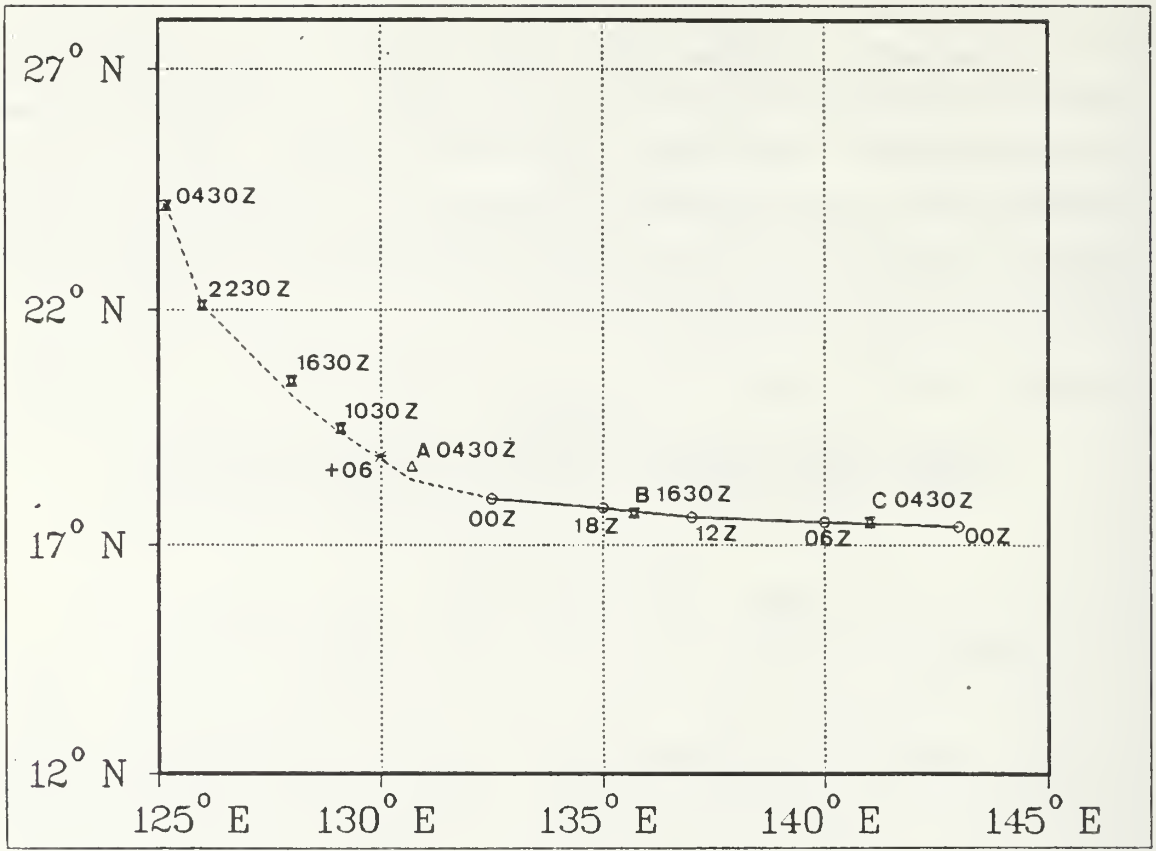

Fig. 2.1 Interpolation procedure for determining a 24-h forecast track and 6-h tentative warning position. 'o', working best track; 'Δ', fix position; '⌛', CLIPER forecast and interpolated positions.

movement discontinuity might be inferred and could not be fitted by a fourth-order polynomial.

TABLE 2

Weighting factors applied when determining a tentative warning position from each fix. 'I' is the time increment between the last warning and the fix.

	Time (Hours)								
	-24	-18	-12	-06	00	6+I	12+I	18+I	24+I
Weight:	20	50	40	10	10	5	1	1	1

When more than one fix is available, a weighted average of the interpolated positions (position D in Fig. 2.2) gives the first iteration of the warning position. The procedure for determining the weights given to different types of fixes will be described in Section 2C. Up to 10 fixes may be included for each warning position determination.

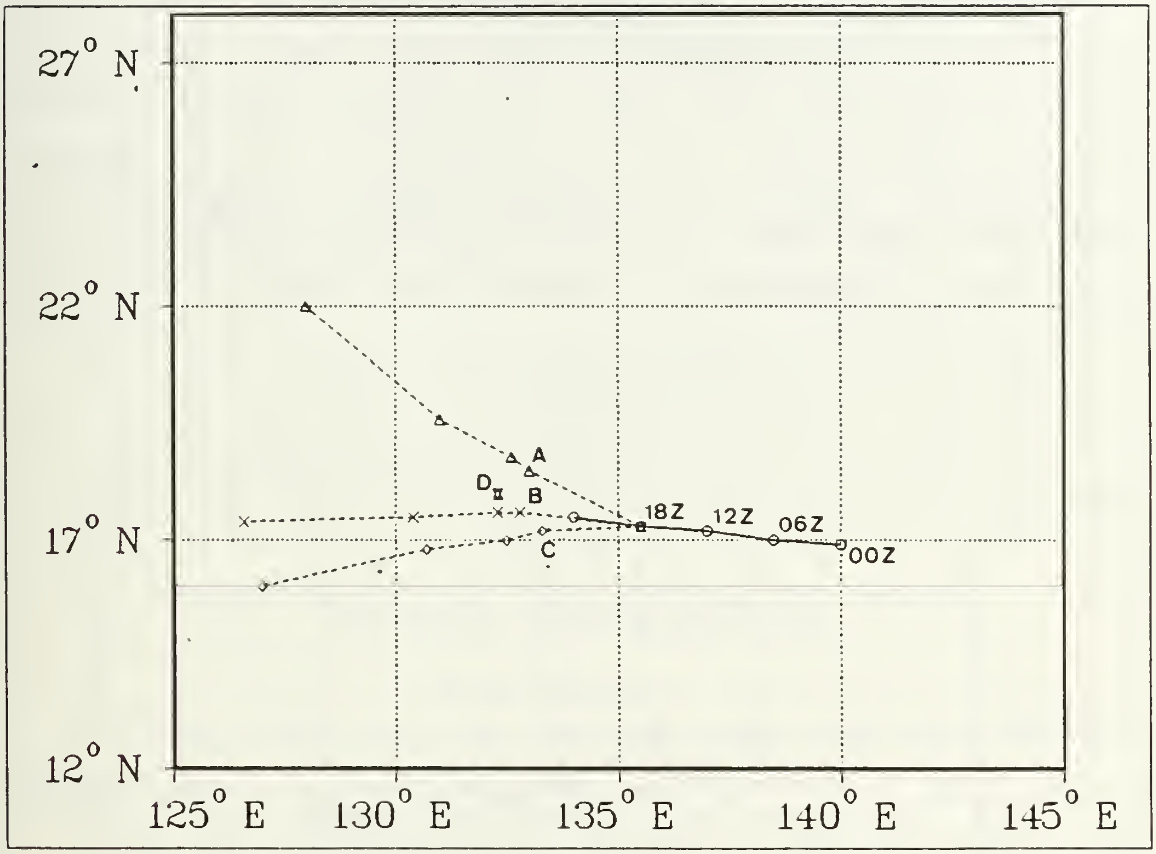

Fig. 2.2 Determination of warning position (D) with with three fixes available. A,B,C are fix positions; 'o', working best track.

Consideration is also given to the potential impact of positioning errors of the fix platforms. In a second iteration, four adjacent positions are generated from the first iteration warning position (point D in Fig. 2.2) by adding an "observational error" in each cardinal direction (Figs.

2.3 and 2.3b). Each error position is treated as a "fix" position with CLIPER forecasts generated and a polynomial curve fit as described above. The weights applied at the specified times in the polynomial curve for the second iteration warning position were changed due to the increase in the number of fitted points (Table 3). The four new tentative positions are weighted equally since each would have an equal probability. The final warning position is determined as the arithmetic average of these four new positions (Fig. 2.3b). Sensitivity tests show that smaller objective warning position errors from the best track result if the observational error iteration is incorporated. Essentially the same improvement occurs if the observational error is 10,15 or 20 n mi. Therefore, an observational error of 15 n mi is taken as the default value.

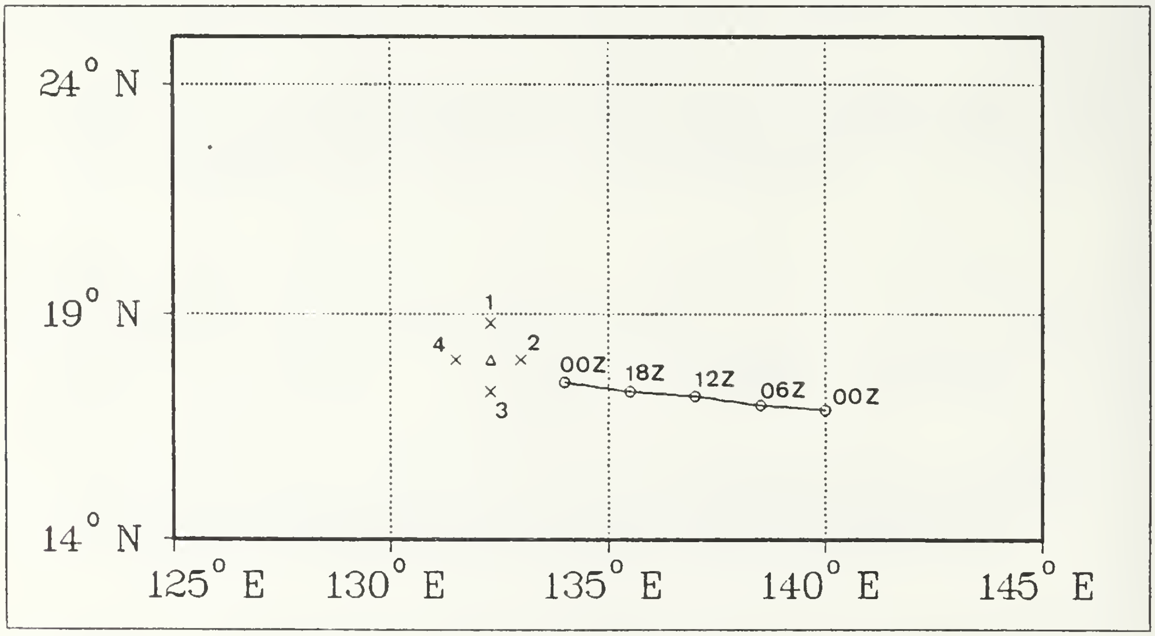

Fig. 2.3a Observational error positions (labeled 1-4) added in cardinal directions and the previous storm positions B and C at -12 and -24 hours.

