An Objective Technique for Estimating Present Tropical Cyclone Locations

WILLIAM T. CURRY, RUSSELL L. ELSBERRY AND JOHNNY C.-L. CHAN*

Department of Meteorology, Naval Postgraduate School, Monterey, CA 93943

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ABSTRACT

A technique is developed and tested for estimating objectively the location of a tropical cyclone from a variety of fixes. The western North Pacific climatology and persistence (WPCLPR) track forecast technique is used to generate a potential track from each fix. A tentative warning position is interpolated from a smooth curve that is fit to the future and past positions. When multiple fixes are available, weighting functions are applied to account for the expected accuracy and the timeliness of each fix. Several empirical factors are determined by sensitivity tests with a dependent sample of eight storms that includes 226 warning positions. An independent sample of 22 storms with 610 warning positions is used to demonstrate that the accuracy of the objective technique is not significantly different from the official Joint Typhoon Warning Center (JTWC) warning positions during 1981–83. The short-term track forecast accuracy with WPCLPR is essentially the same whether the JTWC or the objective warning positions are used. Thus, the objective technique provides an efficient tool for the forecaster to use in establishing the present location of the tropical cyclone.

1. Introduction

The first step in tropical cyclone track prediction is to determine the present location of the storm center. Establishing this "warning position" is a crucial step in the 12–36 h forecast procedure because the future storm motion will resemble the past motion in many cases. That is, persistence is a reasonably accurate approximation for predicting short-term motion. Nearly all of the operational track prediction techniques include a persistence aspect, which emphasizes the requirement for accurate warning positions that are smoothly varying in time. During the post-storm analysis to establish the "best track," the analyst attempts to fit a smooth curve through all of the "fixes" of the storm center. Jarrell et al. (1978) demonstrated that persistence forecasts based on best-track positions would have been superior to the official Joint Typhoon Warning Center (JTWC) forecasts at 24 h during 1966–75 and would have been nearly as good as the 48 and 72 h forecasts. Sanders et al. (1980) discussed the improvements in short-range prediction with a barotropic model that could result from improved initial positions. The goal of this research is to develop and test an objective technique for establishing a warning position that is consistent with short-term track prediction methods.

Many factors contribute to the difficulty in establishing an accurate and representative warning position. First, the tropical cyclone moves as a result of nonlinear processes on several horizontal scales. Thus, looping motion, sudden turns or accelerations/decelerations may occur as the vortex interacts with a changing environmental flow. Furthermore, short-term oscillations in the position of the inner core may occur due to asymmetries in the wind field or heating distribution. Sheets (1985) has proposed a "mass-field envelope" approach of tracking the storm with repeated aircraft reconnaissance that focuses on the translation of the outer region of the core (about twice the radius of maximum winds). Sheets demonstrates that the motion determined by the mass-field envelope technique is more conservative and representative of the future 12 to 24 h motion than is the motion estimated from the positions of minimum central pressure. When this type of aircraft reconnaissance is available, the accuracies of the fixes should be improved, which should be translated into improved warning positions.

The tropical cyclone forecaster may have a variety of fixes based on aircraft reconnaissance, satellites (polar orbiting and geostationary), radars and conventional synoptic analyses of ship and land reports. Each of these sources of information has a different accuracy that must be considered in establishing the warning position. The errors tend to be highly correlated with storm intensity. Minimum errors occur with intense storms that have well-defined eyes, whereas the position errors can be quite large for weak, poorly defined systems. Each of the instrument platforms may also have special error characteristics. Navigational errors may affect the accuracy of the aircraft or satellite fixes (especially for storms far from land), and two radars viewing the storm center through different sectors may not agree in position.

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* Present affiliation: Royal Observatory, Hong Kong.

The accuracies of fixes for all tropical cyclones in the western North Pacific during 1981–83 are summarized in Table 1. The fix accuracy is defined as the distance between the fix and the linearly interpreted position along the best track at the same time as the fix. Median values are given rather than mean values (or standard deviations) because a few very large errors may produce an unrepresentative average in a small sample. The satellite analyst provides a Position Code Number (PCN) as an indicator of the fix accuracy, with 1 or 2 indicating high accuracy (well-defined eye is visible) and 5 or 6 indicating low accuracy. As demonstrated by the groupings in Table 1, these subjective accuracy measures are apparently validated in the postseason comparison of the fixes with the best track, which is the best available estimate of the true position. The aircraft fixes are grouped by navigational and meteorological accuracy less than or greater than 13 and 17 km, respectively. These subjective estimates by the flight meteorologist also seem to be validated in this comparison. No accuracy estimates accompany the radar fixes in the western North Pacific. Extremely few fixes are based on synoptic analysis at the Joint Typhoon Warning Center, so the accuracies of these fixes cannot be established reliably.

