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STATISTICAL POST-PROCESSING OF THE NAVY NESTED TROPICAL CYCLONE--ETC(U)
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STATISTICAL POST-PROCESSING OF THE NAVY NESTED
TROPICAL CYCLONE MODEL AND THE
OPERATIONAL TROPICAL CYCLONE MODEL

James E. Peak
and
Russell L. Elsberry

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A statistical technique proposed by Elsberry and Frill (1980) for adjusting dynamical tropical cyclone motion forecasts is extended to the Two-Way Interactive Nested Tropical Cyclone Model (NTCM) and the operational One-Way Interactive Tropical Cyclone Model (TCMO). The technique utilizes linear regression equations to reduce systematic errors. Backward extrapolation positions are presented as a less expensive, but inferior, alternative to the backward integration positions required by the original technique. A scheme is developed for applying the technique in storm-motion coordinates as well as zonal-meridional coordinates. Tests with 186 NTCM cases indicate moderate improvement in forecast errors by the zonal-meridional regression technique, and slight improvement by the storm-coordinate scheme. In TCMO tests with 212 cases, the zonal-meridional regression equations reduced the forecast errors, but the storm-coordinate equations did not. The technique failed to improve forecast errors in independent tests with NTCM 1981 data, presumably due to differences in error biases, which indicates a need for a larger sample size. Alternatively backward integration positions may be necessary to achieve consistent improvements from this statistical technique. The technique was able to improve 60h-72h forecast errors in TCMO 1981 cases.

ABSTRACT

A statistical technique proposed by Elsberry and Frill (1980) for adjusting dynamical tropical cyclone motion forecasts is extended to the Two-Way Interactive Nested Tropical Cyclone Model (NTCM) and the operational One-Way Interactive Tropical Cyclone Model (TCMO). The technique utilizes linear regression equations to reduce systematic errors. Backward extrapolation positions are presented as a less expensive, but inferior, alternative to the backward integration positions required by the original technique. A scheme is developed for applying the technique in storm-motion coordinates as well as zonal-meridional coordinates. Tests with 186 NTCM cases indicate moderate improvement in forecast errors by the zonal-meridional regression technique, and slight improvement by the storm-coordinate scheme. In TCMO tests with 212 cases, the zonal-meridional regression equations reduced the forecast errors, but the storm-coordinate equations did not. The technique failed to improve forecast errors in independent tests with NTCM 1981 data, presumably due to differences in error biases, which indicates a need for a larger sample size. Alternatively backward integration positions may be necessary to achieve consistent improvements from this statistical technique. The technique was able to improve 60h-72h forecast errors in TCMO 1981 cases.

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1. Introduction

A statistical technique for post-processing tropical cyclone tracks predicted by the Fleet Numerical Oceanography Center (FNOC) Tropical Cyclone Model (TCM) has been devised by Elsberry and Frill (1980). The technique uses multiple linear regression equations to remove systematic bias in the TCM track forecasts. Predictands of the equations are zonal and meridional differences between forecast and best track positions at corresponding times. Predictors are storm latitude and longitude, Julian date, and zonal and meridional components of model-predicted displacement and velocity. Additional predictors are obtained by integrating the model backward in time to -36 h, and calculating the differences between the known positions at -12, -24 and -36 and the corresponding backward integration positions. Elsberry and Frill found that these backward track predictors were very valuable, because they indicate the forecast track errors due to model and initial data deficiencies. That is, the errors that occur in the backward portion of the track may be used to help define the expected errors in the forward portion. The technique reduced TCM independent sample forecast errors by ~100 nmi at 72 h.

Elsberry, Gilchrist and Peak (1981) showed that the same technique can be used to improve forecast tracks of the Hurricane and Typhoon Tracking (HATRACK) scheme. The HATRACK error reduction was also ~100 nmi at 72 h.

The reduction of forecast errors in these research studies is encouraging; however, there are problems with implementing the techniques in an operational mode. The TCM regression scheme tests were restricted by the use of analysis fields for forward integration boundary conditions ("perfect prog"), rather than hemispheric model forecast fields. Best track storm positions, which are not available operationally, have been used rather than warning track positions. The additional computer time required for integrating a model backwards is a potential problem on an operational system. Elsberry and Frill (1980) indicated that changes in a predictive model, and in the data used by the model, may tend to invalidate the regression equations. The version of the TCM now used operationally at FNOC is different from the one that Elsberry and Frill used. The differences include a new method for location of the initial model grid relative to the initial storm center, a stronger storm bogus and a pre-processing technique developed by Shewchuk and Elsberry (1978). As will be seen later, the model no longer exhibits the same error bias characteristics because of these changes. The model is currently initialized with the FNOC northern hemisphere primitive-equation model and global band fields, but will in the near future be initialized with fields from the Navy Operational Global Atmospheric Prediction System (NOGAPS). These new data may further change the model bias.

The purpose of this report is to explore further the usefulness of statistical postprocessing for FNOC operational models. The operational TCM (hereafter referred to as TCMO) is evaluated for the effects of model changes on systematic bias, and the post-processing technique is applied to the operational tracks. In addition, the Two-Way Interactive Nested Tropical Cyclone Model (NTCM) is evaluated for bias and applicability of the postprocessing technique.

2. Backward Extrapolation versus Backward Integration

The original Elsberry and Frill statistical regression scheme requires an additional integration of the TCM to predict the 36 h backward displacement of the storm. The backward track provides a comparison of the model performance to known previous storm positions at -12, -24 and -36 h. This backward track comparison is crucial in statistically determining the corrections to be made to the forward motion forecast. The necessary TCM modifications include re-defining the time interval to be negative rather than positive and setting the analytic heating function to zero. The main disadvantage of this method is the approximately 50% increase in computer time required per model run to provide the backward track. The lack of heating in the backward integration mode may cause the model to predict an unrepresentative track, or perhaps permit dispersion of the vortex circulation so that it is impossible to track the center of the vortex to -36 h.

A method for avoiding a backward integration of the model has been devised. It was noticed that the 36 h backward trajectories of the HATRACK model were quite similar to simple backward extrapolation of the speed and direction components of the 12 h, 24 h and 36 h forward trajectories (Fig. 1). This is because the HATRACK model represents a storm as a point vortex advected by a smoothed, large-scale steering flow. Because of this similarity, comparing the backward extrapolated tracks with the known prior positions may provide the same model bias information as if the comparison is with the backward integration tracks. If the regression scheme could work with backward extrapolation, there would be no need to modify the HATRACK model to run backward. The operational implementation of the scheme would require little more than a means for input of the -12 h, -24 h and -36 h warning track positions and the addition of a regression equation subroutine.

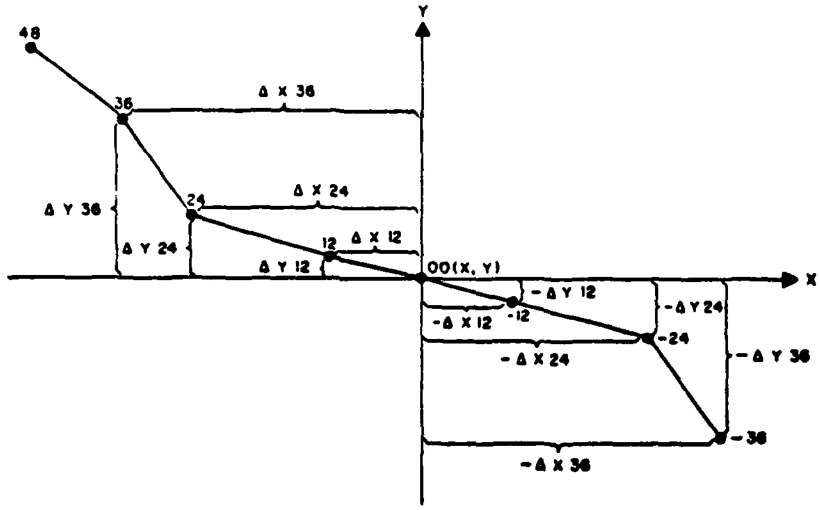


Fig. 1 Method of backward extrapolation of model-predicted storm tracks at 12, 24 and 36 h to obtain positions at -12, -24 and -36 h in lieu of a backward integration of the model