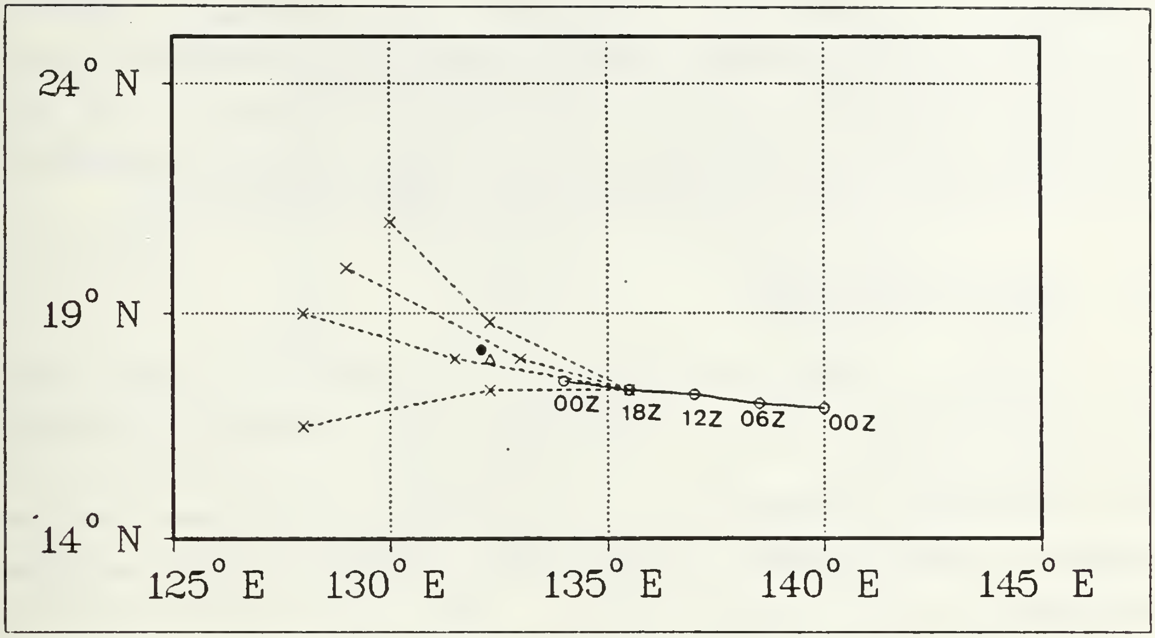

Fig. 2.3b Second iteration of the objective warning position '●'.

TABLE 3

Weighting factors when fitting the second iteration warning position

	Time (Hours)									
	-24	-18	-12	-06	00	+06	+12	+18	+24	+30
Weight:	25	75	45	45	20	15	5	1	1	1

B. INITIAL WARNING PROCEDURE

A special procedure is necessary to start the objective technique with a new storm since the prior "working best track" positions required as input to CLIPER are not available. To generate CLIPER forecasts for the first four warnings, a 24-h history must be developed. All that is required in the objective procedure is a fix about 6 h prior to the first warning time, e.g. a synoptic fix determined by the TDO. A rhumbline course and speed between the most recent fix and the -6 h estimated position is used to extrapolate backward 24 h for the required history. As the warning sequence continues, WBT positions can be included as the -6, -12, -18, or -24 h positions become available.

C. WEIGHTING FACTORS

In the process of blending the various fix positions, the TDO subjectively weights each fix based on the fix platform accuracy (i.e. aircraft fixes are generally more accurate than satellite, e.g. Jarrell,1978) and the fix time. More recent fixes are normally given greater emphasis.

Weighting factors for the aircraft, satellite, radar or synoptic fixes are required for the objective technique to represent the expected accuracy of each fix (Table 4). The satellite analyst assigns an accuracy estimate (Position Confidence Number, PCN) based on the tropical cyclone cloud signature. A PCN value of 1 would be the most accurate estimate while PCN 6 would have the least accuracy. Aircraft fixes are grouped according to a combination of navigation accuracy and meteorological accuracy. The latter is a largely subjective estimate by the Air Reconnaissance Weather Officer (ARWO) of the accuracy of the wind/pressure center location. No indication of the accuracy of the radar fixes is provided, so that all radar fixes are grouped in a single category. Due to the very small number of synoptic fixes, they are grouped with the radar fixes for the purpose of determining accuracy.

JTWC annually evaluates the mean accuracy of satellite, aircraft reconnaissance and radar fixes by comparing them with the BT position at the corresponding time (JTWC Annual Typhoon Reports, 1981-1983). A similar approach has been

TABLE 4

Grouping of the fix platforms for determining accuracy from 1981 - 1983 fixes

Satellite: PCN 5 and 6 (loose organization)
PCN 3 and 4 (well defined organization)
PCN 1 and 2 (eye present)

Aircraft:

Group	Navigation accuracy	Meteorological accuracy
<7<9	< 7 n mi	< 9 n mi
<7>9	< 7	> 9
>7<9	> 7	< 9
>7>9	> 7	> 9

Radar and Synoptic

used with all storms during 1981- 1983 to extract the medians and standard deviations as potential weighting factors for each fix type. To determine the fix accuracy, the time difference between the last known position and the latest fix (hours and minutes) is converted to a percentage of the 6-h increment. This percentage is then used to linearly interpolate the point along the BT that corresponds to the fix time. The distance between the fix and this corresponding BT position then determines the fix accuracy.

Table 5 is a list of the means, medians and standard deviations for the 1981-1983 storm seasons. Ill-defined storms, multiple centers, upper-lower layer cloud signature decoupling, etc., in a small percentage of fixes contribute to large displacements from the official BT. These outliers serve to shift the distribution and bias both the means and the standard deviations. Thus, the median in each group is chosen as a more satisfactory measure of accuracy. As shown in Table 5, the distinction between the 3-yr average median of the most accurate fix platform (Aircraft <7 <9) and least accurate (Satellite, PCN 5 & 6) is only a factor of three. To provide more discrimination between fix types, a third power of the median is utilized.

Consider an example of how the fix platform weighting factors might be applied. Prior to warning time, two satellite fixes (PCN 1 & 6) and one aircraft fix (<7 <9) are received. The determination of the weighted mean position (Fig. 2.2) is then given by the sum over i fixes of:

$$X = \Sigma (Xi * Mi) / \Sigma Mi ,$$

and

$$Y = \Sigma (Yi * Mi) / \Sigma Mi ,$$

where Xi and Yi are the latitude and longitude associated with each fix. Mi is the reciprocal of the median accuracy for the fix type i raised to the third power. In the example: PCN = 1, $Mi = 1/8.5$ and $Mi^3 = 1/614.1$; PCN = 6, $Mi = 1/18.8$ and $Mi^3 = 1/6644.7$; Nav/Met accuracy = <7 <9, $Mi = 1/6.8$ and $Mi^3 = 1/314.4$. Thus, the weighted tentative warning position will be heavily slanted toward the aircraft and PCN = 1 satellite fixes.

The second weighting factor takes into account the fix receipt time. The TDO normally places greater confidence on fixes obtained close to the desired warning time, especially if it agrees with previous expectations. Warning No. 29 for Typhoon Marge during 1983 (Fig. 2.4) illustrates the need for this time bias. Two satellite fixes of equal position confidence (PCN = 2) were received at 12 GMT and 16 GMT in support of the 18 GMT warning. Based on the official forecast, the JTWC must have placed most of their emphasis on the later fix. The objective routine without a time weighting factor would equally weigh the two satellite fixes, which would result in a much slower movement. Therefore, a linear weighting function is assumed using the time difference between the most recent warning position and the fix time (Fig. 2.5). Fix positions obtained five to six hours after the last warning time will be given ten times more weight than fix information received within the first hour after that warning. A second-order weighting function

TABLE 5
Accuracy of fixes (n.mi.) during storm seasons 1981-1983. A slash (/) indicates insufficient sample size and (*) indicates storms with anomalous errors biasing the statistics.

	1981			1982			1983		
	MEAN	MEDIAN	STD DEV	MEAN	MEDIAN	STD DEV	MEAN	MEDIAN	STD DEV
				SATELLITE					
PCN									
5&6	25.8	19.9	24.1	21.1	17.9	16.4	*42.7	18.5	*131.5
3&4	13.4	12.0	9.3	12.2	10.3	8.9	*82.4	12.3	*235.6
1&2	10.0	8.5	7.9	9.6	8.5	6.0	9.8	8.4	7.2
ACCY				AIRCRAFT					
<7<9	8.9	7.5	6.3	7.9	6.3	6.8	*27.8	6.5	*147.5
<7>9	10.6	8.0	9.8	18.6	10.8	19.0	9.3	/	10.6
>7<9	15.5	10.0	27.5	8.2	6.2	8.4	16.8	7.3	68.6
>7>9	15.6	9.2	21.2	12.0	6.9	10.8	*63.2	13.5	*226.7
				RADAR					
	14.1	11.4	15.0	13.1	9.2	13.5	*20.7	7.9	*93.7
				SYNOPTIC					
	12.4	/	8.9	12.6	/	12.1	/	/	/

3-YEAR MEDIAN

SATELLITE PCN		AIRCRAFT ACCY		RADAR	SYNOPTIC
5 & 6	18.8	<7<9	6.8	9.5	N/A GROUPED WITH RADAR
3 & 4	11.5	<7>9	9.4		
1 & 2	8.5	>7<9	7.8		
		>7>9	9.9		

was tested, but the improvement was not significant. Two weighting factors (fix platform and time of receipt) are then included in the determination of the weighted mean position for i fixes as follows:

$$X = \Sigma (Xi * Mi) * Ti \;/ \;\Sigma Ti * Mi,$$

and

$$Y = \Sigma (Yi * Mi) * Ti \;/ \;\Sigma Ti * Mi,$$

where Mi is again the reciprocal of the median displacement raised to the third power and Ti is the time bias.

D. SENSITIVITY TESTS

The goal of the present technique is to synthesize objectively the TDO's procedure in deriving a consistent and accurate warning position. The skill of the objective technique is determined by comparing the objective warning position and JTWC warning position to the corresponding BT position. The ultimate goal is to provide a warning position that will result in reduced short-term forecast errors from the objective aids (in our case, CLIPER).

Typhoon Pat (1982) was selected as the initial test case because it had large warning and forecast errors (Fig. 2.6). The storm tracked to the west-southwest while still in the tropics, decelerated during the recurvature stage and then accelerated following recurvature. It can be seen that Typhoon Pat's movement departs significantly from a smooth, uniform track. Seven additional storms (Thad and Bill-1981; Dot and Gordon - 1982; Marge, Herbert and Abby - 1983) were added to the test data base for a total of 226 warning positions.