An important aspect of the poststorm best-track analysis is simply the advantage of hindsight. If the future positions are known, it is easier to reject a fix that departs from the expected path. In real time, the forecaster must decide whether a new fix represents a true change in path or the fix is erroneous and should be discarded. Knowledge of the likely errors as in Table 1 provides some basis for evaluating the credibility of each fix. The forecaster will then look for additional evidence that supports or refutes that fix. In the case of the best-track analysis, the future positions are already known. Thus, the objective is to fit a smoothly varying curve through the real or fictitious oscillations represented by the combination of fixes. However, a tendency may exist for a *single* fix to become *the* best-track position in the absence of other information. Thus, the best-track analysis is somewhat subjective. Bell (1981) reported that the mean difference between best tracks established by various western North Pacific forecast centers was around 40 km. In this study, the JTWC best track will be the standard of comparison for the warning positions. These positions are expressed in tenths of a degree latitude and longitude, which immediately creates a discretization factor of 11 km (6 n mi). Accuracies of twice this value are essentially as precise a knowledge of the storm center as can be expected.

TABLE 1. Median accuracy (km) of satellite, aircraft and radar fixes of storm centers during 1981–83 in the western North Pacific. Satellite fixes are grouped into three categories according to Position Code Numbers (PCN) that are subjectively assigned by the satellite analyst. Subjective estimates of the accuracy (ACCY) of aircraft reconnaissance fixes are grouped by navigational accuracy (first number) less than or greater than 13 km and by meteorological accuracy (second number) less than or greater than 17 km.

	1981	1982	1983	1981–83
PCN	Satellite			
1 and 2	16	16	16	16
3 and 4	22	19	23	21
5 and 6	37	33	34	35
ACCY	Aircraft			
≤13 ≤17	14	12	12	13
≤13 >17	15	20	17	17
>13 ≤17	19	12	14	15
>13 >17	17	13	25	18
	Radar			
	21	17	15	18

Simpson (1971) proposed a decision-tree approach for systematically evaluating the different types of fixes. However, the decision procedure was subjective. Titus and Jarrell (1985) applied an adaptive form of a Kalman filter to estimate the storm location by combining all available fixes with prior knowledge about the system in such a manner that the mean square error is minimized. Short-term forecasts based on the Kalman filter initial motion vector were superior to JTWC forecasts in 16 of 23 cases from Typhoon Marge in 1983. In the objective technique proposed here, each fix is assessed in terms of the implied future (forecast) position and the requirement to have a smoothly varying path through future and past positions.

2. Operational warning positions

The hindsight aspect of reviewing previous warning positions in light of more recent storm positions is also applied operationally at JTWC. A "working best track (WBT)" is prepared each 6 h by updating prior warning positions to reflect the best estimate of where the storm actually was at those times. Although adjustments might occasionally be made in the poorly known positions as much as 36 to 48 h earlier, most of the adjustments are in the most recent portion of the track.

A change in the JTWC procedure for establishing the warning position was made during 1983. Prior to that season, the fixes received during the 4.5 h since the prior warning were used to extrapolate the next warning position. Extrapolation was necessary since the suite of objective aids to be prepared remotely at Monterey, California, had to be requested about 1.5 h prior to warning time to assure receipt in Guam before warning time. During 1983, the procedure was revised to request the objective aids based on the prior warning time. The forecasts from the various objective aids based on the prior warning time are subsequently used with all recent fixes to establish the official warning position at 6 h. Thus, the principle of evaluating fixes based on future (predicted) locations of the storm is used operationally. This leads to more conservative warning positions because a form of interpolation is being used rather than extrapolation. The disadvantage is that the extrapolation, climatology, analog and dynamical objective aids (see descriptions in the JTWC Annual Reports) have been based on the previous warning position rather than the new warning position, so the forecaster must make adjustments to each of the objective aid tracks. Furthermore, the forecasts are issued about two hours later than in the schedule prior to 1983.

In this study, an objective warning position technique is tested that attempts to simulate the forecaster's reasoning in evaluating fixes. If it can be shown that the objective technique produces superior, or at least similar, accuracies relative to the official JTWC warning positions, the technique might serve as a tool for assuring consistency in the warning position procedure. The goal is to provide objectively a "second opinion" that the forecaster can accept or improve upon based on experience or other knowledge.