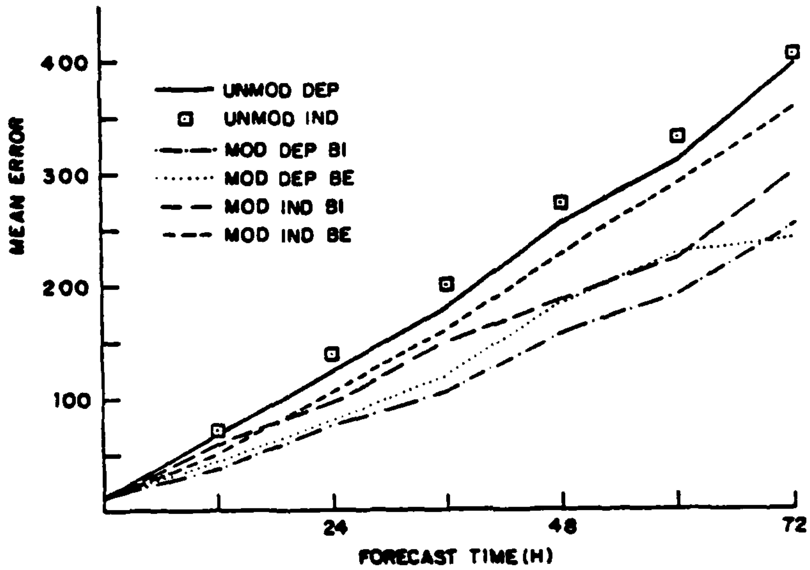


Fig. 2 Mean TCM forecast errors (n.mi.) for 82 western north Pacific tropical cyclone cases. Mean errors are depicted for the unmodified dependent (UNMOD DEP) and independent (UNMOD IND) samples, and the regression modified samples using backward integration (BI) and backward extrapolation (BE) positions

Extrapolated backward tracks and corresponding regression equations were used in lieu of the backward trajectories of Elsberry, Gilchrist and Peak's HATRACK scheme to test the effect on the regression scheme performance. The comparison of the HATRACK regression scheme independent sample modified with equations based on backward integration and the same sample modified with equations based on backward extrapolation can be seen in Table 1. The improvement relative to HATRACK made by the backward extrapolation scheme is comparable to that by the backward integration scheme in terms of the reduction of mean error and in the standard deviation of forecast error. The success of the backward extrapolation scheme may be attributed to the extreme smoothing of the height fields and the simple vortex advection procedure of the HATRACK model. It is unclear whether the extrapolation method will work for more complex, dynamical models such as the TCM or the NTCM. Such an approach is based on the assumption that the model's systematic bias during the early stages of forward integration is similar to that which would be found in backward integration. If the extrapolation scheme can provide the necessary bias information for the regression equations, it would have advantages. The computer time needed to perform backward integration would no longer be necessary, nor would any modification of the model be required, thus providing a faster, less expensive post-processed forecast. Finally, all previous model runs could be used in deriving regression equations without the requirement of calculating a backward integration track for each of the historical cases.

The feasibility of using backward extrapolation to replace backward integration was tested using 82 TCM runs. Backward integration tracks and statistical regression equations already have been derived for this sample. The track error biases of the 82 cases (from 26 storms) are listed in Table 2. The negative zonal (Δx) bias and positive meridional (Δy) bias indicates that the TCM forecast tracks are west and south of a typical storm track toward the northwest.

TABLE 1

Means ($\bar{X}$) and standard deviations (σ) of HATRACK forecast errors (nmi) for 500 mb, 700 mb and 850 mb independent samples; unmodified, modified using backward integration positions, and modified using backward extrapolation positions.

500 mb

Forecast Time	Independent Unmodified $\bar{X}$	Independent Unmodified σ	Independent Modified (Integration) $\bar{X}$	Independent Modified (Integration) σ	Independent Modified (Extrapolation) $\bar{X}$	Independent Modified (Extrapolation) σ
12	78	47	51	37	46	27
24	150	91	104	56	90	60
36	229	136	152	87	145	100
48	310	181	220	146	205	155
60	387	229	296	212	289	212
72	473	259	377	252	366	241

700 mb

Forecast Time	Independent Unmodified $\bar{X}$	Independent Unmodified σ	Independent Modified (Integration) $\bar{X}$	Independent Modified (Integration) σ	Independent Modified (Extrapolation) $\bar{X}$	Independent Modified (Extrapolation) σ
12	81	43	51	32	45	26
24	163	81	93	56	90	58
36	245	122	145	93	153	100
48	325	164	217	141	230	171
60	403	204	304	190	307	244
72	466	225	371	220	388	280

850 mb

Forecast Time	Independent Unmodified $\bar{X}$	Independent Unmodified σ	Independent Modified (Integration) $\bar{X}$	Independent Modified (Integration) σ	Independent Modified (Extrapolation) $\bar{X}$	Independent Modified (Extrapolation) σ
12	83	41	49	28	44	26
24	164	73	92	53	83	51
36	243	115	147	75	141	80
48	322	168	224	166	215	156
60	397	227	298	215	272	227
72	450	268	332	241	342	233

TABLE 2

TCM mean forecast errors (nmi) for 82 western North Pacific Ocean cases.

Forecast Time	Number of Cases	Forecast Error	Zonal (Δx) Error Bias	Meridional (Δy) Error Bias
12	82	69	8	14
24	82	129	-16	45
36	79	187	-38	59
48	67	261	-70	86
60	60	318	-109	104
72	53	399	-172	164

TABLE 3

Two-way interactive NTCM mean forecast errors (nmi) for 186 western North Pacific cases.

Forecast Time	Number of Cases	Forecast Error	Zonal (Δx) Error Bias	Meridional (Δy) Error Bias	Right Angle Error Bias	Speed Error Bias
12	186	74	11	-16	20	-32
24	186	114	-5	-5	15	-46
36	186	155	-20	-15	17	-43
48	185	209	-38	-10	8	-47
60	162	251	-35	-21	4	-36
72	160	319	-60	-8	-14	-60

The 82 cases are randomly divided into 55 dependent cases and an independent sample of 27 cases. The reduction of variances by the regression equations previously derived from the dependent sample using backward integration positions ranged from 46% to 73% and averaged 60%. New regression equations were derived using backward extrapolation positions. The reduction of variance by these equations ranges from 36% to 75% and averages 51%. The new equations chose a slightly smaller proportion of backward track predictors to forward track predictors than was the case for the backward integration equations. This, along with the smaller reduction of variance, indicates that the backward extrapolation positions do not provide as much information about the TCM track bias as do the backward integration positions.

The mean forecast errors of the dependent and independent samples as modified by the statistical equations based on both backward integration and backward extrapolation are depicted in Fig. 2. The decrease in forecast error of the dependent sample is about the same for the two methods from 12 h to 36 h and at 72 h. However, the backward extrapolation method has 25-35 nmi larger errors at 48 h and 60 h. This is consistent with the extrapolation scheme regression equations at 48 h and 60 h having the smallest reduction of variance. The independent sample post-processing decreased the forecast error from 12 h to 36 h by about the same amount for both schemes, but the improvement at 72 h by this backward extrapolation scheme is only half as good as the 100 nmi improvement made by the backward integration scheme. In this case, the backward extrapolation scheme does provide a means for reducing forecast errors, but it does not eliminate as much of the bias as does the backward integration scheme. This indicates that the model probably does not exhibit the same systematic bias in the first 36 h of forward integration as in backward integration. The improvement in forecast error and the selection of backward track predictors by the regression equations are evidence that some of the bias is accounted for by the backward extrapolation method.

3. Right Angle and Speed Error Bias Correction Scheme

Typhoon track forecasts may also contain systematic error bias relative to storm motion (right angle and speed errors) as well as in latitude/longitude coordinates. Forecast right angle and speed errors as defined by FNOC are graphically depicted in Fig. 3. Ignoring the earth's curvature, the forecast (vector) error is given by $\sqrt{(\text{right angle error})^2 + (\text{speed error})^2}$. The right angle and speed errors for a given forecast time depend only on the initial best track position and the forecast and best track positions for that time. Notice especially that if the angle between the best track and the forecast track is greater than 90°, the right angle error is defined as the normal distance from the forecast position to the line connecting the initial and future best track positions. The distance along this line from the future best track to the intersection with the right angle error line is the "speed" error, so-called because it is the displacement error that results from the model's incorrect storm translation speed.