1. Extrapolation versus Interpolation

An extrapolation approach to applying the CLIPER technique to each fix was also tested. A tentative 6-h

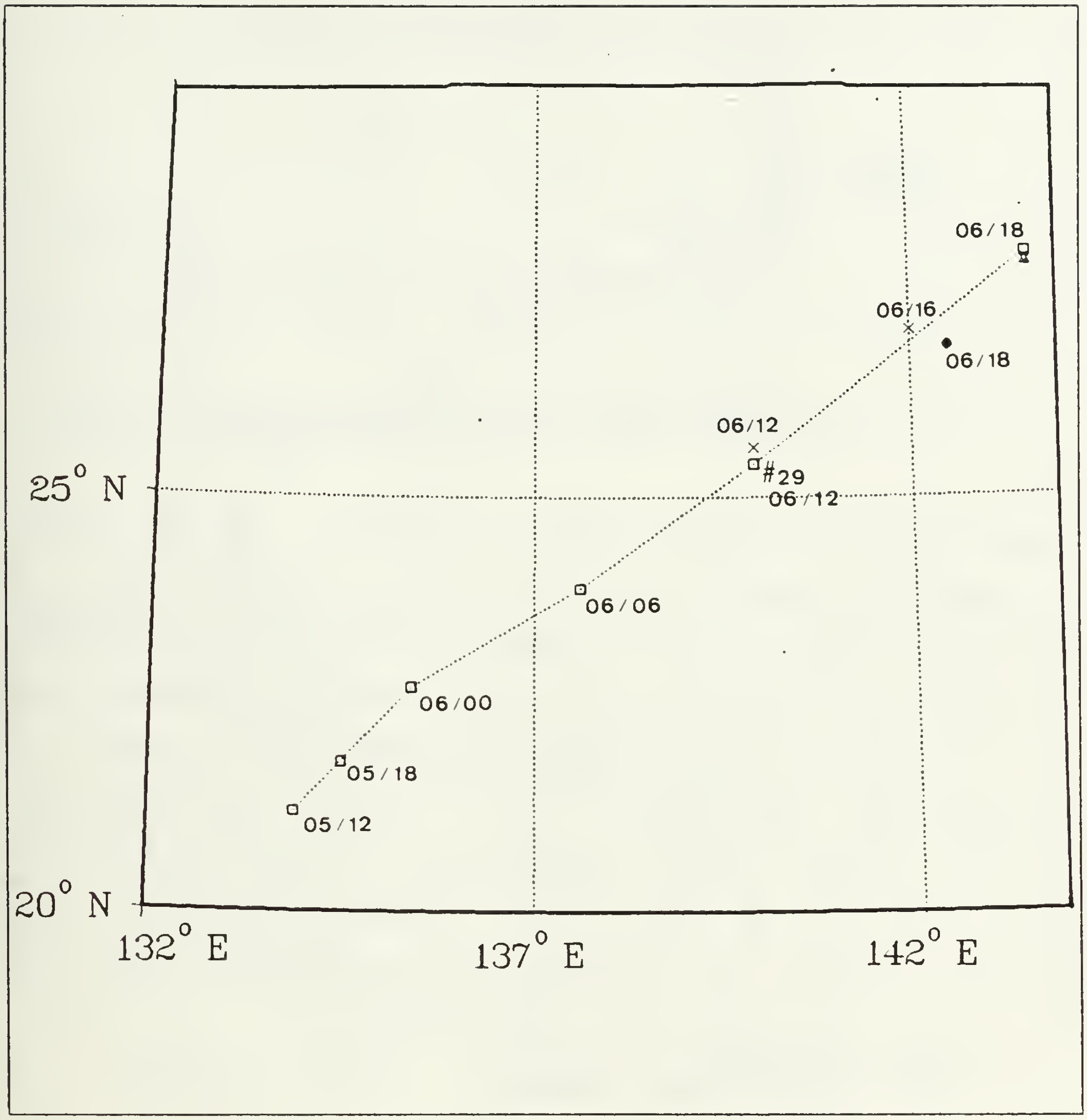

Fig. 2.4 Warning No. 29 Typhoon Marge (1982) illustrating an error in objective warning position due to exclusion of a time bias. '□', best track; '×', fix position; '●', objective warning position; '⧗', JTWC warning position

warning position is determined based on a rhumbline course and speed (dashed line in Fig. 2.7) between the fix and the BT position 12-h prior to the desired warning position. Using the prior 12-h rather than the 6-h position minimizes radical extrapolation angles that might occur if the fix

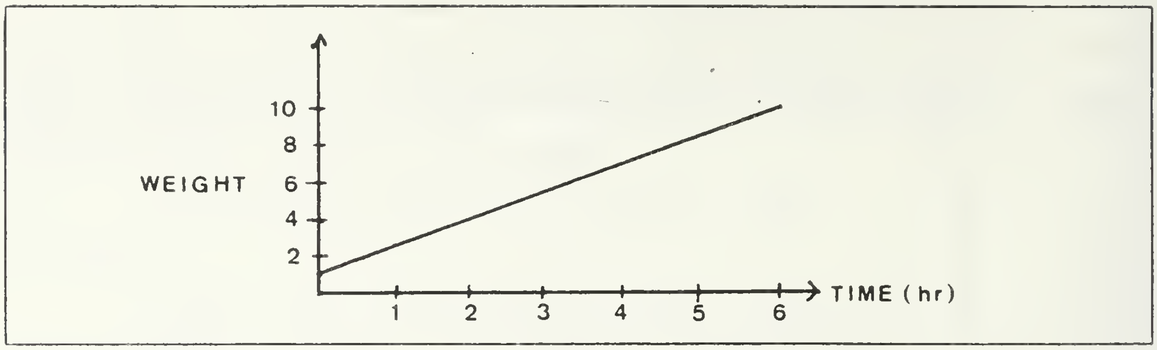

Fig. 2.5 Weighting factors for fixes as a function of the time since the previous warning.

receipt time is early in the 6-h interval. As the required CLIPER inputs are the current, -12 and -24 h positions, the corresponding values in Fig. 2.7 would be the extrapolated warning positions (A or B) and the 18 GMT and the 06 GMT positions from the best track. No time interpolation along the best track is necessary in this approach, in contrast to the interpolation method shown in Fig. 2.1. Although this extrapolation approach is easy to apply, it exaggerates erroneous fixes by the extrapolation. The interpolation method described in Section 2.2 is more conservative as the desired -12 and -24 h positions are interpolated from relatively well known positions along the WBT.

2. <u>Polynomial Curve Fitting</u>

Both third- and fourth-order polynomial curve fitting routines were evaluated in determining the first and second iteration objective warning positons (see Figs. 2.2 and 2.3). Experimentation with the eight-storm data base indicated that choosing the fourth-order polynomial resulted in the smallest initial warning errors. Third-order polynomial curves did not approximate the working BT and forecast track as well and resulted in larger average warning position errors in most cases (Table 6). Higher order

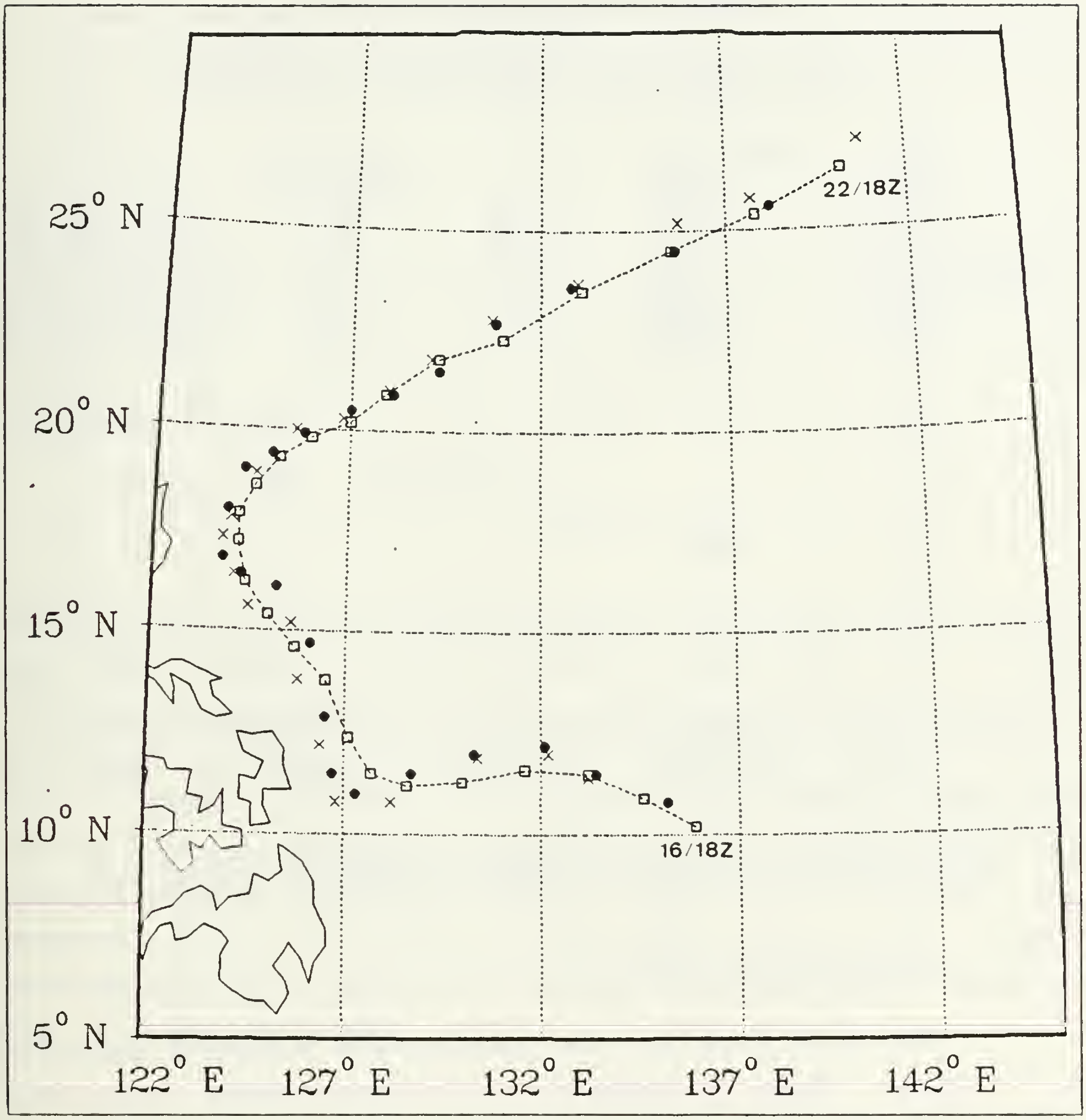

Fig. 2.6 Overall track of Typhoon Pat (1982) from 16 May through 22 May. '□', best track position; '×', JTWC warning position; '●', objective warning position

polynomials would require additional positions to develop the smooth curve and tend to add complication without significant improvement.

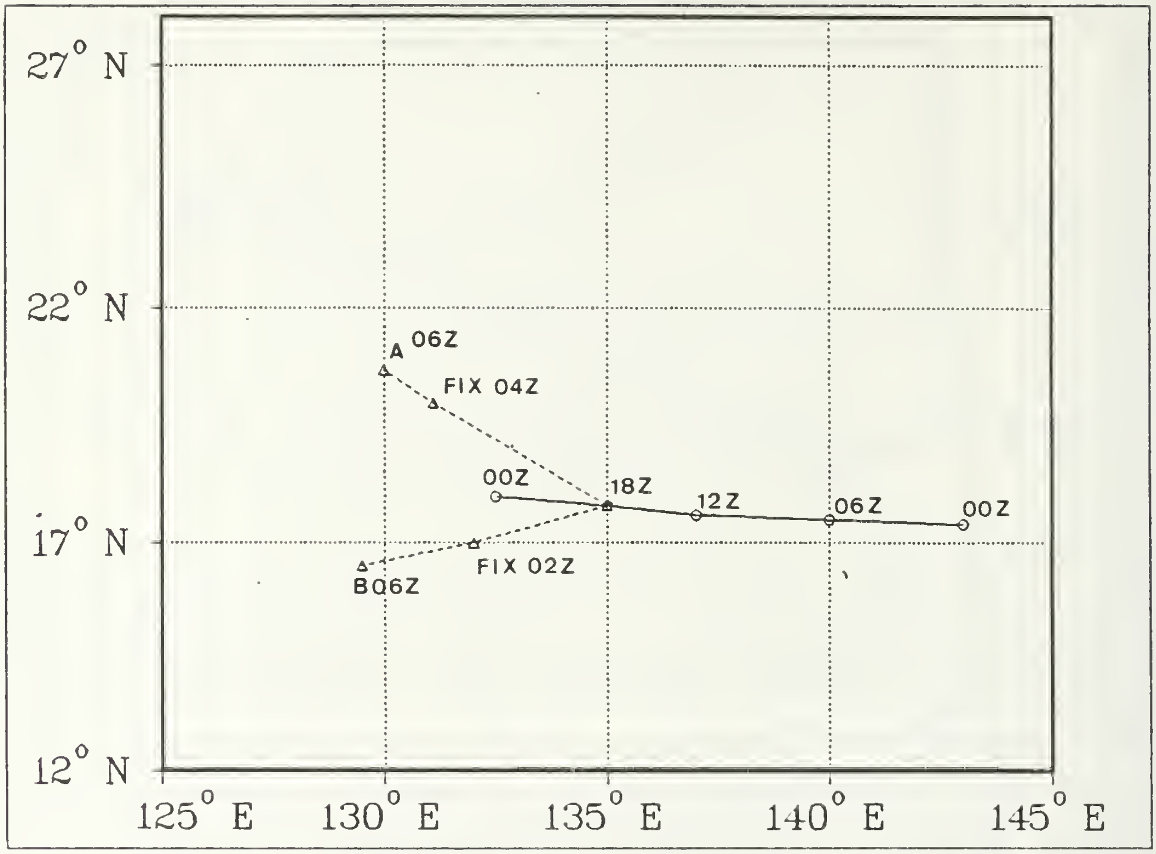

Fig. 2.7 Extrapolated warning positions at 0600Z based on fixes at 0400Z (A) and at 0130Z (B).