3. Objective technique

The primary principle of the proposed objective technique is to simulate the hindsight aspect of viewing each fix in terms of the working best track and the future (forecast) positions assuming that fix is accurate. That is, a credible short-term forecast aid called western North Pacific climatology and persistence (WPCLPR) developed by Xu and Neumann (1985) is applied to each fix to establish the future 12 and 24 h positions. The WPCLPR technique is selected as the forecast aid because it is similar to the widely used CLIPER technique originally derived by Neumann (1972) for the Atlantic and by Neumann and Leftwich (1977) for the eastern Pacific tropical cyclones. These CLIPER techniques use regression equations to relate future storm displacements to the initial latitude/longitude, previous 12 and 24 h zonal and meridional displacements, initial maximum wind speed and the Julian date. The potential predictors in the regression equations include a total of 165 possible products and cross-products of the eight basic variables. Because the track forecasts to 24 h rely heavily on persistence, the primary input to WPCLPR is the past 12 and 24 h movement.

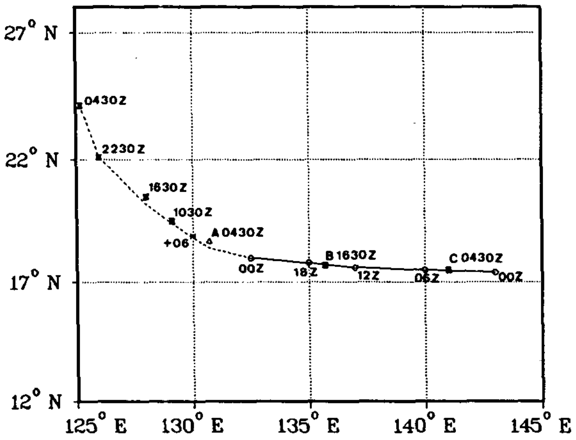

FIG. 1. Illustration of interpolation procedure for estimating a tentative warning position at +6 h based on a single fix (point A) at 0430 UTC. The working best-track positions are represented by a third-order polynomial curve (solid) from which the positions at 12 h (point B) and 24 h (point C) prior to the fix are interpolated. Future positions derived from the 24 h WPCLPR forecast based on this fix are connected by a dashed line (see description in text).

TABLE 2. Empirically derived weighting factors in the third-order polynomial fit of the working best track for the past (negative) 24 h. This polynomial is used to interpolate past positions at intermediate times.

Time (h)				
−24	−18	−12	−06	00
20	15	15	10	10

These WCLPR forecast positions are combined with the known past positions by fitting a smooth (fourth-order polynomial) curve through the points. A tentative warning position, which does not necessarily coincide with the fix position, is then interpolated from the polynomial at the desired warning time. The procedure is illustrated in Fig. 1 for a single fix (point A) at 4.5 h after the previous warning position at 0000 UTC. Past positions at fix time minus 12 h (F − 12) and fix time minus 24 h (F − 24) must be derived to provide the required input to WPCLPR. 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 greater confidence can be placed on the earlier positions, higher weighting factors are given to the −12, −18 and −24 h positions (Table 2). Positions B at 1630 UTC (F − 12) and C at 0430 UTC (F − 24) in Fig. 1 are then interpolated using the coefficients from the third-order polynomial. The other inputs to WPCLPR are the initial maximum wind speed and the Julian date. The outputs from WPCLPR are the 12 and 24 h forecast positions, and a linear interpolation is used to derive positions 6 and 18 h after fix time. A fourth-order polynomial fit of the WPCLPR positions (W + 6 to W + 24) and prior (0000 UTC to W − 24) WBT latitudes (and longitudes) is used to determine a smooth representation of the storm movement. Larger weighting factors (Table 3) are given to the prior positions to assure a smooth evolution from these relatively well known positions. These time-dependent, fourth-order polynomial coefficients are used to interpolate the tentative warning position (the +6 h position in Fig. 1).

TABLE 3. Weighting factors in fourth-order polynomial fit for determining a tentative warning position at +6 h based on working best track from −24 h to 0000 UTC and the WPCLPR forecast positions at 6–24 h after the fix. *I* is the time increment between previous warning (0000 UTC) and the fix.

Time (h)								
−24	−18	−12	−06	00	6+*I*	12+*I*	18+*I*	24+*I*
20	50	40	10	10	5	1	1	1

Each of the steps in the procedure has been tested with a sample of eight storms with 226 warning positions. Third- and fourth-order polynomial fits have been tested with various combinations of weighting factors as in Tables 2–3. For example, the fourth-order polynomial (Table 3) was selected because the resulting warning positions in the dependent sample were about 2 km more accurate.

