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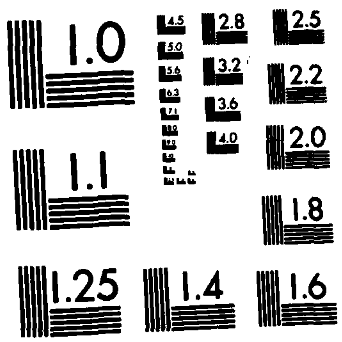
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SOUTHERN HEMISPHERE APPLICATION OF THE NAVY NESTED TROPICAL CYCLONE MODEL

James E. Peak
and
Russell L. Elsberry

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The Navy Nested Tropical Cyclone model is evaluated for performance on southern hemisphere storms in the Australian region. East of 135°E the model exhibits mean forecast errors of 246, 467 and 694 km at 24, 48 and 72 h, respectively. West of 135°E the mean forecast errors are 214, 511 and 745 km at 24, 48 and 72 h. The NTCM tends to have a poleward directional bias in the predicted tracks. This bias may be attributed to the lack of current data, which causes the analysis scheme to revert to climatological values.

The NTCM also did not forecast storm tracks well near the Australia coast, especially in the western cases, presumably due to lack of consideration of land/sea effects.

In a homogeneous sample comparison with TYAN78, the NTCM performed worse in terms of forecast error at early forecast times and better at late forecast times east of 135°E. West of 135°E, the model performance is generally poorer than the analog scheme at all forecast times.

The regression post-processing technique of Peak and Elsberry (1981) when applied to the NTCM forecasts results in a reduction of the eastern region sample forecast errors by as much as 150 km at 72 h. The western region forecast improvement is even greater, such that the regression modified NTCM forecasts are superior to TYAN78 in both test regions.

TABLE OF CONTENTS

A

LIST OF FIGURES

LIST OF TABLES

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1. Introduction

Tropical cyclone forecasters have in the past relied primarily on analog and statistical-climatological aids for objective guidance. More recently, dynamical models have provided routine guidance for most northern hemisphere tropical cyclones. Development of these dynamical models has progressed such that dynamical guidance appears to be comparable or superior to the official forecasts, especially beyond 24 h (Elsberry, 1979).

Southern hemisphere tropical cyclone forecast aids generally have been patterned after those used in the northern hemisphere. Such techniques are hampered by a deficiency of atmospheric data near the tropical cyclone and in the surrounding region. Aircraft reconnaissance has only recently been attempted on southern hemisphere storms, so that the locations of the storm centers are less accurate than for Atlantic and western north Pacific tropical cyclones.

Among the current southern hemisphere forecast aids is an analog method used by the Joint Typhoon Warning Center called TYAN78 (Ocean Data Systems, Inc., 1978), which is an updated version of the earlier analog scheme (Jarrell and Wagoner, 1973). Brand and Blelloch (1976) developed a simulated analog technique called SWPAC which is similar to a climatology and persistence model which is used by the National Hurricane Center for Atlantic storms. The Australian Bureau of Meteorology has developed an analog scheme called CYCLOGUE as part of its operational guidance (Annette, 1978). Chong et. al. (1980) devised a regression scheme which provided forecasts with smaller errors than the official Australian Bureau predictions. There are currently no operational dynamical model forecasts made for southern hemisphere tropical cyclones.

The Joint Typhoon Warning Center (JTWC) at Guam was recently tasked to expand its area of forecast responsibility to include tropical cyclones in the southern hemisphere. JTWC currently uses the analog and statistical/climatological aids including TYAN78 as guidance in preparing these forecasts. The success of dynamical models in predicting northern hemisphere tropical cyclone tracks (Harrison, 1981; Harrison and Fiorino, 1982) indicates a potential for improving forecasts in the southern hemisphere as well.

During the 1982-1983 storm season, JTWC will begin operational testing of the Navy Nested Tropical Cyclone Model (NTCM) on southern hemisphere storms. This paper presents an evaluation of the NTCM performance for selected storms in the Australian region during the period of 1975-1980. These results should provide a basis for estimating the performance of the model when it becomes operational in the southern hemisphere tropical cyclone basins. Another objective of this paper is to determine whether the operationally-analyzed wind fields in the data-sparse southern hemisphere are adequate to support a dynamical tropical cyclone model. One might expect the southern hemisphere storms to be more difficult to predict because of the early recurvature and rapid poleward motion of many of these storms. On the other hand, one expects that a dynamical model is more likely to be capable of predicting this type of motion than are the statistical and analog techniques. This potential provides the motivation for testing the dynamical model in the southern hemisphere.