3. Weighting Functions

The next step in the sensitivity analysis concerned a "Goodness of Fit" approach. If the smooth polynomial curve correctly fits the past and forecast positions, it is presumed that a better approximation to the official BT will follow. Greater emphasis is given to the prior (-6 to -24 h) positions since they are considered "known" at warning time. The evaluation was to determine whether larger weights should be given to the later forecast positions (+18 and +24 hour), to the earliest forecast positions (warning position and +6 hour), or to treat equally all forecast positions. Larger weights at the tentative warning position

TABLE 6

Average warning position error (n mi)
with 3rd or 4th order polynomial curves

Storm	No. of Warnings	JTWC	Polynomial Order 3rd	Polynomial Order 4th
TY Pat (82)	24	24.9	19.3	18.4
STY Abby (83)	50	11.1	16.0	15.0
TY Thad (81)	28	25.6	26.3	26.1
TY Marge (83)	30	18.4	24.1	23.1
TY Gordon (82)	37	15.5	16.3	15.4
TS Herbert (83)	10	14.3	12.6	12.7
TY Bill (81)	16	18.7	18.9	17.3
TY Dot (82)	31	17.1	20.3	18.7
Total	226			
Weighted Average		17.6	19.4	18.4

and the +6-h forecast generate better results in six out of the eight storms in the test data base (Table 7). This increase in accuracy of initial warning position is consistent with the expected importance of persistence.

Table 8 is a list of the average warning position errors after inclusion of the time bias (Section 2C). The early forecast position weighting emphasis in Table 7 was adopted for these tests. All eight storms had reduced warning position errors when the time weighting factor in Fig. 2.5 was included.

TABLE 7

Average warning position error (n.mi.) of the eight-storm data base emphasizing early (00/+06) or late (+18/+24) warning positions

Storm	No. of Warnings	JTWC	Weighting +18/+24	Emphasis 00/+06
TY Pat (82)	24	24.9	18.6	17.5
STY Abby (83)	50	11.1	15.1	13.6
TY Thad (81)	28	25.6	26.5	27.8
TY Marge (83)	30	18.4	23.4	22.4
TY Gordon (82)	37	15.5	15.6	14.8
TS Herbert (83)	10	14.3	12.8	14.8
TY Bill (81)	16	18.7	17.4	15.9
TY Dot (82)	31	17.1	19.0	18.5
Total	226			
Weighted Average		17.6	18.7	18.0

TABLE 8

Average warning position errors (n mi) after inclusion of the time weighting factors

Storm	No. of Warnings	JTWC	Inclusion of Time Bias
TY Pat (82)	24	24.9	18.0
STY Abby (83)	50	11.1	12.7
TY Thad (81)	28	25.6	27.4
TY Marge (83)	30	18.4	19.6
TY Gordon (82)	37	15.5	14.0
TS Herbert (83)	10	14.3	12.9
TY Bill (81)	16	18.7	14.9
TY Dot (82)	31	17.1	16.8
Total	226		
Weighted Average		17.6	16.7

III. RESULTS AND DISCUSSION

In this section, the objective technique will be compared to JTWC's procedure with respect to the average warning position error and the resulting 24-h forecast position. Several storms will be highlighted to illustrate the strengths and weaknesses of the objective scheme. A stratification of the storms by intensity will also be illustrated.

Subsequent to the testing phase (described in Section 2D), 22 additional storms were run for a total of 637 independent warning positions. Inclusion or exclusion of a particular storm from the three-year data base is based on the following constraints:

(1) A fix position 6 h prior to the first warning (to initiate the objective technique) must exist;

(2) Since the current objective technique is limited to 10 fixes per warning, storms with a large number of radar fixes per warning were not included;

(3) Storms with a majority of their path outside the latitude/longitude domain of the CLIPER regression equations were not used; and

(4) Several storms that were either short-lived or included periods of time during which JTWC warnings were unavailable were not included.

A. INITIAL POSITION ERRORS

The accuracy and consistency of the objective technique as compared to JTWC can be measured by the means and standard deviations of the initial position errors. Table 9 lists these statistics for the 8-storm test base and indicates if the objective position error for each storm is smaller (W), the same as (T) or larger (L) than JTWC. Tables 11 - 13 indicate the same statistics for the 22-storm independent sample. As shown in these summaries, the objective technique produced a more accurate warning position in 1981 and 1982. The objective technique resulted in smaller errors for 6 of 7 storms during 1981 and 3 of 7 storms during 1982. The percentage of storms in the win and tie categories represents 100% of the 1981 storms and 71% of the 1982 storms. Within the independent data set, Typhoon Nelson (1982) represents the best performance of the objective technique while Typhoon Bess (1982) had the worst record compared to JTWC.

Presumably, the change in the JTWC warning procedure during 1983 resulted in smaller overall errors compared to the objective scheme for the 1983 storms. This change may also account for the improvement in JTWC's performance in 1983 compared to 1982 and 1981. A reduction in the number of storms in which the objective scheme produced smaller errors (3 of 8 storms) results in a win and tie percentage of only 50% for 1983. Continued testing of the objective technique with 1984 storms is required to determine whether 1983 was an anomalous year.

The yearly summaries also indicate that the objective technique will produce a more consistent warning position, since the standard deviations were smaller overall for all three years as compared to JTWC. Tables 11 - 13 indicate that 5 of 7 storms in 1981, 4 of 7 storms in 1982 and 4 of 8

TABLE 9

Summary of warning position errors (n.mi.) for JTWC (JT) and objective (OBJ) for the 8-storm test data base. A win (W), tie (T) or loss (L) for the objective technique is indicated and the Student-t score is given.

Storm	No. of Warnings	Avg.		Std. Dev.		WTL	t
		JT	OBJ	JT	OBJ		
TY Dot (82)	31	20	20	13	14	T	-.11
TS Herbert (83)	10	18	16	10	5	W	-.44
STY Abby (83)	50	11	13	10	9	L	.81
TY Pat (82)	24	27	18	16	10	W	-2.47*
TY Thad (81)	28	26	27	31	36	L	.20
TY Marge (83)	30	20	22	17	18	L	.27
TY Gordon (82)	37	15	14	10	9	W	-.67
TY Bill (81)	16	19	15	13	12	W	-.84
Total	258						
Weighted Average		18.5	17.9	14.8	14.4		

* Difference between the objective error and JTWC official error is significant at 95% confidence level

storms in 1983 had smaller standard deviations. The Student-t test is made for each storm to test whether the difference between the objective warning position error and that of the JTWC is significant at the 95% confidence level. For the 22-storm independent data base, only Typhoon Nelson (1982) would have had significant reductions in warning position error if the objective technique had been used. However, the warning positions of Tropical Storm Ben (1983), Super Typhoon Forrest (1983) and Tropical Storm Georgia (1983) would have been significantly degraded. Examples from these four storms and others of the 22-storm sample will now be examined to determine when the objective technique should or should not be expected to provide accurate initial position guidance.

Fig. 2.6 indicates the relationship of the official BT, the JTWC warning positions and the objective technique warning positons for Typhoon Pat (1982). The objective technique performs very well during the recurvature (change of a dominant northwest to northeast movement around the subtropical ridge axis) and seems to provide a very consistent acceleration track after recurvature. Ten of the 30 storms analysed were recurving systems. Of these ten, six storms had overall smaller initial warning position errors when employing the objective technique. However, a problem does arise in situations where rapid acceleration follows a slow movement during recurvature. For example, the CLIPER forecast for the 18 GMT 22 August 1981 warning position of Typhoon Thad (Fig. 3.1) is based on the slow recurvature around the ridge axis from 12 GMT 21 August through 06 GMT 22 August. During the post-season analysis, the TDO seems to have discounted the fix information (positions A,B and C in Fig. 3.1) to arrive at the accelerated 18 GMT 22 August warning position. It does appear that the objective warning technique based on CLIPER may be too conservative during these rapid acceleration cases.

Typhoon Ben (1982) illustrates a scenario in which the CLIPER-based objective technique will not perform well. As can be seen in Fig. 3.2, the latitudes of the objective warning positions are quite accurate. However, the CLIPER model does not anticipate the non-climatological westward movement in the northern latitudes.