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

In the second stage of the procedure, consideration is given to the potential impact of typical positioning errors. Four adjacent positions are generated from the first iteration warning position (point D in Fig. 2) by adding an "observational error" in each cardinal direction (Fig. 3). Each error position is treated as a "fix," with WPCLPR 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 are changed due to the increase in the number of fitted points (Table 4). The four new tentative positions are weighted equally since each "observational error" would have an equal probability. The final warning position is determined as the arithmetic average of these four new positions (Fig. 3). As indicated above, the empirical constants in Tables 2–4 and the inclusion or omission of the various steps in the procedure have been tested by varying one factor while holding the remaining factors fixed. These sensitivity tests show that slightly smaller objective warning position errors result if the observational error iteration is incorporated. Essentially the same improvement occurs if the "observational error" is 18, 28 or 37 km (10, 15 or 20 n mi). Therefore, an observational error of 28 km is taken as the default value. Although the weighting factors in Tables 2–4 are not necessarily optimum, the sensitivity testing has provided a basic technique that is suitable for testing the objective warning position technique. In the original interactive design concept for the technique, the user would have the option of selecting third- or fourth-order polynomials with different weighting functions and a choice of omitting or retaining different iterations. Thus, the present form of the technique could be considered as "default" values to be used in a menu-driven interactive application.

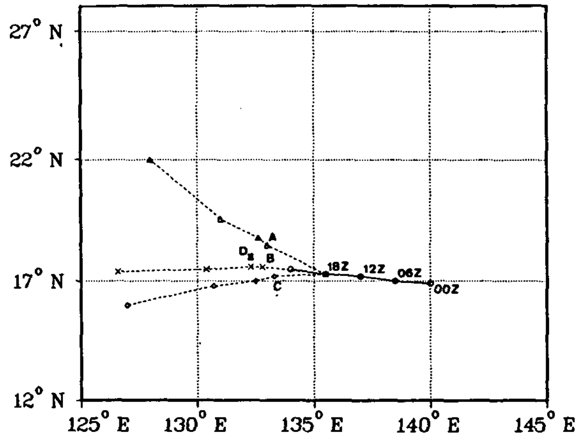

FIG. 2. Weighted combination of three tentative warning positions based on three fixes at A, B and C to derive a first iteration warning position (point D). The working best track is connected by a solid line.

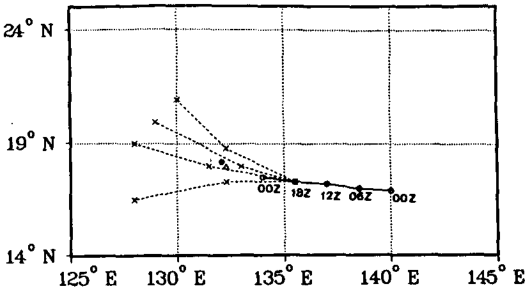

FIG. 3. Second iteration of the objective warning position (dot) based on WPCLPR tracks through four "fixes" in which an observational error has been added in the cardinal directions to the first iteration warning position.

4. Weighting factors

In the operational procedure of blending the various fix positions, the forecaster subjectively weights each fix based on the fix platform accuracy (e.g., Table 1) and the fix time. More recent fixes are normally given greater emphasis. It would be desirable for the objective

TABLE 4. Weighting factors as in Table 3 except for the second iteration in which observational errors are added in the cardinal directions.

Time (h)									
−24	−18	−12	−06	00	+06	+12	+18	+24	+30
25	75	45	45	20	15	5	1	1	1

warning position technique to simulate similar weighting functions.

Based on Table 1, subjective estimates of the relative accuracies of the satellite fixes and of the aircraft fixes are available. The median values within each of the groups for the three-year sample shown in Table 1 are selected as a measure of expected accuracy. The distinction between the median values of the most accurate fix platform (aircraft < 13 < 17) and the least accurate (satellite, PCN 5 and 6) is only a factor of three. Based on sensitivity tests that raise these values to some power to provide more discrimination between fix types, a third power of the median is selected. A linear-time weighting function is specified used the time difference between the most recent warning position and the fix time. Fix positions obtained 5 to 6 h after the previous warning time are given ten times more weight than fix information received within the first hour after that warning. Inclusion of the time weighting factors reduced the warning position errors in the dependent sample by 2 km. Tests with other time weighting functional forms and other weighting values with the linear function produced smaller improvements in the dependent sample.

Thus, the weighted mean position for i fixes as in Fig. 2 is

$$\bar{x} = \sum_i \frac{T_i x_i}{A_i^3} \Big/ \sum_i \frac{T_i}{A^3}, \qquad (1)$$

where x_i is the latitude or longitude of the tentative warning position based on a fix with an expected accuracy A_i and a time factor T_i. For example, suppose a highly accurate aircraft reconnaissance fix ($A = 13$), two satellite fixes with PCN = 1 ($A = 16$) and PCN = 6 ($A = 35$), and a radar fix ($A = 18$) are available. The aircraft reconnaissance position would have about twice as much influence as the PCN = 1 satellite fix, about 20 times the influence of the PCN = 6 satellite fix, and about 2.5 times the influence of the radar fix. Thus, the weighted tentative warning position will be heavily slanted toward the aircraft, PCN = 1 satellite and radar fixes. Of course, the time of these fixes is also a factor in (1). For example, a recent radar fix might contribute as much as an aircraft fix that is several hours old.