2. The model

The NTCM is a three-layer, primitive-equation model with a moving, two-way interactive fine mesh grid embedded in a coarse grid channel. Details of the NTCM are given by Harrison (1973, 1981). The model is currently used for predicting tracks of north Pacific Ocean tropical cyclones.

To facilitate comparisons with the northern hemisphere version, the model used in this study was chosen to be identical to the northern hemisphere version, except for the trivial changes necessary for the southern hemisphere application. These changes include the direction of the bogus vortex spin and the sign of the Coriolis parameter. Another modification became necessary due to the grid structure of the tropical analysis that is available to initialize the model. The Fleet Numerical Oceanography Center (FNOC) global band analysis is performed on a Mercator projection from 60°N to only 40°S. If the southern hemisphere application was simply a mirror image of that in the northern hemisphere, all storms south of 13.6°S would cause the relocation of the coarse mesh grid to extend beyond 40°S. As the southern edge of the coarse mesh grid must be limited to 40°S, the initial fine mesh grid position that is centered on the storm location is not constrained to be initially at the same coarse mesh location, as is the case in the northern hemisphere application. In particular, the initial position of the fine mesh grid is allowed to be considerably closer to the poleward boundary to fit the coarse grid within the global band domain. Fortunately, the vast majority of the southern hemisphere tropical cyclones experience a rapid decay well before they approach the southern boundary of the domain.

The sensitivity of the model to a fixed coarse mesh boundary at 40 degrees latitude was tested for three northern hemisphere cases. An example (Fig. 1) illustrates that the predicted track with a hypothetical 40°N coarse grid limit begins to depart significantly from the standard model forecast after only 24 h of integration. The reason the effects are felt so quickly is that the application of a free-slip wall boundary condition during the initialization and during the integration distorts the wind and geopotential fields some distance from the poleward edge of the domain. When the wall is placed closer to the initial storm location, a poleward moving storm comes into the modified flow region earlier. Later in the integration, the wall effect becomes more noticeable as the boundary condition on the coarse mesh grid tends to inhibit flow normal to this boundary. As a consequence, the storm must eventually move parallel (either eastward or westward) to the wall. Fortunately, this fixed southern boundary at 40°S will no longer be a problem since the global band analysis is currently being extended to cover the entire globe. One might expect that the predictions based on these fields will be superior to the tests reported here, because the initial position of the poleward boundary can be placed as far away as desired from the tropical cyclone center.