Typhoon Nelson (1982) is characteristic of systems in which the objective technique should produce accurate warning positions. The first two-thirds of Typhoon Nelson's track (Fig. 3.3) is consistent with a persistence-type track. Objective aids which stress persistence for the short-term forecast, such as CLIPER, are expected to verify well in these situations. Throughout this portion of Typhoon Nelson's track, the average JTWC warning position error was 21.4 n mi with a standard deviation of 14.1 n mi, while the objective scheme resulted in an average error of 15.7 n mi with a standard deviation of 9.7 n mi The later portion of Nelson's track (Fig. 3.4) included a

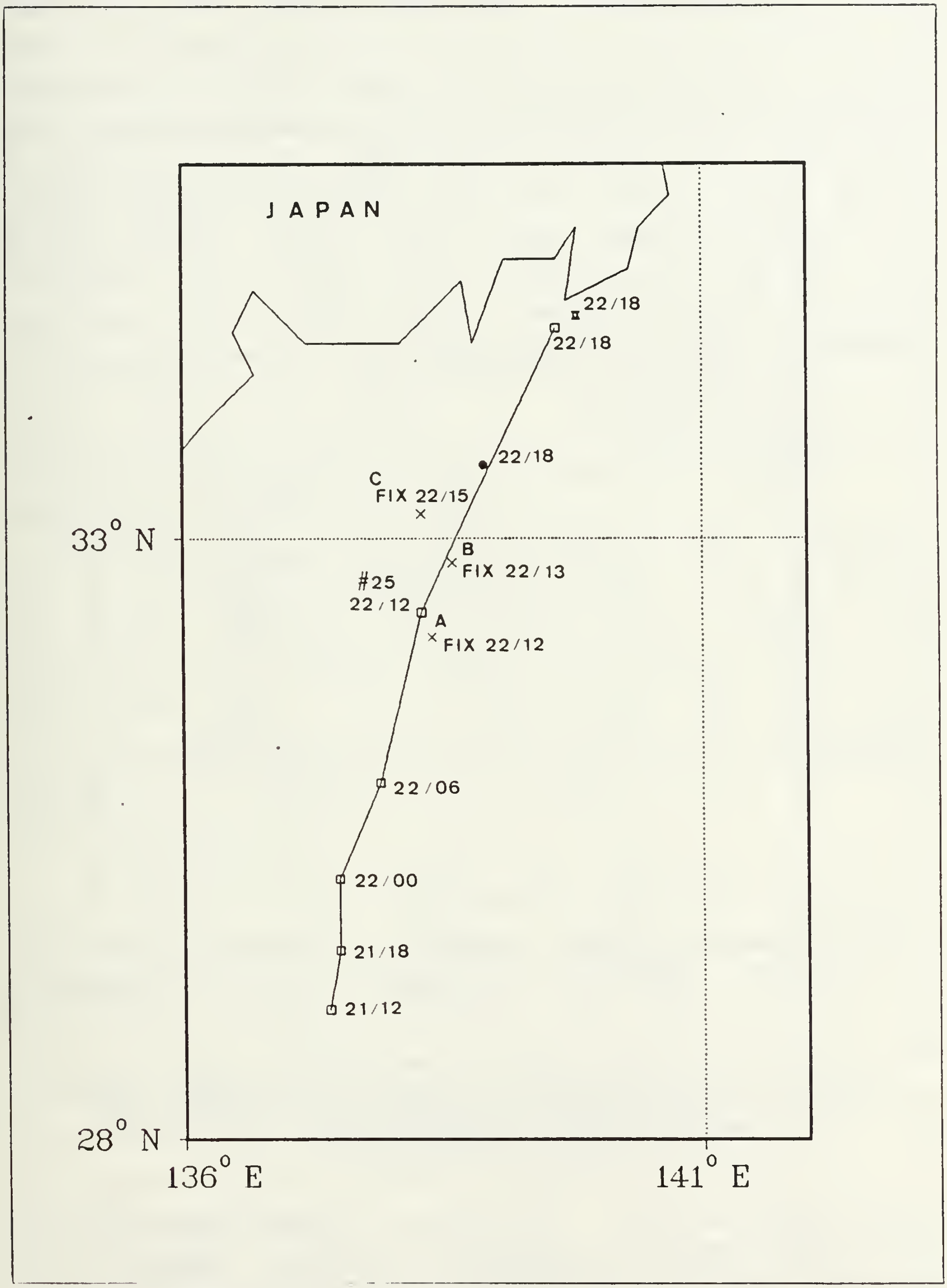

Fig. 3.1 Warning No. 25 of Typhoon Thad (1981). Example of forecast problem when rapid acceleration follows a slow recurvature path.'□', best track position;'×', fix position; '●',objective warning position;'⧗',JTWC warning position.

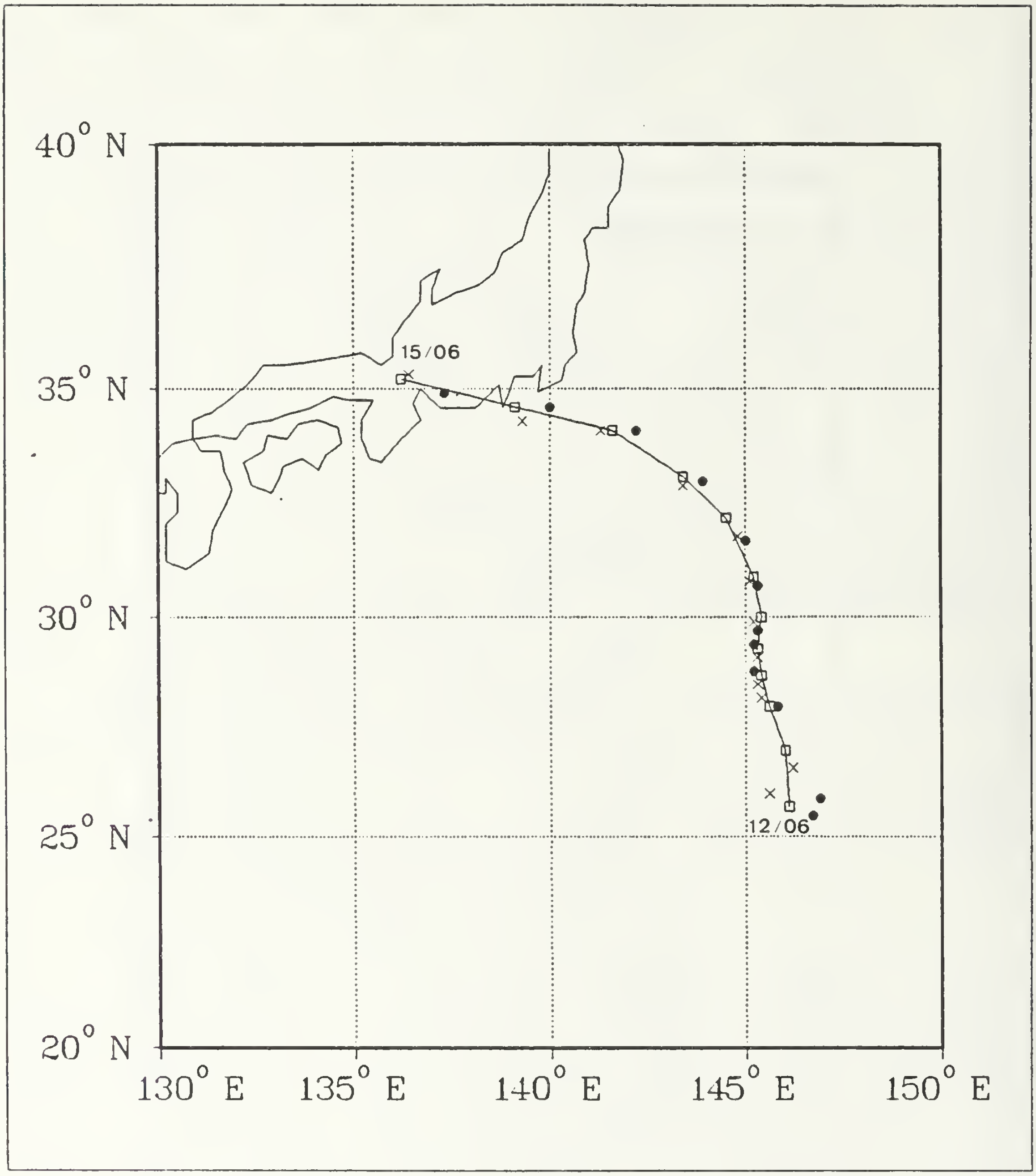

Fig. 3.2 Overall track of Tropical Storm Ben (1983) from 12 August through 15 August. '□', best track position; '×', JTWC warning position; '●', objective warning position.

counterclockwise loop. An objective scheme based highly on persistence would not be expected to handle looping tracks very well. Due to the slow forward speed between warnings, the objective technique still had a smaller average warning position error (20.2 n mi, standard deviation 11.5 n mi) compared to JTWC (average position error 26.1 n mi, standard deviation 20.2 n mi). Unfortunately, this skill in looping situations does not hold for all of the cases. Six other storms (Pamela during 1982 and Percy, Lex, Abby, Bess and Sperry during 1983) had a loop sometime during their lifespan. Only three of the looping storms (Nelson, Sperry and Bess) had smaller warning position errors during the looping phase when using the objective scheme. In each of these three storms, there was relatively slow movement through the loop. In the remaining cases, the objective technique based on CLIPER did not handle the rapid direction changes associated with a tight loop.

The use of the objective technique should not be ruled out in all non-climatological situations. As an example, the entire lifespan of Tropical Storm Sperry (1983) consisted of a clockwise loop in the region east of the Philippines (Fig. 3.5). Once again the slow speeds throughout the majority of the loop allowed the objective technique to produce smaller warning position errors than JTWC (see Table 13).

The TDO may have to adjust the objective warning position when additional knowledge not reflected in the fix positions is available. Such a situation appeared for the warning position of Typhoon Thad on 00 GMT 23 August 1981. The objective technique relied on two satellite fixes shown in Fig. 3.6 Although the resulting objective warning position was consistent with the prior storm track, the position error was 105 n mi compared to a JTWC error of 30 n mi Evidently, the TDO had more information than the two satellite fixes provided.

In summary, the 30-storm sample provides a fair representation of the various forecasting scenarios including recurvature and looping cases as well as straight tracks. It has been shown that the objective technique will provide a reliable warning position in most situations, including some cases in which slow loops or erratic movement is experienced. In an operational version of the objective technique, the TDO should have the capability of interactively bogusing additional information for situations in which the fixes do not reflect the best estimate of the actual storm location.

B. 24-H FORECAST EVALUATION

A second comparison between the objective and JTWC warning position is to determine which method provides the most accurate 24-h forecasts. The JTWC and the objective warning positions were used with the -12 and -24 h best track positions in the CLIPER scheme to forecast the +24 h position. It was expected that initiating CLIPER with more accurate warning positions would result in more accurate short-term forecasts when compared to the +24 h BT position. The control case is a CLIPER forecast generated entirely with BT positions which should produce better short-term forecasts than either the JTWC or objective warning positions. Because the first 24 h of each storm track is required as past history in CLIPER, the first four warning positions in each sample cannot be evaluated. Furthermore, the warning positions during the last 24 h of each storm are eliminated to allow for the +24 h verification positions. The total number of verifiable warning positions in the sample was reduced to 456 and the short-lived Tropical Storm Sperry was eliminated in this evaluation.

Tables 14 - 16 are listings of the 1981 - 1983 summaries in the same format as the tables for the initial position error evaluation. As expected, the 24-h forecasts based entirely on BT positions were the most accurate. As in the initial position evaluation above, the 24-h forecasts based on the objective warning positions compared favorably with those based on JTWC warning positions during 1981 and 1982. The average 24-h forecast error for the objective scheme was 122 n mi for 1981 and 113 n mi for 1982. This can be compared to 127 n mi for 1981 and 111 n mi for 1982 based on JTWC's warning positions. The percentage of win and tie category storms was 55% in 1981 and 60% in 1982. However, only 20% of the storms during 1983 had better forecasts from the objective warning positions. According to the Student-t scores in Tables 14 - 16, none of the differences between the objective technique forecast errors and those of the JTWC were significant at the 95% confidence level. The standard deviations in Tables 14 - 16 indicate the 24-h forecasts based on the objective warning positions were slightly more erratic for 1982 (65 n mi) and 1983 (66 n mi) compared to forecasts from JTWC warning positions during 1982 (62.9 n mi) and 1983 (60 n mi)

The initial position error categories (Tables 11 - 13) are compared in Table 10 to the 24-h forecast position categories from Tables 14 - 16. Optimally, all storms in the win category of the initial position evaluation would be expected to result in a win category in the 24-h forecast position evaluation. It was not expected that storms with initial position losses would result in 24-h forecast position wins. As indicated in Table 10, most of the storms do fall in the win-win and loss-loss categories. However, two cases (Super Typhoon Marge (1983) and Typhoon Ken (1982)) fall in the loss-win category, i.e. an initial position error loss for the objective technique results in a 24-h forecast position win. Both storms were characterized by recurving tracks. A relatively large number of storms (6) with a win in terms of smaller initial position errors nevertheless had a corresponding loss in terms of a 24-h forecast comparison. Of the six storms, three (Elsie (1981), Bill (1981) and Thelma (1983)) were recurving systems. Two others (Kit (1981) and Nelson (1982)) were basically westward tracks, although Kit contained two radical course changes. Tip (1983) had a short-lived track through the South China Sea. Fig. 3.7 illustrates one possible explanation of the disparity. While the objective scheme produces a more accurate warning position (A in Fig. 3.7) compared to JTWC, the recurvature to the northeast is forecast too late if the objective warning position is used in CLIPER.