5. Accuracy of warning positions

An independent sample of 637 warning positions from 22 storms is derived by the objective technique for comparison with the official JTWC positions. Inclusion of a storm in the sample is based on the following constraints.

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

(ii) Since the current objective technique is limited to 10 fixes per warning, storms with a large number of radar fixes per warning are excluded.

(iii) Storms with a majority of their path outside the latitude/longitude domain of the WPCLPR are not included.

(iv) Storms that are either short-lived or have extended periods of time during which JTWC warnings are unavailable are excluded.

An example from the developmental sample is given in Fig. 4. Both the objective and the JTWC warning positions are to the north of the best track as Typhoon Pat turned westward along 11°N, and both positions are to the west of the best track during the subsequent sharp turn to the north. Although seemingly valid fixes exist to support these deviations from the best track, the best-track analyst subjectively discarded these fixes. The objective warning positions in Typhoon Pat are quite close to the best track during recurvature period. However, the objective technique does not perform well when a rapid acceleration follows a slow movement during recurvature (Fig. 5). Only three fixes are available in this case, and fix A coincides with the prior warning time (1200 UTC). Since the last fix C at 3 h after the warning time did not indicate the large acceleration, the objective warning position is too conservative. By contrast, the official JTWC position is quite accurate, as the forecaster anticipated the rapid acceleration.

Since the WPCLPR technique performs best with persistence-type tracks, the objective warning procedure also tends to be most accurate in these situations. Less accuracy is expected during looping periods or with other anomalous track conditions. Such an example is given in Fig. 6. Neither the objective nor the official JTWC warning position is very accurate when

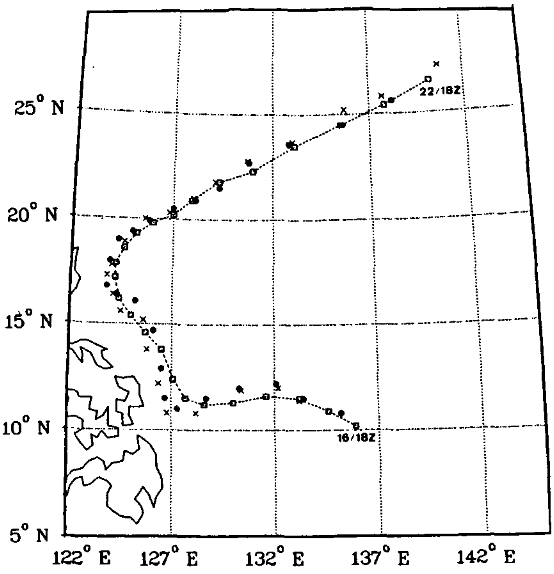

FIG. 4. Path (dashed) of Typhoon Pat during 16–22 May 1982 as indicated by 6 h best track (squares), JTWC warnings (×) and objective warning positions (dots).

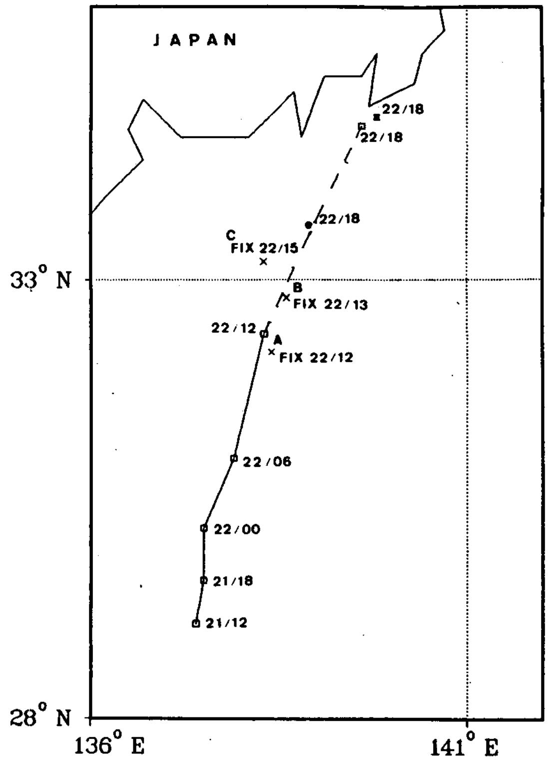

FIG. 5. Best-track positions (boxes) of Typhoon Thad during 1200 UTC 21 August 1981 to 1800 UTC 22 August 1981. These fixes (A, B and C) are used to establish the official JTWC warning position (II) and the objective warning position (dot) at 1800 UTC 22 August 1981.