The regression post-processing technique of Elsberry and Frill (1980) uses a latitude/longitude coordinate system, although it can theoretically be used in storm coordinates to correct for right angle and speed error biases. In such a scheme, right angle and speed error adjustments become the predictands of the regression equations, rather than zonal and meridional adjustments. Due to the definition of right angle and speed error in cases where a forecast track direction is in error by greater than 90° (Fig. 3b), there is an ambiguity in applying the storm coordinate error and adjustments. The same right angle and speed correctors may produce two different, valid best track positions. For example, a negative right angle error (forecast left of best track) and a negative speed error (forecast is too slow) which is larger than the distance from the initial best track

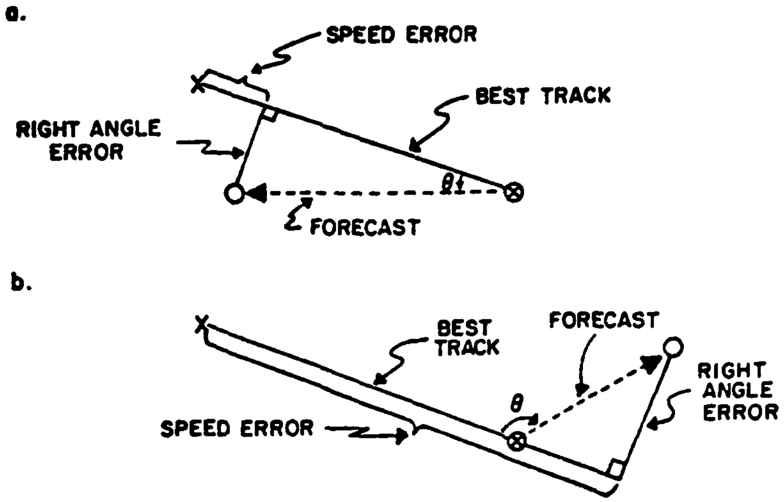


Fig. 3 Definition of right angle and speed error, where ⓧ is the initial best track position, X is the future best track position; and a. the angle (θ) between the forecast track and the best track is $< 90^{\circ}$; b. $\theta > 90^{\circ}$

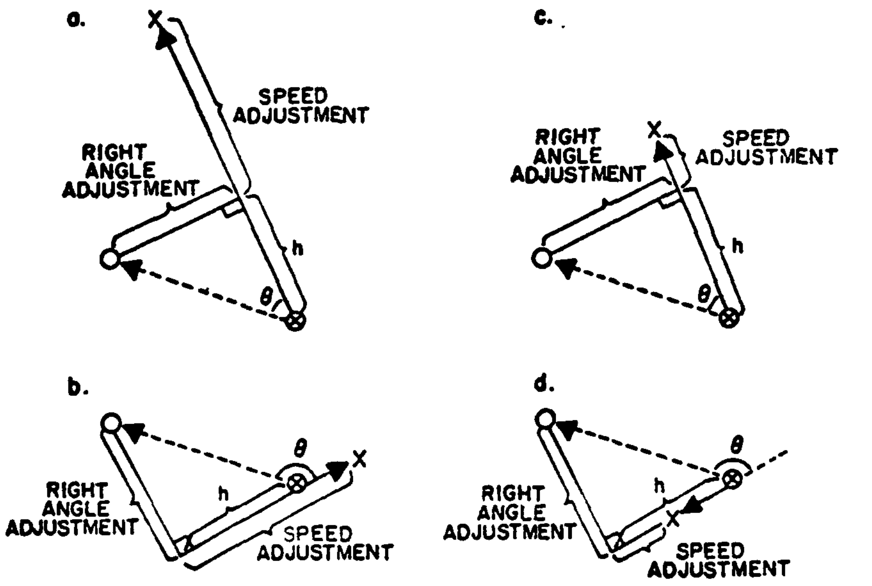


Fig. 4 Four ways of applying right angle and speed adjustments. Symbols as in Fig. 3; and h is the distance from the intersection of the right angle adjustment line to the initial best track position. a. $\theta < 90^{\circ}$ and speed error adjustment $> h$, b. $\theta > 90^{\circ}$ and speed error adjustment $> h$, c. $\theta < 90^{\circ}$ and speed error adjustment $< h$, d. $\theta > 90^{\circ}$ and speed error adjustment $< h$

to the right angle error intersection point, can be applied as in Fig. 4a or Fig. 4b. Both ways of applying the correctors predict a best track position more to the right (counteracting the error to the left) and farther along the best track line (counteracting the too-slow error). On the other hand, if the right angle and speed errors are negative and the speed error is smaller than the distance to the intersection between the best track and the line defining the right angle error, the application in Fig. 4c is valid. In this case the position in Fig. 4d is not valid because the negative speed error adjustment must put the best track position farther along the best track line, not farther back. The position shown in Fig. 4d would be valid if the speed error was positive (forecast too fast).

When both best track positions are valid, the following criteria are used to choose the most likely to be correct:

1) Successive track positions should be farther away from the initial position;
2) If both positions are farther than the preceding forecast position, choose the one that is closest to the preceding forecast position;
3) Successive positions should not change direction of motion by more than 90 degrees;
4) If both positions change direction of motion by more than 90 degrees, choose the one farthest away from the initial position.

In tests using actual right angle and speed errors as if they were correctors, these criteria resulted in the right choice for ambiguous situations in all but very unusual storm tracks, and the mean bias that was accrued from wrong choices was approximately $\pm$ 10 nm.

4. Post-Processing of NTCM Tracks

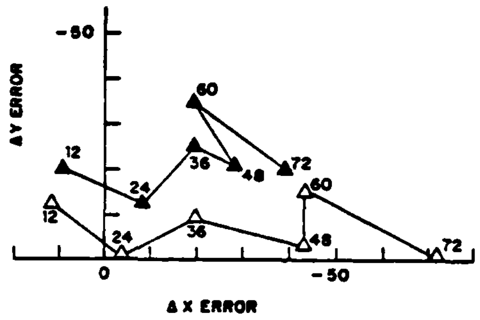
a. Description of the data sample

The model used in this experiment is the Two-Way Interactive Nested Tropical Cyclone Model (NTCM). Recent NTCM performance evaluations have been made by Harrison (1981), Harrison and Fiorino (1982) and Matsumoto (1981). In this study, the model is initialized with analysis fields, and verified with best track positions. The data base, kindly provided by M. Fiorino and E. Harrison of the Naval Environmental Prediction Research Facility (NEPRF), consists of 186 model runs on 36 storms.

The error bias characteristics of the forecasts in the data base are shown in Table 3, Fig. 5 and Fig. 6. The zonal error has a westward bias similar to, but smaller than, the TCM, and a small northward meridional bias. The right angle and speed bias reveals a tendency to forecast to the right of the best track (except at 72 h) and to be slow.

Backward integration tracks have not been run with the NTCM because of the expense of computer time for this many cases. The objective of this experiment is to use backward extrapolation positions in lieu of backward integration tracks, and yet improve the track forecasts by removing some of the systematic bias.

In these tests, the 186 cases are randomly divided into a 124-case dependent sample and a 62-case independent sample. In an attempt to provide similar error bias characteristics between the dependent and independent samples, several random samples were analyzed, and the samples which had the most comparable error biases were used. For this reason, different dependent and independent samples were chosen for the zonal-meridional scheme tests than for the storm-coordinate tests. It can be seen in Fig. 5 that the systematic zonal and meridional bias trend is similar between the dependent and independent samples. The independent



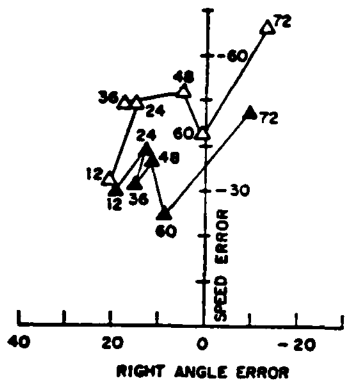


Fig. 5 Mean zonal (Δx) and meridional (Δy) errors (n.mi.) of NTCM dependent (Δ) and independent (▲) samples

Fig. 6 Mean right angle and speed errors (n.mi.) of NTCM dependent (Δ) and independent (▲) samples

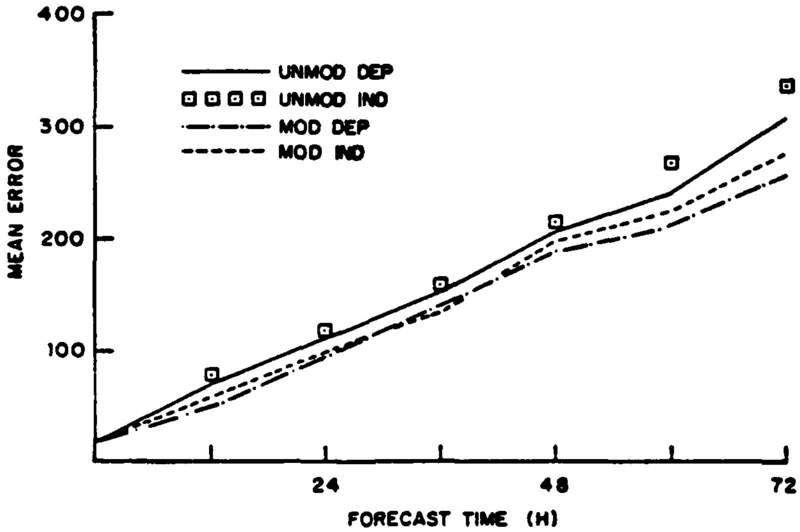


Fig. 7 Mean NTCM forecast errors (n.mi.) for 186 western north Pacific tropical cyclone cases. Mean errors are depicted for the unmodified (UNMOD) and zonal-meridional regression modified (MOD) dependent (DEP) and independent (IND) samples

sample, however, has a more negative meridional bias and, at later forecast times, a less negative zonal bias. The independent sample for the storm coordinate tests (Fig. 6) has a more negative speed bias and a more positive right angle bias at later forecast times, although the trend is again similar. These differences may indicate the necessity of a larger sample.

b. Zonal-Meridional Adjustment Test

Zonal and meridional regression equations were derived for the 124 case dependent sample using the backward extrapolation positions. The reduction in variance by the regression equations ranged from 12% to 41% and averaged 26%. This is considerably less than the reduction in variance by the TCM backward integration and backward extrapolation schemes. If the experience with the TCM tests is a valid guideline, a NTCM backward interpolation scheme may not be able to reduce significantly the variance. On the other hand, the smaller reduction in variance may indicate that the NTCM 12 h, 24 h and 36 h positions do not reveal as much information about the backward track bias as would a model integration.