The discussion above does not support the expected coupling between the more accurate initial warning position and a more accurate short-term forecast position. This is illustrated in the following storms. The objective technique resulted in significantly smaller initial warning position error (objective technique, 17 n mi; JTWC, 23 n mi) for Typhoon Nelson (see Table 12). However, the average 24-h forecast error from the objective warning positions(124 n mi) was larger than forecast errors based on the JTWC warning positions (111 n mi). Table 17 is a list of the CLIPER 24-h forecast errors for Typhoon Nelson based on the BT position, JTWC warning position and objective warning position. In this case, CLIPER forecasts with objective initial positions provide less accurate forecasts from 12 GMT 24 March 1982 through 12 GMT 27 March 1982 (warnings 25 - 36, Table 17) as Typhoon Nelson passes over the Philippines. The CLIPER forecasts from objective positions are again less accurate than from JTWC positions from 18 GMT 29 March through 06 GMT 31 March 1982 (warnings 45 - 51, Table 17) during the looping phase.

In contrast, Typhoon Marge is a case in which there are larger warning position errors for the objective technique and smaller 24-h forecast errors from those warning positions (Table 18). Objectively initiated CLIPER forecasts performed better from 12 GMT 31 October through 12 GMT 02 November 1983 (warnings 5 - 13, Table 18) while Marge was in the formative stages (< 65 kt) and then again from 18 GMT 03 November through 00 GMT 05 November 1983 (warnings 18 - 23, Table 18) during the initial stages of recurvature. In both periods, Typhoon Marge was about to make a major course change. In this case, the JTWC warning positions fell on the wrong side of the turn as shown previously in Fig. 3.7 and the corresponding CLIPER track departs significantly from the actual storm movement.

The characteristics of Tropical Storm Winona (1982) and Typhoon Dot (1982) are very similar in both time of occurrence (one month apart) and storm track (Typhoon Dot track approximately 5° north of Tropical Storm Winona). In both storms, the average initial position error evaluation resulted in a tie between the objective technique and the JTWC procedure (Winona, 22 n mi; Dot, 20 n mi). In the 24-h forecast evaluation, JTWC's warning positions resulted in smaller forecast error for Tropical Storm Winona (99 n mi compared to 110 n mi for the objective scheme). However, the objective technique's initial positions provided a superior forecast position error for Typhoon Dot (93 n mi compared to 105 n mi for forecasts from the JTWC warning positions).

C. SENSITIVITY TO STORM INTENSITY

The objective warning position errors or the corresponding 24-h forecast errors are examined for sensitivity to storm intensity. The 30-storm data base is stratified into storms of >130 kt (Super Typhoon), >65 kt (Typhoon) and <65 kt (Tropical Storm and Depressions). It should be noted that the storms were of the indicated intensity for only part of their lifetimes, which may affect the results. Table 19 lists the total number of storms in each stratification and the percentage of win, tie or loss for both average initial position error and 24-h forecast position error. The most intense storms had the lowest percentage of win and tie cases for the objective scheme for both evaluations. This is attributed to the most intense storms are also the easiest to locate by the JTWC and are given increased emphasis on their track forecasts. The objective technique may well be performing at the same level but would appear to be degraded in relation to JTWC in these intense storm situations. Table 19 also indicates that good warning positions are produced by the objective technique for storms of Typhoon intensity and lower.

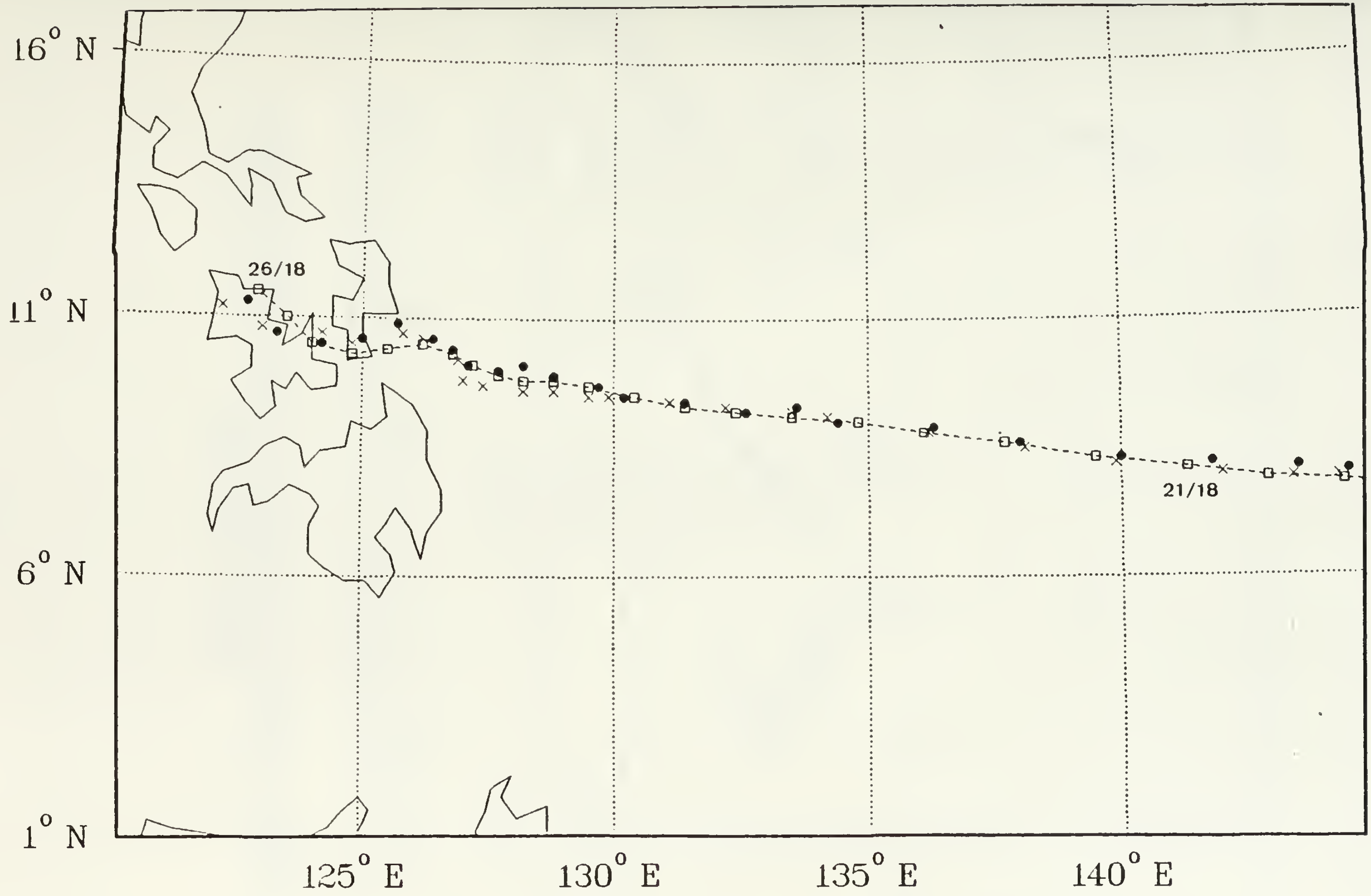

Fig. 3.3 Track of Typhoon Nelson (1982) from 21 March through 26 March. '□', best track position; '×', JTWC warning position; '●', objective warning position.

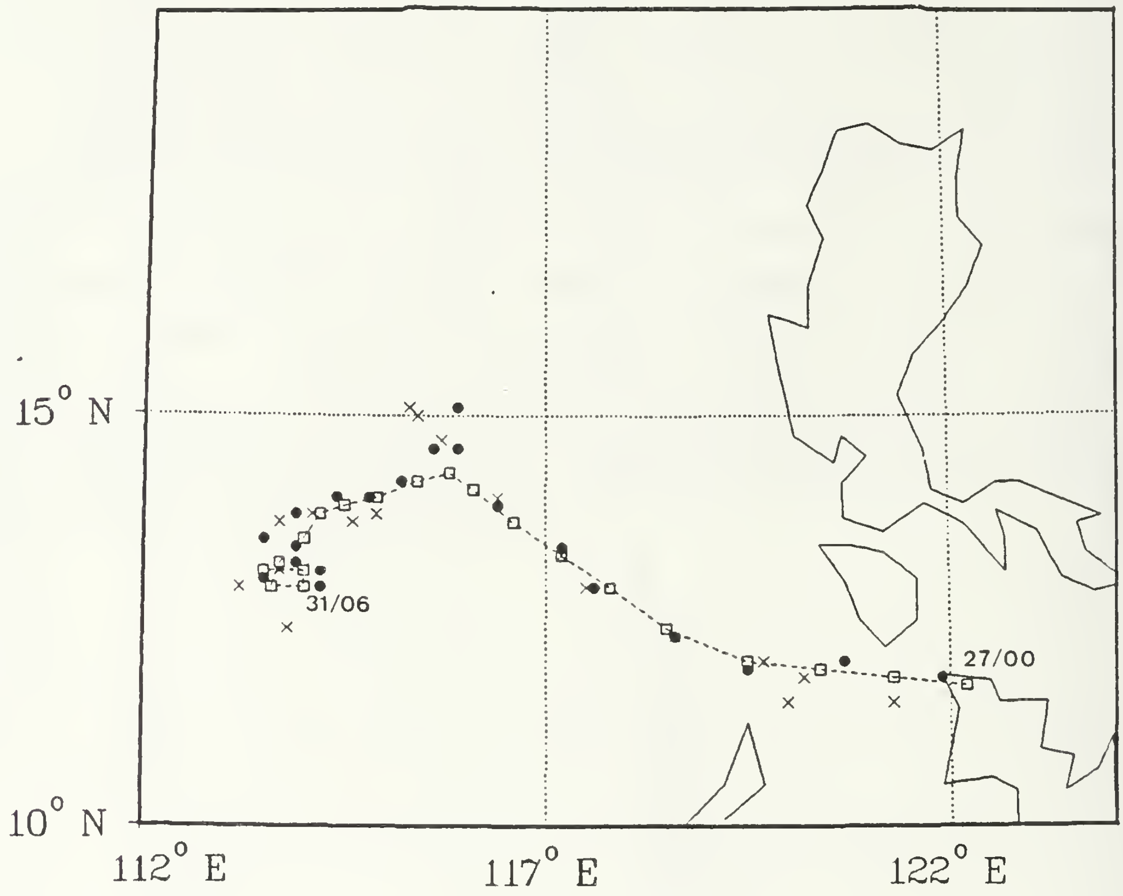

Fig. 3.4 Track of Typhoon Nelson (1982) from 27 March through 31 March. '□', best track position; '×', JTWC warning position; '●', objective warning position