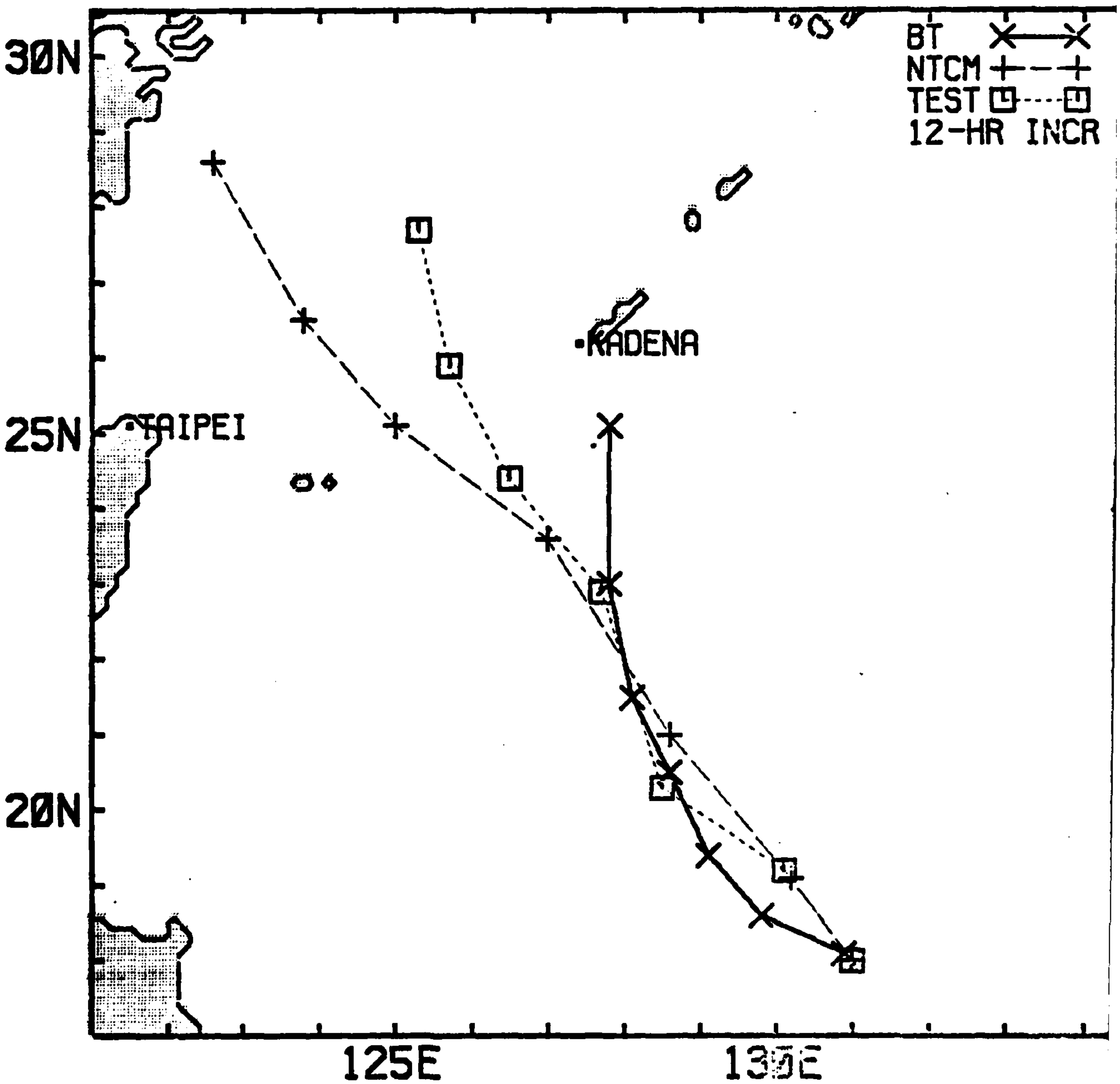

Fig. 1. NTCM forecasts for typhoon Tip at 00 GMT 15 Oct. 1979 from the standard northern hemisphere model (labelled NTCM) and the shifted fine mesh grid version limiting the coarse mesh grid to 40°N (labelled TEST).

3. Model performance.

The NTCM was tested on 185 cases from 34 storms in the Australian region which occurred during 1975-1979. An attempt was made to select cases on a random basis, however, the availability of archived FNOC data fields for the model initialization dictated to some extent which cases were selected.

A. Storms east of 135°E.

Mean error statistics for the cases east of 135 E are given in Table 1. The forecast error is defined as the distance between the forecast position and the corresponding best track position. The NTCM performance as measured by forecast error for these cases is not as good as in the northern hemisphere where the forecast errors are on the order of 210, 390 and 585 km at 24, 48 and 72 h, respectively (Harrison and Fiorino, 1982). The NTCM performance appears to be comparable or slightly superior to Brand and Blelloch's (1976) SWPAC analog technique (243, 501 and 748 km forecast error at 24, 48 and 72 h respectively), and to Annette's (1978) CYCLOGUE analog (272, 575 and 713 km forecast error at 24, 48 and 72 h respectively). It should be emphasized that the error statistics for these analog schemes are based on much smaller sample sizes (SWPAC had 41, 40 and 25 cases at 24, 48 and 72 h respectively; CYCLOGUE had 43, 22 and 21 cases at 24, 48 and 72 h, respectively). Because the samples are different, one must excercise caution in interpreting these error statistics.

In evaluating the model performance, it is useful to consider not only the magnitude of the forecast error, but also how that error compares to the actual distance the storm has moved. For example, a forecast with a 72 h error of 200 km may be considered good if the storm has moved 500 km during that period. However, the same 200 km error might be regarded as a poor forecast if the storm has moved only 100 km. The observed distance (Fig. 2), a measure of how far the storm has moved, is the distance between the best track position and the initial storm position. Notice that this is always smaller than the length of the storm trajectory, because of the curved path between the two endpoints.

Table 1. Mean error statistics for southern hemisphere NTCM cases east of 135°E.