The mean forecast errors (Fig. 7) of the independent sample are only slightly larger than those of the dependent sample from 12h to 48 h, but they are 27 nmi and 29 nmi larger at 60 h and 72 h. This may be another indication that the sample sizes are too small.

The regression scheme is very successful in reducing both the means and standard deviations of the zonal and meridional error biases in the independent sample (Table 4). This reduction is noteworthy considering the differences in these biases (shown in Fig. 5), and indicates that even though the regression equations are unable to reduce much of the variance, most of the systematic error in the sample is reduced by the equations.

TABLE 4

NTCM independent sample means ($\bar{X}$) and standard deviations (σ)(nmi) of zonal and meridional error bias before and after regression modification.

NTCM ERROR BIAS

Forecast Time (h)	Number of Cases	ZONAL $\bar{X}$	ZONAL σ	MERIDIONAL $\bar{X}$	MERIDIONAL σ
12	62	10	59	-21	64
24	62	-8	97	-14	97
36	62	-19	128	-25	127
48	62	-28	180	-21	164
60	54	-20	224	-35	192
72	53	-39	295	-20	229

REGRESSION ERROR BIAS

Forecast Time (h)	Number of Cases	ZONAL $\bar{X}$	ZONAL σ	MERIDIONAL $\bar{X}$	MERIDIONAL σ
12	62	-6	48	0	51
24	62	-4	86	4	84
36	62	-6	117	2	112
48	62	-1	170	10	152
60	54	4	194	-10	167
72	53	10	249	-8	184

The post processing decreases the mean forecast error (Fig. 7) of the dependent sample by 15-20 nmi from 12 h to 48 h, and decreases the error by 28 nmi at 60 h and 52 nmi at 72 h. The modified independent sample errors show the same error decrease from 12 h-48 h, and even more decrease at 60 h (38 nmi) and 72 h (61 nmi). Scatterplots of the unmodified independent sample forecast errors vs the regression modified forecast errors (Fig. 8) reveal that the regression scheme improves the forecasts of about 2/3 of the cases at 24 h, 48 h and 72 h. Thus, 1/3 of the NTCM forecasts are actually degraded by the regression correction. Better regression equations from a larger sample might be able to improve poor forecasts without degrading the good forecasts. It is also possible that more stratified samples (e.g. dependent on recent tracks) might be used for developing improved regression equations.

An alternative method of reducing the bias might be to simply add the mean bias value of a dependent sample to each case. However, because the error for a particular case is a function of track direction and speed, this 'direct bias removal' method does not necessarily produce improved forecasts, even though the bias is eliminated (Table 5). This indicates the advantage of using a statistical scheme to eliminate bias.

c. Storm-Coordinate Test

For this study, new dependent and independent samples were randomly chosen because the right angle and speed error biases of the previous samples are quite dissimilar. New predictors were defined to include the right angle and speed errors of the -12 h, -24 h and -36 h positions. Regression equations derived for the right angle and speed correctors of the new dependent sample show a 13% to 44% reduction of variance, and an average of 26%. The average variance reduction was about the same between the right angle and speed error equations, except that the 12 h position correctors of the right angle error reduced the

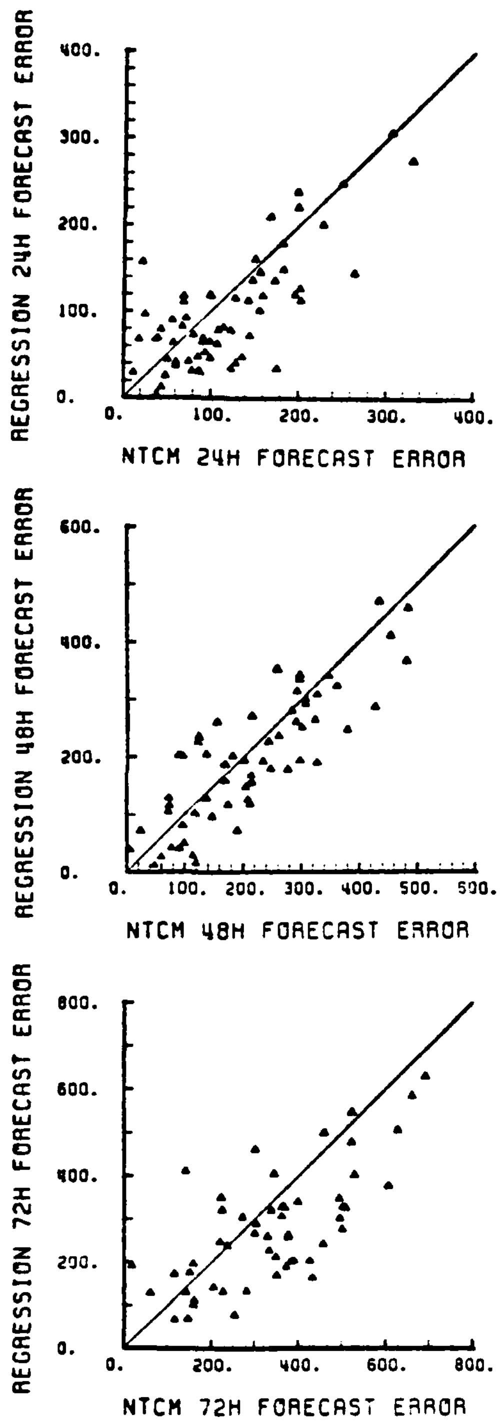


Fig. 8 Scatterplots of NTCM independent sample forecast errors (n.mi.) versus zonal-meridional regression modified independent sample forecast errors for a. 24 h forecast, b. 48 h forecast and c. 72 h forecast

TABLE 5

Mean NTCM forecast errors (nmi), zonal (Δx) error bias, and meridional (Δy) error bias before and after direct bias removal.

Dependent Sample

	Before Direct Bias Removal			After Direct Bias Removal		
Forecast Time	Forecast Error	Zonal Bias	Meridional Bias	Forecast Error	Zonal Bias	Meridional Bias
12	72	12	-13	70	0	0
24	112	-4	-1	112	0	0
36	154	-20	-9	153	-1	0
48	206	-43	-4	204	-1	0
60	242	-43	-15	237	-2	0
72	309	-71	-2	300	-3	0

Independent Sample

	Before Direct Bias Removal			After Direct Bias Removal		
Forecast Time	Forecast Error	Zonal Bias	Meridional Bias	Forecast Error	Zonal Bias	Meridional Bias
12	78	10	-21	75	-2	-7
24	118	-8	-14	118	-4	-13
36	157	-19	-25	156	0	-16
48	215	-28	-21	213	14	-17
60	269	-20	-35	266	22	-20
72	339	-39	-20	338	29	-19

variance by approximately 43% and the speed error correctors reduced the variance by only 14%. The right angle equations typically included as predictors the zonal displacement from the -12 h extrapolated position to the initial position and the right angle error of the -12 h position compared to the -12 h best track. The speed error equations typically included the meridional initial position to -24 h position displacement and the initial storm longitude. This may indicate that the speed error bias is mainly in the zonal track displacement and is dependent on how far west the storm is located.

The mean forecast errors of the new dependent sample are similar to the old sample, but the new independent sample has a much smaller error at 60 h and 72 h (Fig. 9). The regression scheme has little effect on the error of either the dependent or the independent samples from 12 h to 48 h, even though the bias is significantly reduced (Table 6). By 60 h and 72 h there is some improvement (32 nmi at 72 h for the dependent and 22 nmi for the independent) but the error reduction is still not as large as in the zonal-meridional scheme. It should be recalled that once the regression correctors for a position were determined, the ambiguity described in Section 3 had to be resolved to apply the correctors. Some of the forecast error is due to this factor. The regression modified tracks improve only half of the cases at 24 h and 48 h, and slightly more than half of the cases at 72 h (Fig. 10). The statistical scheme apparently cannot capture the error dependence in storm coordinates. Part of the reason for this is that an adjustment for speed error causes a change in the calculation of the right angle error. The interrelation between the speed and right angle errors makes this approach difficult to interpret.