Typhoon Nelson is interacting with the Philippine Islands. Although both positioning methods are quite good during the northwestward track, they miss the abrupt left turn near 14°N, 116°E. The objective technique actually has smaller errors during the looping episode at 114°E. During the entire period shown in Fig. 6, the average objective warning position error is 37 km with a standard deviation of 21 km, whereas the JTWC position error is 48 km with a standard deviation of 37 km. When the direction changes are more rapid in association with a tight loop, the objective technique is less accurate.

As indicated in the Introduction, the accuracy of fixes is less for weak storms in which a circulation center cannot be easily identified from satellite, radar or even aircraft reconnaissance. The accuracy of the objective warning positions relative to the JTWC positions is illustrated in Fig. 7 for different maximum wind groupings. For wind speeds above typhoon intensity (greater than 65 kt), the objective and JTWC positions generally agree within 28 km (15 n mi). However, the discrepancies between the JTWC and the objective methods become larger as the storm intensity decreases. For the 15 m s^{-1} (30 kt) or less category, 30% of the JTWC positions are more accurate than the objective method by at least 28 km (15 n mi). However, 22% of the objective positions exceed the accuracy of the JTWC positions by at least 28 km (15 n mi). That is, both JTWC and the objective method are subject to large errors in weak storms because of the inherent inaccuracies in the fixes. As the storms become stronger and erratic fixes are less frequent, the JTWC and the objective technique become more consistent.

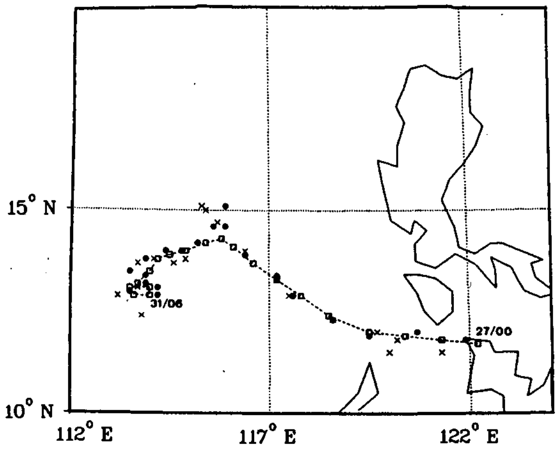

FIG. 6. As in Fig. 4, except for Typhoon Nelson from 0000 UTC 27 March 1982 to 0600 UTC 31 March 1982.

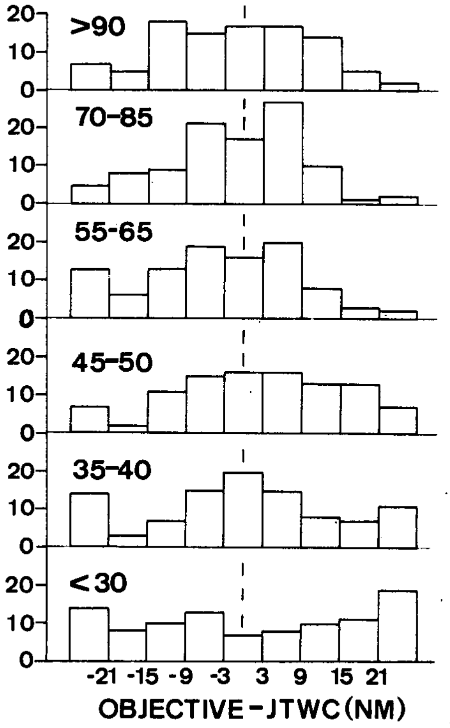

FIG. 7. Histograms indicating percent of objective minus JTWC warning position differences within 11 km (6 n mi) increments for tropical cyclones with maximum wind speeds in knots (one kt is equal to 0.52 m s^{-1}) in the ranges shown. A negative value indicates that the objective warning position is more accurate than the official JTWC position. The dashed vertical line indicates equal accuracies.

TABLE 5. Means and standard deviations of JTWC (JT) and objective (OBJ) warning position errors (km) for the independent sample storms during 1981. *N* is the number of warning positions; Win (W), Tie (T) or Loss (L) refers to objective position accuracy relative to JTWC; TS is Tropical Storm, TY Typhoon, and STY Supertyphoon. The Student's t-test parameter is also shown with an asterisk if the difference is significant at the 95% confidence level.