	24h	48h	72h
Forecast error FE (km):	246	467	594
Observed distance OD (km):	307	565	833
Ratio FE/OD:	.30	.83	.33
Right angle error (km):	147	314	460
Speed error (km):	172	233	434
Number of cases:	113	115	114

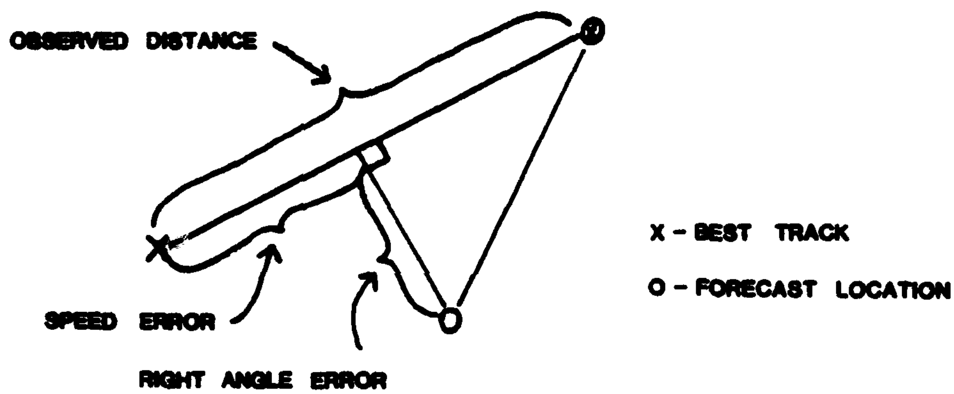

Fig. 2. Schematic illustration of observed distance, right angle error and speed error definitions.

If the ratio of the mean forecast error (FE) to the mean observed distance (OD) is less than 1, some skill in forecasting may be said to exist. In the northern hemisphere, the NTCM exhibits FE/OD values of .58, .55 and .60 at 24, 48 and 72 h which can be regarded as a 40-45% skill in forecasting. For these southern hemisphere cases, the NTCM forecasts have only a 17-20% skill.

The right angle error (Fig. 2) is defined as the normal distance from the forecast position to the line connecting the initial and best track positions. Thus, it is a measure of how well the model predicts the direction of the storm motion. The distance along this line from the best track to the intersection with the right angle error line is defined as the speed error (Fig. 2), because it measures the displacement error that results from the incorrect prediction of storm translation speed. The NTCM has a smaller right angle error than the speed error at 24 h (Table 1), but has a smaller speed error than right angle error at longer forecast times.

Neal (1977) defined five categories of southern hemisphere storm motion: southeastward, southwestward, recurvature to the southeast, recurvature to the southwest, and looping motion. Table 2 summarizes the NTCM performance according to these storm motion categories. Each case is placed into a particular category according to the subsequent 72 h best track, rather than its complete history. Thus, a forecast case from the early stages of an eastward recurving storm which later fits into category 3 may first have been classified in category 2. The NTCM performs best, in terms of the FE/OD ratio, when the storm is moving to the southwest (category 2). One such forecast is presented in Fig. 3. The model was able to predict both kinds of recurving storms (categories 3 and 4) moderately well. The worst model performance was in cases of looping storms (category 5). In these cases, the poor FE/OD ratio can be partially attributed to the small observed distances of looping storms rather than to large forecast errors. Storms moving to the southeast (category 1) were also handled poorly.

The right angle and speed error biases reveal some of the NTCM systematic error characteristics. The forecasts generally exhibit

Table 2. Summary of NTCM performance east of 135°E according to categories of storm movement (best track) defined by Neal (1977). The relationship of the 72h prediction to the best track is indicated in column 1 by a ●P symbol.

	Movement Category	% of Cases	Average FE/OD	Right Angle Error Bias	Speed Error Bias
1.		18	1.08	strongly right of best track	slow
2.		42	0.63	slightly left of best track	slow
3.		20	0.82	left (12-36h) right (48-72h)	slow
4.		7	0.81	left of best track	slow
5.		13	1.35	right (12-48h) left (60-72h)	slow