The speed errors (Table 6) for the unmodified dependent and independent samples are almost constant from 12 h to 72 h, although the values are smaller for the independent sample. The right angle errors are generally small in both

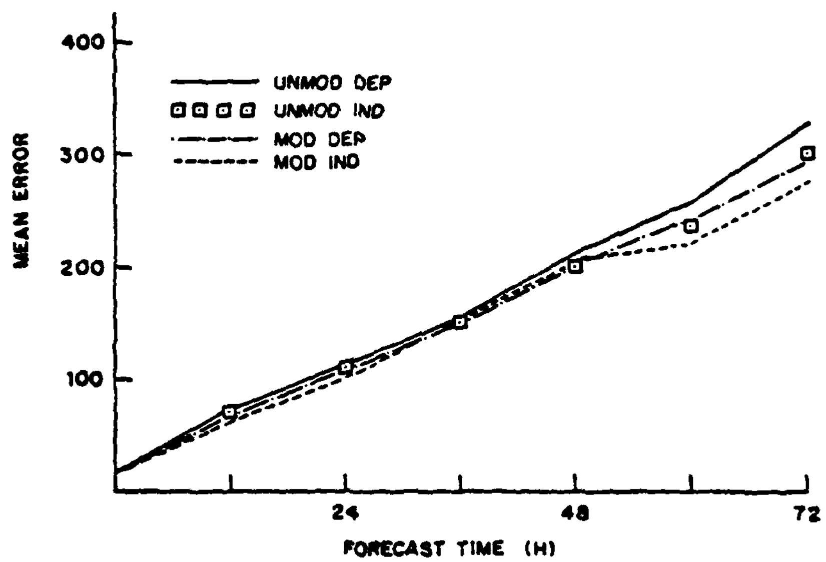


Fig. 9 As in Fig. 7, except for right angle/speed error regression scheme

TABLE 6

Mean NTCM error bias (nmi) before and after regression modification using right angle/speed error regression.

DEPENDENT

Forecast Time	Number of Cases	UNMODIFIED Right Angle	UNMODIFIED Speed	MODIFIED Right Angle	MODIFIED Speed
12	124	21	-33	6	-9
24	124	16	-50	-4	-10
36	124	17	-49	-4	-14
48	123	5	-52	0	-17
60	108	1	-42	-1	-18
72	106	-12	-67	-5	-18

INDEPENDENT

Forecast Time	Number of Cases	UNMODIFIED Right Angle	UNMODIFIED Speed	MODIFIED Right Angle	MODIFIED Speed
12	62	20	-30	9	-9
24	62	13	-40	-3	4
36	62	16	-31	1	10
48	62	13	-37	14	-1
60	54	10	-24	11	-9
72	53	-18	-47	-24	-35

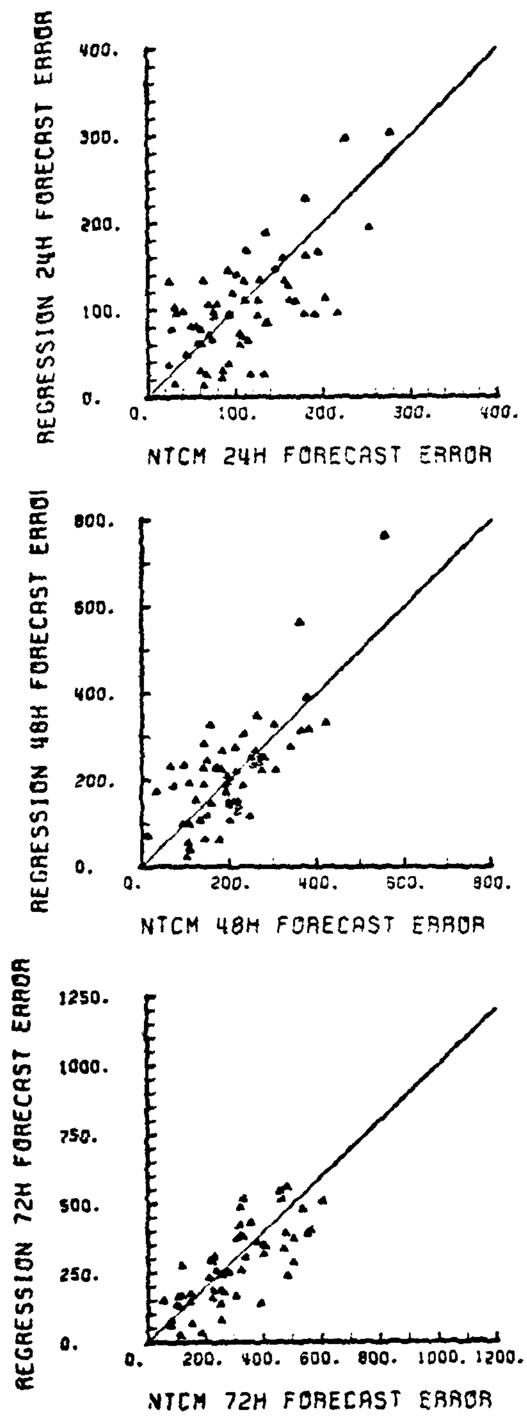


Fig. 10 As in Fig. 8, except for right angle/speed error regression

samples. It may be reasonable then to simply add right angle and speed correctors equal to the mean values. This was done using the dependent sample right angle and speed error mean value correctors on both samples (Table 7). The bias is reduced, but because of the ambiguity problem, there is still some bias after this direct bias removal. Furthermore, the forecast errors are made worse, indicating that a simple correction factor approach will not work.

d. Tests with 1981 Data

(1) Analysis cases

Both post-processing schemes have been tested with a new independent sample of 87 NTCM runs from the 1981 typhoon season. These cases are not the operational model forecasts initialized with 12 h forecast fields. Rather, they are the model runs initialized with analysis fields. Best track positions are not yet available for 1981 storms, so warning tracks have been used in the verifications.

New regression equations have been derived using all 186 cases from the previous dependent and independent samples. The reduction in variance by the equations ranged from 10% to 45% and averaged 27%. This is slightly more than the reduction in variance by the dependent sample alone.

The error bias characteristics of the 1981 cases is somewhat different from those of the 1975-1980 cases. The mean zonal and meridional errors of the new sample depicted in Fig. 11 may be compared with those in Fig. 12. The 12 h and 60 h errors are similar to the previous cases. The 24 h-48 h zonal errors are also about the same as before, but the meridional biases are the opposite sign. There is practically no bias in the new 72 h forecasts.

The mean forecast errors for the 1981 cases (Fig. 13) are generally larger than in the earlier sample (Fig. 7), except at 72 h. The zonal-meridional regression scheme provides a small improvement in the 12 h-36 h forecast errors, but degrades the forecasts from 48 h to 72 h. The regression equations, being

TABLE 7

Mean NTCM independent sample forecast error (nmi), right angle error bias, and speed error bias before and after direct bias removal.

Dependent Sample

Forecast Time	Before Direct Bias Removal: Forecast Error	Before Direct Bias Removal: Right Angle Bias	Before Direct Bias Removal: Speed Bias	After Direct Bias Removal: Forecast Error	After Direct Bias Removal: Right Angle Bias	After Direct Bias Removal: Speed Bias
12	75	21	-33	83	6	-10
24	116	16	-50	127	3	-11
36	156	17	-49	166	3	-10
48	212	5	-52	225	1	-9
60	258	1	-42	270	0	-8
72	329	-12	-67	350	-2	-13

Independent Sample

Forecast Time	Before Direct Bias Removal: Forecast Error	Before Direct Bias Removal: Right Angle Bias	Before Direct Bias Removal: Speed Bias	After Direct Bias Removal: Forecast Error	After Direct Bias Removal: Right Angle Bias	After Direct Bias Removal: Speed Bias
12	72	20	-30	77	5	-5
24	110	13	-40	121	0	0
36	153	16	-31	168	1	10
48	205	13	-37	220	9	6
60	238	10	-24	253	10	12
72	301	-18	-47	324	-9	7

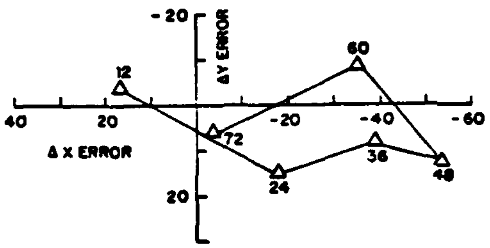


Fig. 11 Mean zonal (Δx) and meridional (Δy) errors (n.mi.) of 87 NTCM 1981 cases

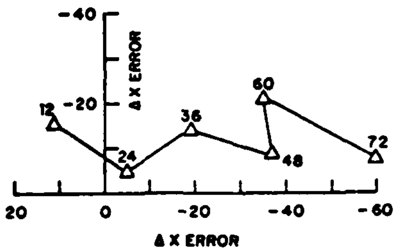


Fig. 12 Similar to Fig. 11 except for 186 NTCM 1975-1978 cases

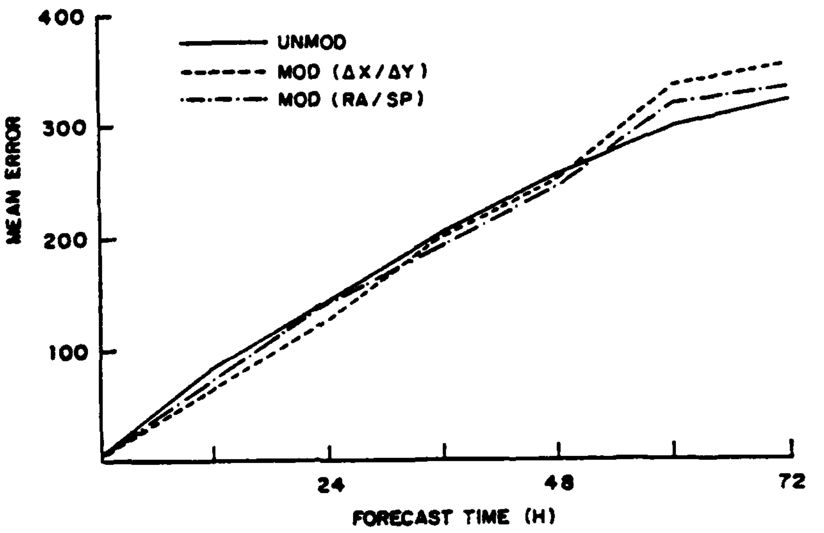


Fig. 13 Mean NTCM forecast errors (n.mi.) for 87 1981 cases; unmodified (UNMOD), and modified (MOD) with zonal-meridional regression equations (Δx/Δy) and with right angle/speed error equations (RA/SP) from the dependent sample