		Mean		Standard deviation			
Storm	*N*	JT	OBJ	JT	OBJ	WTL	*t*
TY June	23	39	30	26	17	W	−1.18
TS Roy	19	41	41	28	30	T	0.06
TY Clara	34	41	30	35	15	W	−1.67
STY Elsie	33	34	24	20	13	W	−2.00
TY Hazen	40	45	37	24	24	W	−1.28
TS Jeff	20	63	54	37	22	W	−0.88
TY Kit	45	32	30	22	20	W	−0.38
Total	214						
Weighted average		41	34	26	20		

Following the practice at JTWC, the performance of the objective technique is summarized by individual storms (Tables 5–7). A win (W), tie (T) or loss (L) relative to the corresponding JTWC positions for that storm is indicated. The objective technique generally produces a more accurate warning position during 1981 and 1982. The objective technique results in slightly smaller errors for 6 of 7 storms during 1981 and 3 of 7 storms during 1982. The percentage of storms in the win plus tie categories represents 100% of the 1981 storms and 71% of the 1982 storms. 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 during 1983 compared to 1982 and 1981. A reduction in the number of storms in which the objective scheme produces smaller errors (3 of 8 storms) results in a win plus tie percentage of only 50% for 1983. A Student's t-test is made for each storm to determine 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 sample, only Typhoon Nelson (1982) would have had significant reductions in warning position error if the objective technique had been used. However, the warning positions for two tropical storms (Ben and Georgia during 1983) would have been degraded. While the average of errors for Supertyphoon Forrest (1983) were only 28 km (15 n mi) for the objective technique, the JTWC errors were exceptionally low (19 km).

These annual summaries also indicate that the objective technique produces more consistent warning positions, since the standard deviations are smaller than for the JTWC positions. Specifically, 5 of 7 storms in 1981, 4 of 7 storms in 1982, and 4 of 8 storms in 1983 have smaller standard deviations.

When only one fix is available, no weighting is involved in the objective technique. In a sample of 57 cases with a single fix, the mean accuracy of both the objective and the JTWC warning positions is 54 km (29 n mi). This is nearly 50% larger than the overall accuracy of the two methods, even though the official JTWC warning position and the best track are often identical early and late in the storm cycle when single (or no) fix situations typically occur. The standard deviations for the 57 single-fix cases are 35 and 39 km for the objective and JTWC positions, respectively. These values are also larger than the overall sample

TABLE 6. As in Table 5 except for 1982.

		Mean		Standard deviation			
Storm	*N*	JT	OBJ	JT	OBJ	WTL	*t*
TY Nelson	55	43	32	30	19	W	−2.15*
TS Winona	20	41	41	24	24	T	0.08
STY Bess	45	30	39	19	32	L	1.43
TY Judy	30	35	34	41	26	W	−1.31
TY Ken	36	26	28	11	20	L	0.23
TY Nancy	31	22	20	20	11	W	−0.01
TY Pamela	68	39	39	41	28	T	0.00
Total	285						
Weighted average		35	34	28	24		

TABLE 7. As in Table 5 except for 1983.

		Mean		Standard deviation			
Storm	*N*	JT	OBJ	JT	OBJ	WTL	*t*
TY Tip	17	24	22	22	15	W	−0.08
TS Ben	12	32	63	15	43	L	2.35*
STY Forrest	31	19	28	11	19	L	2.25*
TS Georgia	13	19	35	15	20	L	2.31*
TY Lex	17	34	34	24	28	T	−0.01
TY Percy	24	41	50	41	24	L	1.01
TS Sperry	9	63	56	54	43	W	−0.28
TS Thelma	15	59	46	61	24	W	−0.61
Total	138						
Weighted average		34	39	28	24		

standard deviations. Thus, both JTWC and the objective scheme are less accurate and less consistent in the single-fix situations.

6. Effects on short-term forecasts

As indicated in the Introduction, improved warning positions should result in reduced short-term forecast errors. To test this assertion, the JTWC and the objective warning positions are used with the −12 and the −24 h best-track positions in the WPCLPR to forecast the +24 h position. The best-track positions are used due to the nonavailability of working best-track positions, which would have provided a better evaluation of operational utility. The control case is a WPCLPR forecast generated entirely with best-track positions, which should produce better short-term forecasts than either the JTWC or the objective warning positions. Because the first 24 h of each storm track is required as past history in WPCLPR, the first four warning positions in each storm 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 is reduced to 456 and the short-lived Tropical Storm Sperry is eliminated in this evaluation.

Summaries of the 1981–83 samples are shown in Tables 8–10 in the format as for the initial position error evaluations. As expected, the 24 h forecasts based entirely on best-track positions are the most accurate. During 1981 and 1982, the 24 h forecasts based on the objective warning positions compare favorably with those based on JTWC warning positions. That is, the average 24 h forecast errors for the objective scheme (217 km for 1981 and 215 km for 1982) are not significantly different from the corresponding 230 and 204 km WPCLPR errors based on JTWC's warning positions. The percentage of win plus tie category forecasts for the objective technique is 55% in 1981 and 60% in 1982. However, only 20% of the forecasts during 1983 have smaller errors from the objective warning positions. According to the Student's *t* test scores in Tables 8–10, none of the differences between the JTWC and the objective technique forecast errors are significant at the 95% confidence level. Thus, the objective warning positions essentially provide a short-term forecast performance similar to the official JTWC warning positions.