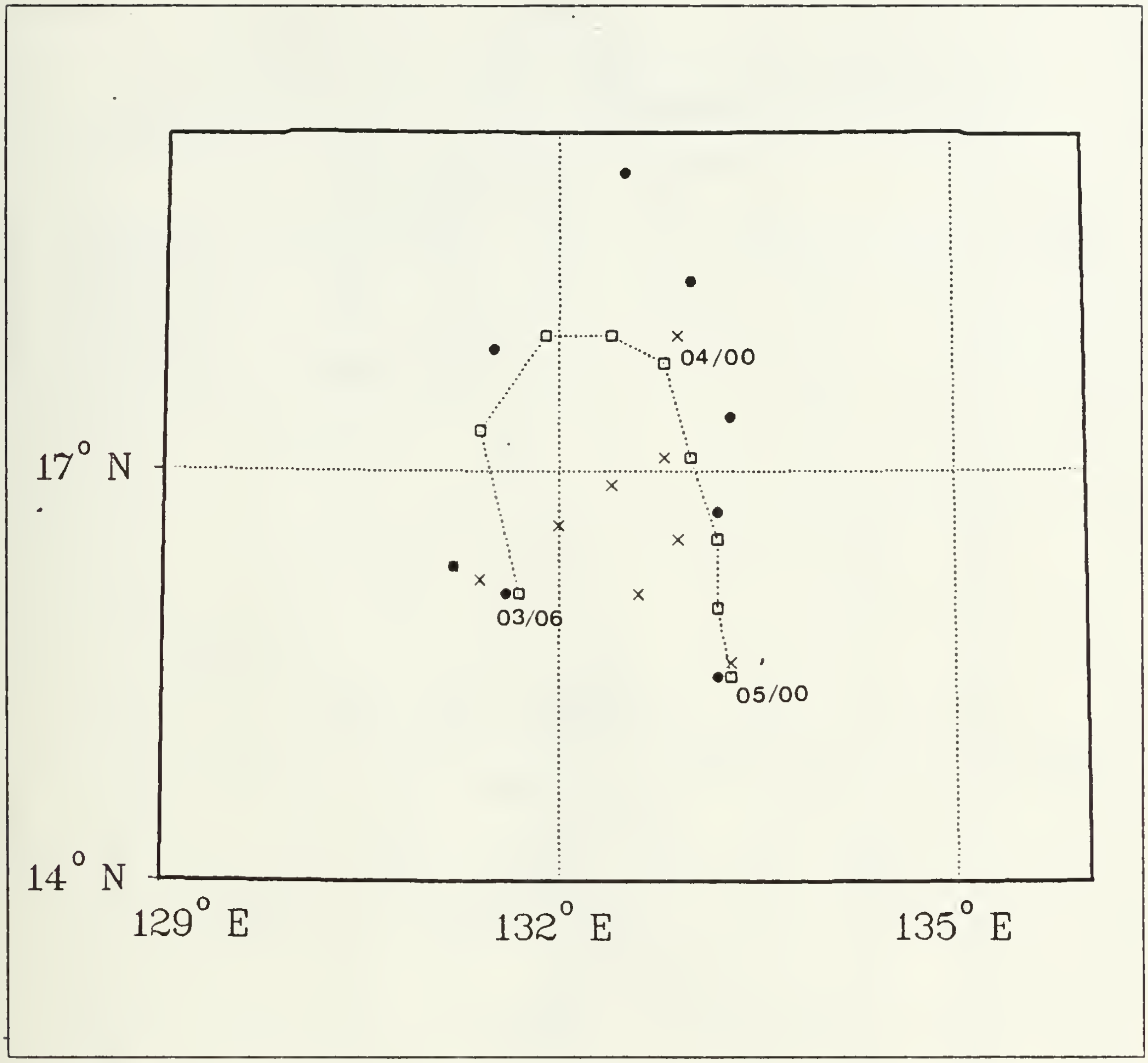

Fig. 3.5 Overall track of Tropical Storm Sperry (1983) from 03 December through 05 December. '□', best track position; '×', JTWC warning position; '●', objective warning position.

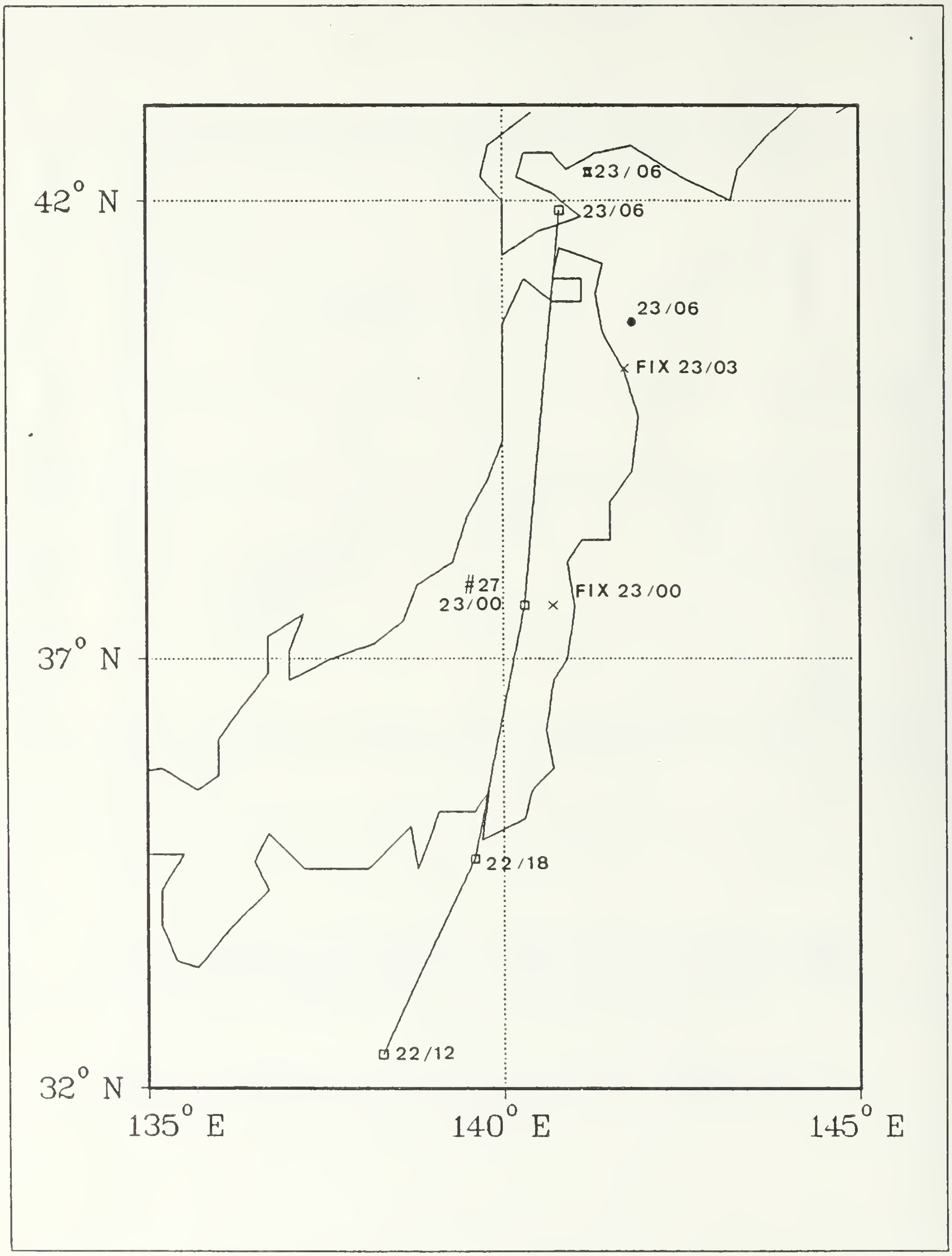

Fig. 3.6 Warning No. 27 of Typhoon Thad (1981). Fixes 'x', '□', best track position; '⌧' JTWC warning position; '●', objective warning position.

TABLE 10

Summary of 24-h forecast error category (win, tie, loss) versus initial position error category.

		24-h Forecast Category		
		WIN	TIE	LOSS
Initial	WIN	7	2	6
Position	TIE	2	0	3
Category	LOSS	2	0	7

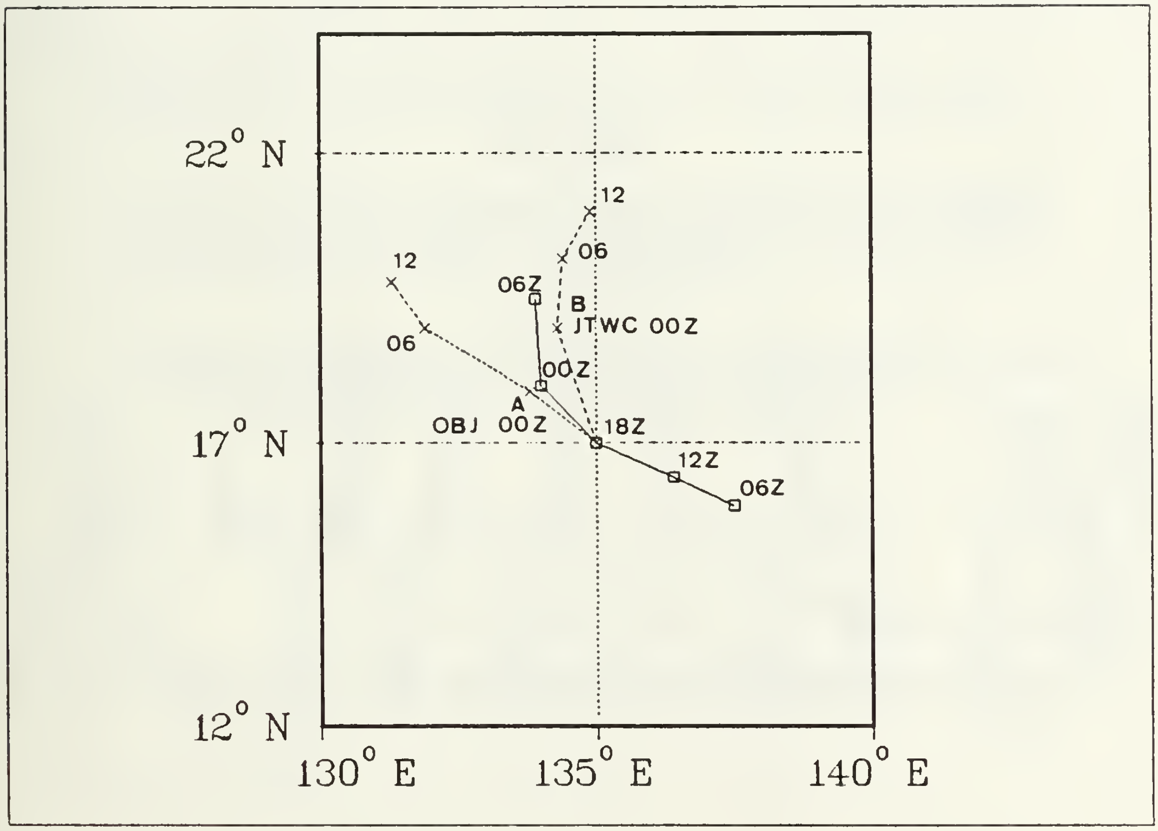

Fig. 3.7 Example of a larger forecast error from a warning position (A) that is more accurate than the official position (B).