derived from the pre-1981 cases, always correct for error biases pertinent to that sample. When the biases deviate from their expected behavior, especially to the extent of being of the opposite sign as in these cases, the regression equations are correcting for the wrong errors.

The characteristics of the predictors are also different in the new cases. To illustrate, the zonal regression equation to correct for bias in the 60 h forecast is:

$$DXCR60 = 139.94-10.83\ XXLAT-0.91\ BYER12-8.85\ VX6072+13.10\ VY0012 \quad (1)$$

where DXCR60 = zonal correction (nmi) for 60 h forecast

XXLAT = initial storm latitude (degrees)

BYER12 = meridional error of the -12 h extrapolated position

VX6072 = zonal component of storm velocity from 60 h - 72 h

VY0012 = meridional component of storm velocity from 00 h - 12 h.

Since the equation is linear, it holds for average values of the variables as well. From the pre-1981 sample, XXLAT = 19.3, BYER12 = 19.4, VX6072 = 2.9, and VY0012 = 5.9. Using these values in (1), DXCR60 = -35.1 nmi which is a good prediction of the actual value of -35.8 nmi From the 1981 cases, XXLAT = 18.9, BYER12 = 26.6, VX6072 = -1.9, and VY0012 = 7.0 resulting in DXCR72 = +19.6 nmi which is an incorrect correction of the actual value of -35.8 nmi.

There is enough difference in the model performances on this season's storms to make the equations based on past performance inappropriate. This indicates a need for a larger sample of model runs from which to derive the regression equations. If a large enough sample is used, the equations should be able to account for small seasonal variations in model forecast characteristics.

(2) Operational Cases

Both post-processing schemes have been tested with a sample of 67 NTCM operational runs from the 1981 typhoon season. The model was initialized with 12 h forecast fields in these cases.

The error biases of these cases are considerably different from the biases of the pre-1981 cases (Fig. 16 vs Fig. 12 and Fig. 17 vs Fig. 15), especially in the meridional and speed error components. The forecast errors (Fig. 18) are progressively larger, and are approximately 170 nmi larger at 72 h. Because of these differences, the regression equations have generally detrimental effects on the forecast errors.

5. Tests of Post-Processing for the Operational TCM

a. Description of Data Sample

The Navy One-Way Interactive Tropical Cyclone Model (TCMO) forecasts during the 1980-1981 typhoon seasons had accuracies competitive with the NTCM (Matsumoto, 1981). However, if a systematic bias exists in the TCMO forecasts, a regression correction should provide even better forecast guidance.

A data base of 212 operational TCMO forecasts on 40 storms from 1979-1980 was kindly provided by T. Tsui of NEPRF for this study. The 12 h, 36 h and 60 h forecast positions were not archived by FNOC, so those positions have been interpolated to provide the 12-hourly positions needed to derive the backward extrapolation positions.

The TCMO forecast tracks tend to be west and slightly north of the storm track (Fig. 19 and Table 8). The small Δx biases at 12 h and 24 h, and the small Δy bias throughout the forecast, indicate that the Shewchuk-Elsberry adjustment scheme effectively corrects for the meridional bias and 00-24 h zonal bias. In storm coordinates, the model tracks are usually to the left of the actual track and are slow (Fig. 20 and Table 8). The random division of the data into

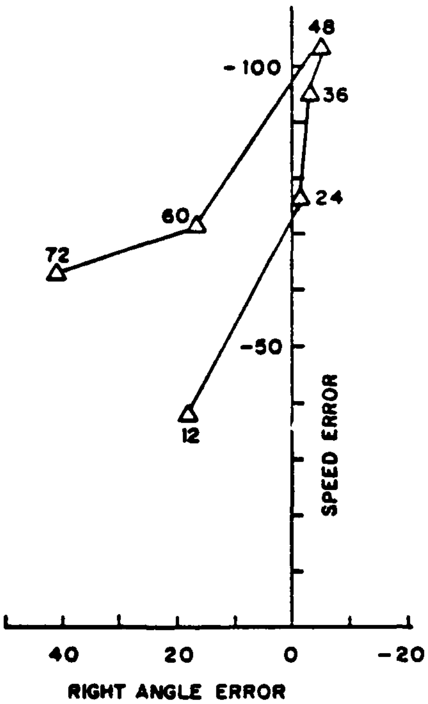


Fig. 14 Mean right angle and speed errors (n.mi.) of 87 1981 NTCM cases run from analysis fields

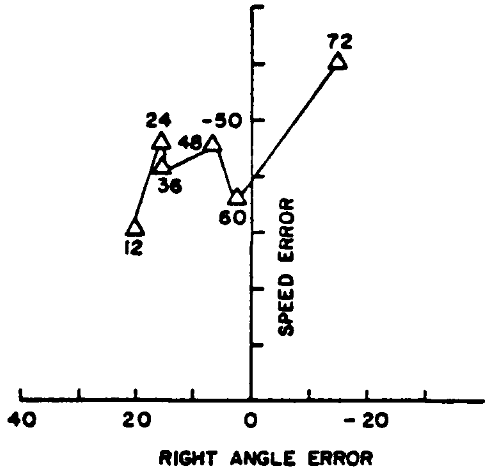


Fig. 15 Similar to Fig. 14 except for 186 NTCM 1975–1978 cases

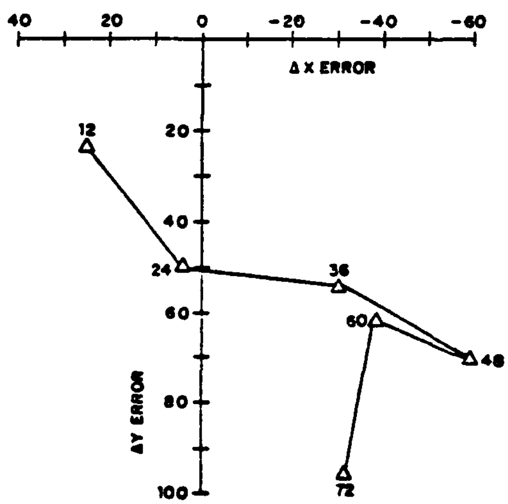


Fig. 16 Mean zonal (Δx) and meridional (Δy) errors (n.mi.) of 67 1981 NTCM cases run from 12 h forecast fields

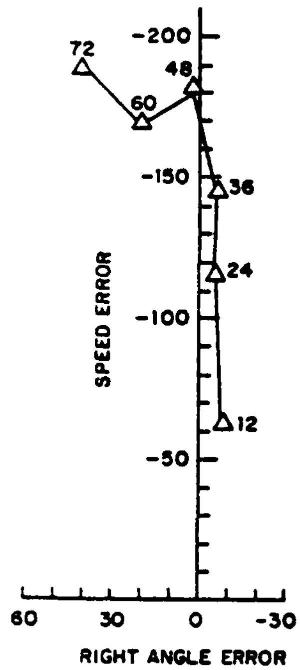


Fig. 17 Mean right angle and speed errors (n.mi.) of 67 1981 NTCM cases run from 12 h forecast fields