7. Conclusions

An objective technique has been developed for establishing a warning position of a tropical cyclone based

TABLE 8. Means and standard deviations of 24 h forecast errors (km) for WPCLPR initiated with best-track (BT) positions, JTWC (JT) and objective (OBJ) warning positions during 1981 storms. Other symbols as in Table 5.

		Mean			Standard deviation				
Storm	*N*	BT	JT	OBJ	BT	JT	OBJ	WTL	*t*
TY June	16	130	204	141	72	85	100	W	−1.92
TS Roy	12	198	280	240	107	145	104	W	−0.80
TY Clara	25	106	148	128	63	100	67	W	−0.91
STY Elsie	25	183	202	212	132	145	152	L	0.21
TY Hazen	33	212	258	258	96	104	106	T	0.00
TS Jeff	10	343	458	419	87	130	117	W	−0.69
TY Kit	31	167	213	215	95	102	117	L	0.07
Total	152								
Weighted average		180	230	217	95	113	109		

TABLE 9. As in Table 8 except for 1982.

		Mean			Standard deviation				
Storm	*N*	BT	JT	OBJ	BT	JT	OBJ	WTL	*t*
TY Nelson	46	189	206	230	93	120	100	L	1.02
TS Winona	11	148	183	204	96	152	158	L	0.31
STY Bess	38	208	239	245	113	120	126	L	0.23
TY Judy	23	146	189	178	117	119	128	W	−0.30
TY Ken	28	131	161	159	91	93	109	W	−0.07
TY Nancy	24	102	122	122	52	65	70	T	−0.01
TY Pamela	56	226	248	265	150	148	178	L	−0.55
Total	226								
Weighted average		178	204	215	107	119	128		

on all center fixes received during the 6 h since the last warning. The primary assumption is that a climatology and persistence (WPCLPR) track prediction scheme provides the future storm locations to be expected if that fix is accurate. A tentative warning position is interpolated from a fourth-order curve fit through the future positions and the past positions. If more than one fix is available, the tentative warning positions are summed with weighting factors that reflect the timeliness and expected accuracy for these fixes. Such an objective technique is necessarily empirical and the weighting factors selected are not optimum. However, tests with independent cases indicate that the accuracies of the objective warning positions are not significantly different from the official Joint Typhoon Warning Center (JTWC) positions during 1981–83. Changes in operational procedures at JTWC during 1983 seem to have eliminated a slight advantage that the objective technique had for the 1981 and 1982 storms in the sample. The short-term (24 h) track forecasts with WPCLPR based on objective and official warning positions are essentially the same, and both are poorer forecasts than WPCLPR produces with best-track positions.

One benefit of such an objective warning position technique is that the forecaster would have a “second opinion” to compare with his own assessment of the fixes. The forecaster would soon learn to recognize situations when the objective technique provides poor guidance that should be rejected. Some examples, such as rapid accleration following a slow translation during recurvature and a rapid direction change during looping, are illustrated above. An objective technique may also result in more consistency from shift to shift. This feature could be particularly important for JTWC, which has a complete turnover of forecasters each two years. A novice forecaster may be less likely to make erroneous choices if a conservative objective technique is available for guidance.

The objective technique will be most effective if it is implemented with an interactive graphics display. Such a provision for rapid display and calculations of future tracks for alternate fix positions would greatly enhance the utility of the objective technique. One desirable feature that has not been included in the present scheme is an objective method for rejecting an “obviously” erroneous fix. Such a decision can now only be made with human intervention.

The intent of this work is not to supplant the forecaster. Rather, the objective warning technique is a tool that could make the forecaster more efficient and consistent. Of course, there is also a danger that a forecaster may blindly follow statistical guidance that works best for “meteorologically dull” situations. Ideally, the use of the objective guidance will allow the forecaster to concentrate on the meteorological situation and

TABLE 10. As in Table 8 except for 1983.

		Mean			Standard deviation				
Storm	*N*	BT	JT	OBJ	BT	JT	OBJ	WTL	*t*
TY Tip	10	76	107	109	46	70	61	L	0.07
TS Ben	5	470	482	506	339	328	371	L	0.11
STY Forrest	24	137	146	165	85	100	100	L	0.63
TS Georgia	6	107	107	165	37	24	85	L	1.56
TY Lex	10	143	139	182	93	106	146	L	0.75
TY Percy	17	356	398	437	93	87	98	L	1.23
TS Thelma	6	250	261	265	93	208	161	L	0.04
Total	78								
Weighted average		206	222	248	104	111	122		

scrutinize more carefully the implications of the automated technique. In that case, the technique could contribute to more accurate short-term track forecasts of both "dull" and "difficult" tropical cyclones.

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