TABLE 11

Summary of warning position errors (n.mi.) for JTWC (JT) and objective (OBJ) for the independent sample storms during 1981. Entries are similar to Table 9.

Storm	No. of Warnings	Avg. JT	Avg. OBJ	Std. Dev. JT	Std. Dev. OBJ	WTL	T
TY June	23	21	16	14	9	W	-1.18
TS Roy	19	22	22	15	16	T	.06
TY Clara	34	22	16	19	8	W	-1.67
STY Elsie	33	18	13	11	7	W	-2.00
TY Hazen	40	24	20	13	13	W	-1.28
TS Jeff	20	34	29	20	12	W	-.88
TY Kit	45	17	16	12	11	W	-.38
Total	214						
Weighted Average		22	18	14	11		

TABLE 12

Summary of warning position errors (n.mi.) for JTWC (JT) and objective (OBJ) for the independent sample storms during 1982. Entries are similar to Table 9.

Storm	No. of Warnings	Avg JT	Avg OBJ	Std. Dev. JT	Std. Dev. OBJ	WTL	T
TY Nelson	55	23	17	16	10	W	-2.15*
TS Winona	20	22	22	13	13	T	.08
STY Bess	45	16	21	10	17	L	1.43
TY Judy	30	19	18	22	14	W	-1.31
TY Ken	36	14	15	6	11	L	.23
TY Nancy	31	12	11	11	6	W	-.01
TY Pamela	68	21	21	22	15	T	.00
Total	285						
Weighted Average		19	18	15	13		

* Difference between the objective error and JTWC official error is significant at 95% confidence level

TABLE 13

Summary of warning position errors (n.mi.) for JTWC (JT) and objective (OBJ) for the independent sample storms during 1983. Entries are similar to Table 9.

Storm	No. of Warnings	Avg.		Std. Dev.		WTL	T
		JT	OBJ	JT	OBJ		
TY Tip	17	13	12	12	8	W	-.08
TS Ben	12	17	34	8	23	L	2.35*
STY Forrest	31	10	15	6	10	L	2.25*
TS Georgia	13	10	19	8	11	L	2.31*
TY Lex	17	18	18	13	15	T	-.01
TY Percy	24	22	27	22	13	L	1.01
TS Sperry	9	34	30	29	23	W	-.28
TS Thelma	15	32	25	33	13	W	-.61
Total	138						
Weighted Average		18	21	15	13		

* Difference between the objective error and JTWC official error is significant at 95% confidence level

TABLE 14

Summary of 24-h forecast errors (n.mi.) from CLIPER initiated with best track (BT) position, JTWC (JT) and objective (OBJ) warning positions for the 1981 storms.

Storm	No. of Warnings	Avg.			Std. Dev.			WTL	T
		BT	JT	OBJ	BT	JT	OBJ		
TY June	16	70	110	76	39	46	54	W	-1.92
TS Roy	12	107	151	129	58	78	56	W	-.80
TY Clara	25	57	80	69	34	54	36	W	-.91
STY Elsie	25	99	109	114	71	78	82	L	.21
TY Hazen	33	114	139	139	52	56	57	T	.00
TS Jeff	10	185	247	226	47	70	63	W	-.69
TY Kit	31	90	115	116	51	55	63	L	.07
Total	152								
Weighted Average		97	124	117	51	61	59		

TABLE 15

Summary of 24-h forecast errors (n.mi.) from CLIPER initiated with best track (BT) positions, JTWC (JT) and objective (OBJ) warning positions for the 1982 storms.

Storm	No. of Warnings	Avg.			Std. Dev.			WTL	T
		BT	JT	OBJ	BT	JT	OBJ		
TY Nelson	46	102	111	124	50	65	54	L	1.02
TS Winona	11	80	99	110	52	82	85	L	.31
STY Bess	38	112	129	132	61	65	68	L	.23
TY Judy	23	79	102	96	63	64	69	W	-.30
TY Ken	28	71	87	86	49	50	59	W	-.07
TY Nancy	24	55	66	66	28	35	38	T	-.01
TY Pamela	56	122	134	143	81	80	96	L	.55
Total	226								
Weighted Average		96	110	116	58	64	69		

TABLE 16

Summary of 24-h forecast errors (n.mi.) from CLIPER initiated with best track (BT) positions, JTWC (JT) and objective (OBJ) warning positions for the 1983 storms.

Storm	No. of Warnings	Avg.			Std. Dev.			WTL	T
		BT	JT	OBJ	BT	JT	OBJ		
TY Tip	10	41	58	59	25	38	33	L	.07
TS Ben	5	254	260	273	183	177	200	L	.11
STY Forrest	24	74	79	89	46	54	54	L	.63
TS Georgia	6	63	58	89	20	13	46	L	1.56
TY Lex	10	77	75	98	50	57	79	L	.75
TY Percy	17	192	215	236	50	47	53	L	1.23
TS Thelma	6	135	141	143	104	112	87	L	.04
Total	78								
Weighted Average		111	120	134	56	60	66		

TABLE 17

Summary of 24-h forecast position errors statistics (n mi) for Typhoon Nelson

Wrng. No.	Best TracK	JTWC Wrng.	Obj. Wrng.	Obj-JTWC
6	82	158	130	-28
7	68	83	88	5
8	56	76	101	25
9	88	88	100	12
10	124	86	86	0
11	178	312	178	-133
12	214	199	228	29
13	183	251	262	11
14	142	232	198	-34
15	91	143	152	9
16	49	91	79	-12
17	52	57	71	15
18	65	81	56	-25
19	62	70	87	17
20	57	53	79	27
21	65	61	74	13
22	68	81	64	-17
23	72	48	80	31
24	65	42	77	35
25	58	47	88	41
26	88	40	88	48
27	123	78	111	33
28	147	155	152	-3
29	121	126	153	27
30	77	122	116	-6
31	131	121	147	26
32	122	147	151	4
33	165	84	131	47
34	217	93	175	82
35	50	113	134	21
36	9	22	44	22
37	64	92	71	-22
38	23	42	42	0
39	41	54	45	-9
40	88	88	99	11
41	114	138	126	-12
42	140	233	188	-45
43	164	200	264	64
44	147	239	208	-32
45	119	103	163	60
46	127	117	158	42
47	125	122	156	34
48	90	105	118	13
49	72	65	106	40
50	82	60	133	73
51	191	85	127	42
Avg. Disp.	102	111	124	
Std. Dev.	50	65	54	

TABLE 18

Summary of 24-h forecast position errors statistics (n mi) for Typhoon Marge

Wrng. No.	Best Track	JTWC Wrng.	Obj. Wrng.	Obj-JTWC
5	49	128	93	-35
6	65	41	11	-30
7	151	311	88	-224
8	172	205	215	10
9	108	125	195	70
10	39	187	32	-155
11	74	87	74	-13
12	71	147	71	-76
13	159	199	143	-56
14	189	258	258	0
15	139	108	158	50
16	96	76	136	60
17	61	31	67	36
18	10	32	17	-15
19	99	122	62	-60
20	114	147	137	-10
21	91	77	106	29
22	81	134	112	-23
23	80	134	90	-44
24	187	240	231	-9
25	249	247	277	30
26	360	377	406	29
27	546	487	545	58
Avg. Disp.	139	170	153	
Std. Dev.	117	112	127	

TABLE 19

Performance of objective technique based on intensity stratification

Storm Intensity	No. of Storms	Warning Position		Forecast Position	
		%W-T	%L	%W-T	%L
> 130 Kts	5	20	80	20	80
> 65 Kts	17	82	18	53	47
< 65 Kts	8	75	25	43	57

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

An objective technique for determining the warning position of a tropical cyclone has been developed and shown to be a viable forecasting "tool" for the tropical cyclone forecaster. The thought processes of the TDO have been synthesized by the objective method of generating the "working best track" and future 24-h storm track, and the inclusion of the spatial and temporal weighting factors. This technique provides a consistent "first-guess" for the inexperienced forecaster (Morford, 1979) or a first step in an objective format (Simpson, 1971; Elsberry, 1984) for forecasting tropical cyclone movement. Compared to the JTWC warnings, the three year (1981 - 1983) sample indicates slightly more accurate and consistent warning positions from the objective scheme. On a storm-by-storm basis, 21 of the 30 storms had either improved or comparable warning position errors.

JTWC's method of blending the +6-h forecast positions from the objective aids with the latest fix information to determine the warning position, which was initiated in 1983 (Sandgathe, 1985), is similar in principle to this objective technique. During 1983, JTWC's method resulted in a smaller average warning position error. However, the objective technique still provided a more consistent position as indicated by the smaller standard deviation.

Nine of the 30 storms tested had larger warning position errors than JTWC. Of these nine, five storms either looped or departed significantly from climatological tracks. It is these difficult forecasting scenarios in which the TDO requires the best possible guidance. The CLIPER method does not include synoptic fields as predictors (Neumann, 1972) and thus will require additional guidance to handle these situations.

The overall evaluations based on the 24-h forecast comparisons were not as promising. The total average forecast error was slightly smaller than JTWC's when using the objective scheme, due mainly to the reduced errors during 1981. Only 45% of the 30 storms had improved or comparable forecast errors when CLIPER was initiated with the objective warning position instead of the JTWC warning position. It is difficult to explain this diminished performance as exemplified by the tracks of Tropical Storm Winona (1982) and Typhoon Dot (1982) described in section III-B. Comparing the standard deviations of the 24-h forecasts, it is apparent that there is not a significant difference in the consistency of the forecast positions in the 30 storms tested. Interestingly, the JTWC average 24-h forecast error would have been reduced in 16 of the 30 storms if the CLIPER forecast from the warning position had been used as guidance.

The objective technique when applied to the strongest storms (> 130 kts) had the poorest performance relative to JTWC in terms of both warning positions and 24-forecast errors. This may be attributable to intense storms normally being characterized by well-defined eyes and circulation patterns that are easier to define accurately. JTWC will also place more emphasis on their forecasts for storms with more destructive capability. It may not be that the objective technique is performing worse, and that JTWC's performance is improved for intense storms.

The objective technique will require subjective enhancement by the TDO in looping scenarios and during periods of rapid acceleration after recurvature. Finally, the CLIPER model is readily compatible to desk-top computers and provides a fast, interactive forecasting model for the TDO. Optimally, the TDO will be able to quickly generate and evaluate a revised "working best track", warning position and short-term forecast track every time new fix information is received.

B. RECOMMENDATIONS

The CLIPER regression coefficients were derived for a limited time and space domain. New coefficients should be derived for a sample that includes JTWC's entire area of responsibility. CLIPER contains no synoptic field information or physical interpretations. Dynamic models such as the One-way (Interactive) Tropical Cyclone Model (OTCM) or the Nested Tropical Cyclone Model (NTCM) incorporate both synoptic data and physics and I would recommend that the objective scheme be coupled with each of these dynamic models to determine which pairing results in the greatest reduction of both warning position error and forecast position error. Finally, a real-time study of the objective scheme utilizing fix information and official JTWC warning positions should be conducted as a follow-on to this study.

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