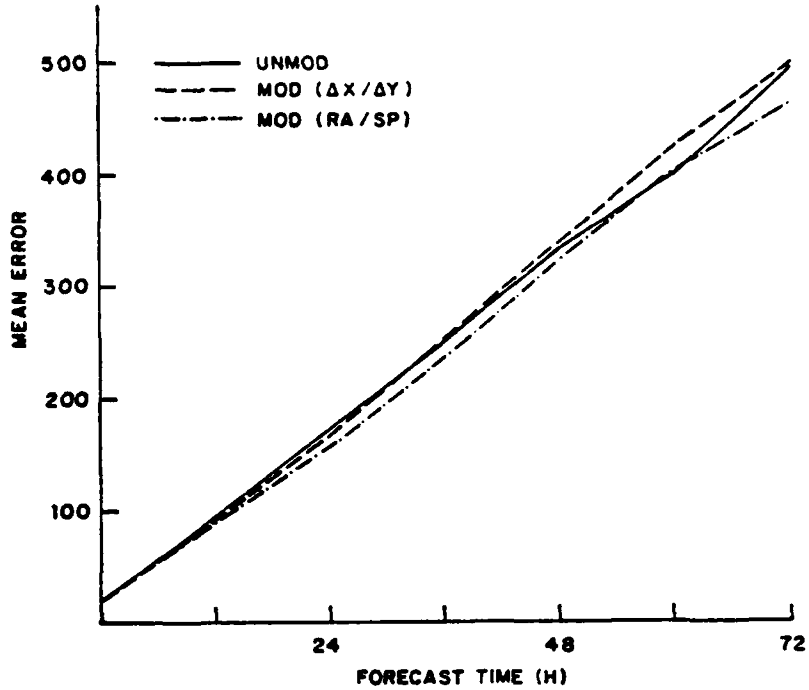


Fig. 18 Similar to Fig. 12 but for 67 1981 NTCM cases run from 12 h forecast fields

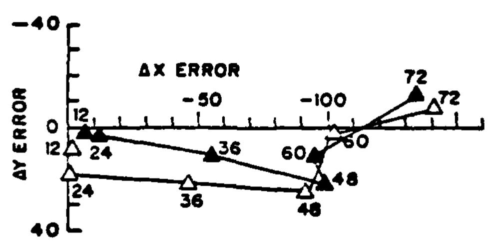


Fig. 19 Mean zonal (Δx) and meridional (Δy) errors (n.mi.) of TCMO dependent (Δ) and independent (▲) samples

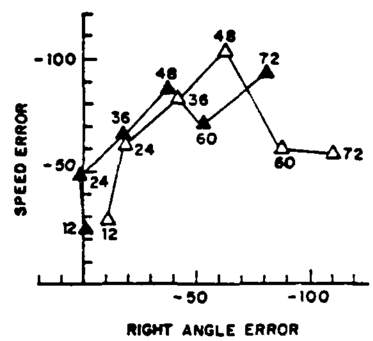


Fig. 20 Mean right angle and speed errors (n.mi.) of TCMO dependent (Δ) and independent (▲) samples

TABLE 8

Operational one-way interactive tropical cyclone model (TCMO) forecast errors (nmi), 12, 36 and 60 h positions interpolated.

Time	Number of Cases	Forecast Error	Zonal (Δx) Error Bias	Meridional (Δy) Error Bias	Right Angle Error Bias	Speed Error Bias
12	212	65	-4	7	-8	-28
24	212	119	-4	13	-12	-58
36	212	181	-49	19	-33	-75
48	212	253	-94	24	-55	-98
60	157	278	-101	6	-75	-64
72	157	355	-139	-0	-100	-72

TABLE 9

TCMO independent sample means ($\bar{X}$) and standard deviations (σ)(nmi) of zonal and meridional error bias before and after regression modification.

TCMO ERROR BIAS

Forecast Time (h)	Number of Cases	ZONAL $\bar{X}$	ZONAL σ	MERIDIONAL $\bar{X}$	MERIDIONAL σ
12	71	-6	58	2	45
24	71	-10	108	4	81
36	71	-55	160	12	129
48	71	-100	222	20	187
60	55	-96	254	11	183
72	55	-133	336	15	256

REGRESSION ERROR BIAS

Forecast Time (h)	Number of Cases	ZONAL $\bar{X}$	ZONAL σ	MERIDIONAL $\bar{X}$	MERIDIONAL σ
12	71	-2	44	-6	47
24	71	-7	74	-11	83
36	71	-5	118	-11	124
48	71	-14	198	-6	178
60	55	-14	238	13	193
72	55	-19	324	24	239

dependent (141 cases) and independent (71 cases) sets provided very well-matched bias characteristics in the zonal-meridional samples (Fig. 19) and well-matched right angle-speed error biases (Fig. 20).

b. Zonal-Meridional Correction Tests

Zonal and meridional regression equations were derived for the 141-case dependent sample using backward extrapolation positions. The variance reduced by the equations ranges from 8% to 45%, and averages 21%. The zonal equations generally resulted in a greater reduction in variance than did the meridional equations, except at 72 h.

The regression scheme decreases the forecast error of the dependent sample by 18 nmi, 35 nmi and 76 nmi at 24 h, 48 h and 72 h respectively (Fig. 21). The modified independent sample errors are decreased 16 nmi, 27 nmi and 37 nmi at 24 h, 48 h and 72 h. As in the NTCM tests, the independent sample error is decreased significantly, but the decrease is not as large. The decrease in zonal bias of the independent sample is considerable (Table 9). Furthermore, the standard deviations of the zonal and meridional errors are generally decreased by the regression modification. The track error after the regression correction is less than the unmodified track error in almost 2/3 of the 71 cases (Fig. 22).

The storm-coordinate scheme was also attempted for the TCMO tracks but produced average errors about the same or larger than the unmodified TCMO.

c. Tests with 1981 TCMO forecasts

Post-processing has also been tested with a new independent sample of 69 TCMO runs from the 1981 typhoon season. The 12 h, 36 h and 60 h positions were available in this case. Warning track positions were used for track verification.

The zonal error biases of these cases are similar to the previous cases (Fig. 23 versus Fig. 24), but are larger at 60 h and 72 h. The meridional bias

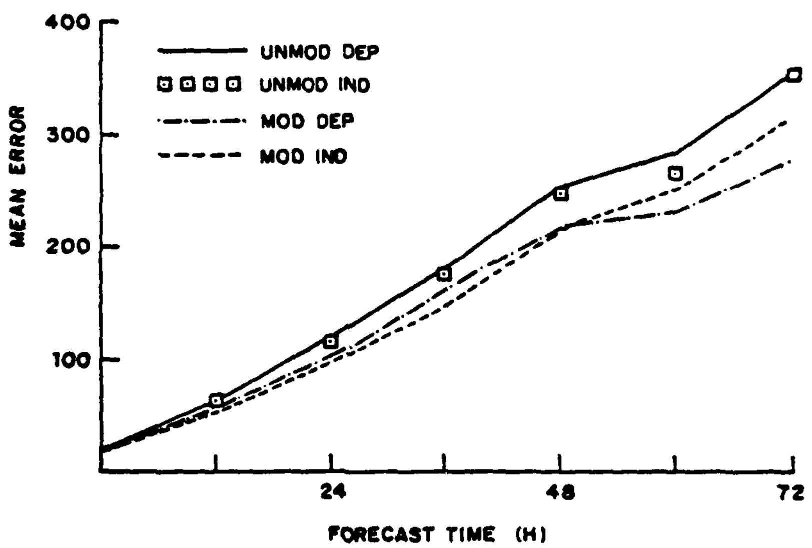


Fig. 21 Mean TCMO forecast errors (n.mi.) for 212 western north Pacific tropical cyclone cases. Mean errors are depicted for the unmodified (UNMOD) and zonal-meridional regression modified (MOD) dependent (DEP) and independent (IND) samples

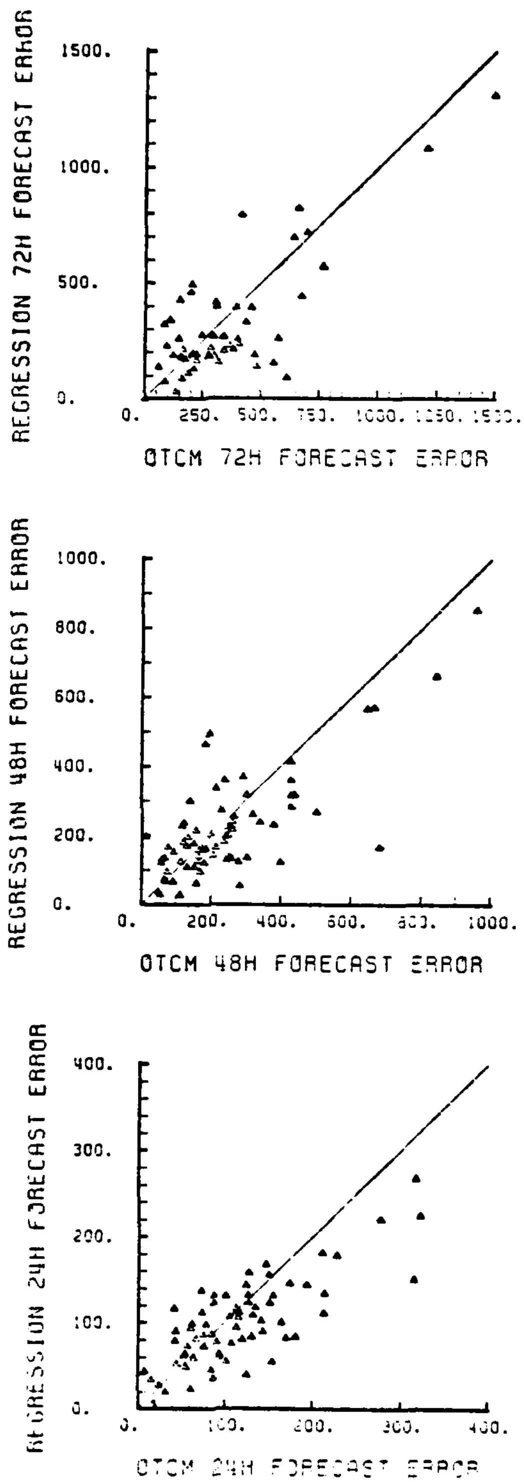


Fig. 22 Scatterplots of TCMO independent sample forecast errors (n.mi.) versus zonal-meridional regression modified independent sample forecast errors for a. 24 h forecast, b. 48 h forecast, and c. 72 h forecast

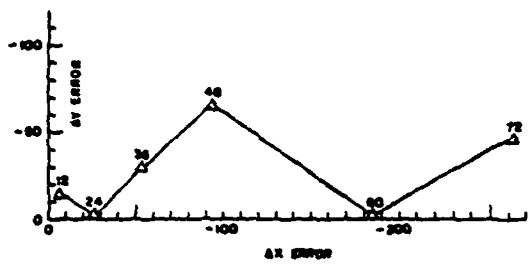


Fig. 23 Mean zonal (Δx) and meridional (Δy) errors (n.mi.) of 69 1981 TCMO cases

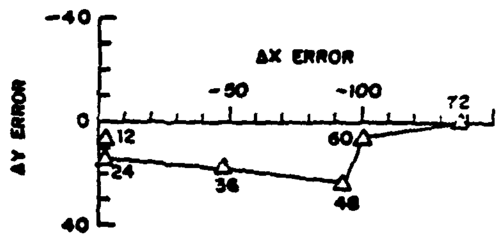


Fig. 24 Similar to Fig. 23 except for 212 TCMO 1979-1980 cases

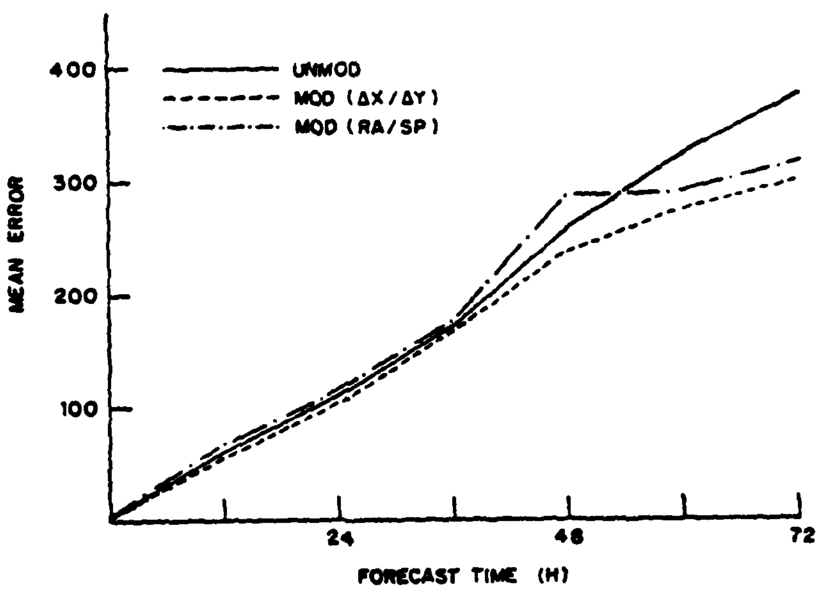


Fig. 25 Mean TCMO forecast errors (n.mi.) for 69 1981 cases; unmodified (UNMOD) and modified (MOD) with zonal-meridional regression euqations from the dependent sample

is larger and of the opposite sign at 36 h and 48 h. The forecast errors for the new sample are about the same as for the earlier runs (Fig. 25 versus Fig. 21). The differences in error bias keep the zonal-meridional regression equations from improving the forecasts from 12 h to 36 h, but they still are able to provide considerable improvement at 60 h and 72 h.

The storm-coordinate error biases for these 1981 cases are different from the 1979-1980 cases (Fig. 26 versus Fig. 27), especially the speed error from 48 to 72 h. Nevertheless, the forecast errors are reduced at 60 h and 72 h (Fig. 25) by about the same amount as the zonal-meridional scheme improvement.

6. Conclusions

A statistical technique using multiple linear regression equations to remove systematic bias in TCM track forecasts has been developed by Elsberry and Frill (1980). The value of the technique has already been established by Elsberry and Frill for an earlier version of the TCM, and for *HATRACK* (Elsberry, Gilchrist and Peak, 1981). The purpose of this report is to evaluate the applicability of the scheme to the TCMO and NTCM models.

The main disadvantage of the post-processing technique is the time and cost of integrating the model backward to determine -12, -24 and -36 h positions to be compared with the corresponding prior storm positions. This comparison is crucial in statistically determining the corrections to be made to the forward model forecast. A possible alternative explored here is to use simple backward extrapolation of the +36 h track forecast. This method is shown to provide the same HATRACK forecast accuracies as those which result from using backward integration positions. When tested with TCM tracks, the backward extrapolation scheme reduces the forecast errors by about 1/2 of the reduction made when using backward integration. This indicates some value in the correction scheme in an application to a dynamic model for which it is more costly to provide a backward integration.

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consistently. If the bias characteristics change from season to season, as the NTCM has in 1981, the regression scheme will result in a misapplication of the bias correctors. When the tropical cyclone models begin to be run from NOGAPS fields, rather than FNOC hemispheric model fields, there may be different biases and hopefully, smaller systematic errors than presently exist. From this study, it appears that post-processing of the tracks, using zonal and meridional correctors, will continue to improve the forecasts.

A method is devised for correcting right angle and speed error biases with the regression scheme. Because the definition of right angle and speed error is dependent on the best track position (the predictand in the scheme), there is some ambiguity when attempting to apply the regression correctors. Rules have been formulated to select the most likely of the ambiguous positions.

The zonal-meridional regression scheme with backward extrapolation decreases the NTCM and TCMO 72 h independent sample forecast errors by 61 nmi and 37 nmi respectively. If the TCM comparisons between backward extrapolation and backward integration are valid, then it can be expected that using backward integration positions would provide even more improvement.

Dynamical typhoon track models usually forecast storm paths better than storm speeds. Thus, it would be desirable to use the storm-coordinate scheme to correct for speed error bias. The tests with the scheme improved the NTCM 72 h independent sample forecast error by only 22 nmi. Apparently the storm-coordinate scheme cannot capture as much error bias dependence. The speed error regression equations typically include the 00 to -24 h zonal displacement and the initial storm longitude as predictors. This may indicate that a zonal correction scheme already accounts for the speed error bias, thus making a storm coordinate scheme unnecessary.

Analysis of some NTCM forecasts from the 1981 season reveals that the NTCM error bias is different from that displayed during previous seasons. The regression scheme does not reduce forecast errors in this sample, because the differences in model bias and predictor values tend to invalidate the regression equations. This seems to indicate the need for a larger sample size.

Although the zonal-meridional scheme provides encouraging results, there are limitations to its use. Storms must have a 36 h history, the model forecast must extend at least to +36 h, and most importantly, the model must perform

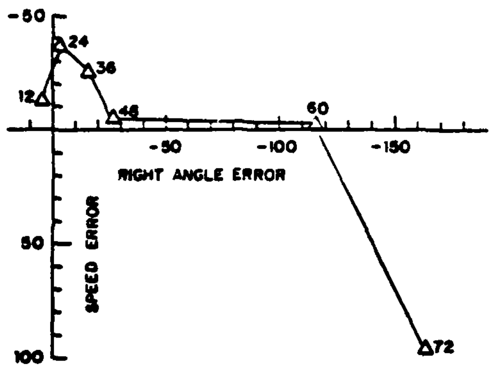

Fig. 26 Mean right angle and speed errors (n.mi.) of 69 1981 TCMO cases

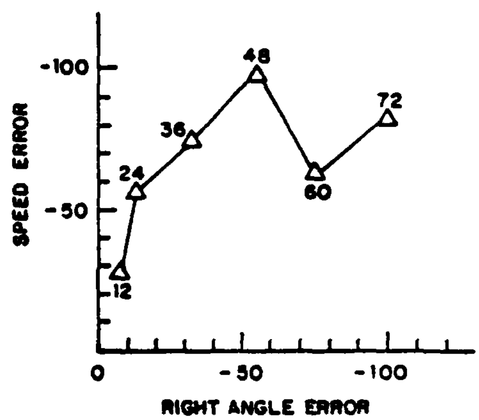

Fig. 27 Similar to Fig. 26 except for 212 TCMO 1979-1980 cases

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