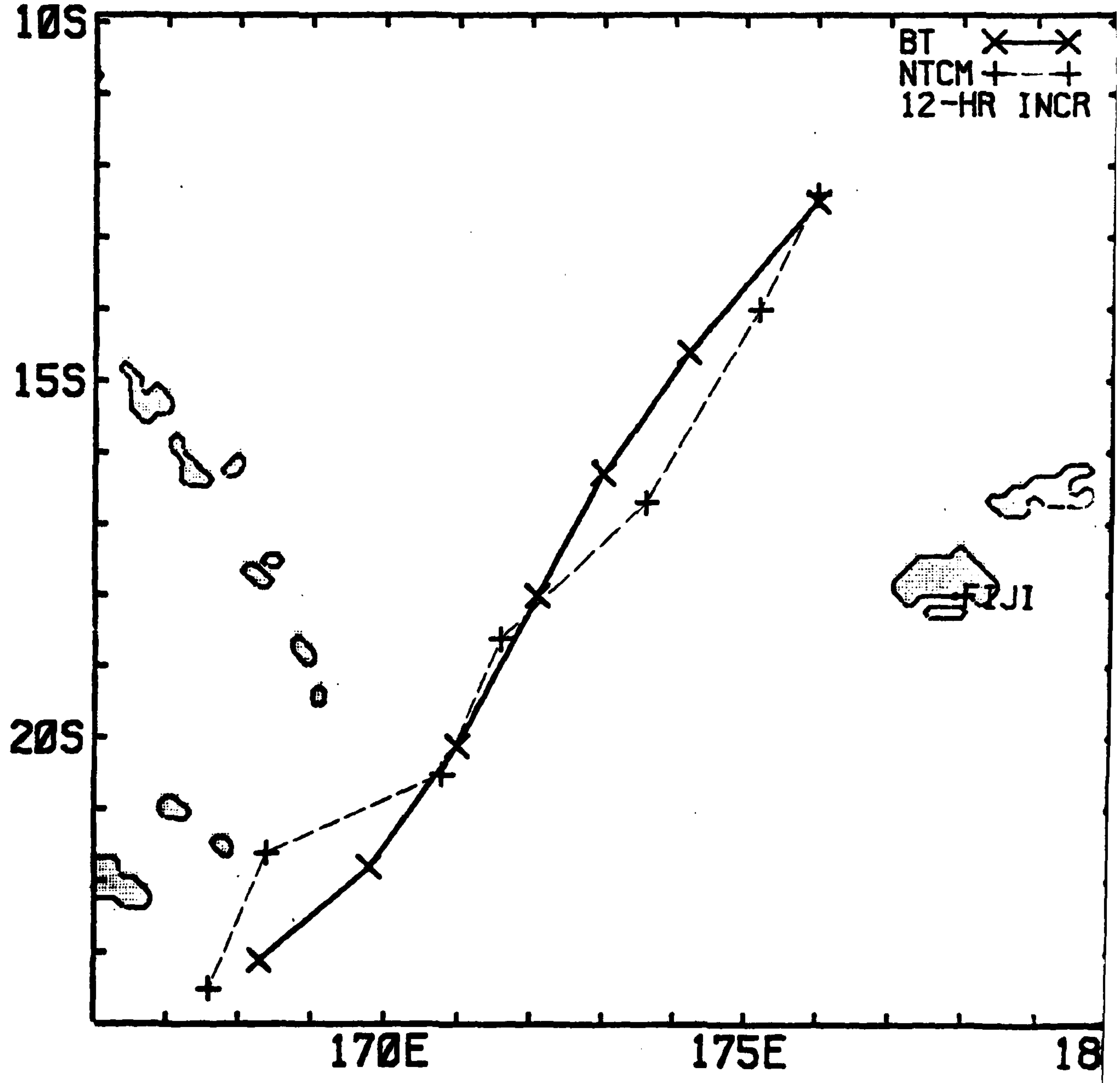

Fig. 3. NTCM forecast for cyclone Bob at 12 GMT 3 Jan. 1978.

a poleward bias in direction and slow translation speeds. This slow tendency is more severe than for the northern hemisphere version, which also predicts storm direction very well (Harrison, 1981; Fiorino and Harrison, 1982).

The difference in performance between the two hemispheres may be due to the paucity of atmospheric data available for the FNOC southern hemisphere analyses. If data are sparse, the resulting analysis fields are based mostly on climatology. The mean summer southern hemisphere upper atmosphere (for example, Palmen and Newton, 1969) is characterized by a subtropical ridge extending from 160°E to 170°W which produces a southward or southwestward environmental flow in the eastern Australia region. The persistent presence of this climatological feature in the model data could cause the poleward track direction bias. Such a steering flow would also indicate why the model does well with category 2 storms but not with category 1 storms.

B. Storms west of 135°E

The mean error statistics for the cases west of 135°E are given in Table 3. The forecast errors are smaller at 24 h and larger at 48 h and 72 h compared to the eastern region cases (Table 1). Notice also that the forecast error/observed distance ratio shows comparable skill at 24 h but has values exceeding 1.0 at 48 h and 72 h. The NTCM did not perform as well as the SWPAC analog (179, 389, and 595 km forecast error at 24, 48 and 72 h for 92, 92 and 66 cases) (Brand and Blelloch, 1976), or the CYCLOGUE analog at forecast intervals other than at 24 h (276, 481 and 623 km error at 24, 48 and 72 h for 74, 55 and 32 cases) (Annette, 1978). As pointed out by Neal (1977), 73% of the storms in the western Australia region move to the southwest or recurve to the east versus only 39% of those in the eastern region. Thus, the storm tracks in the western area are more uniform in behavior which is an advantage for analog methods in this region.

It can be seen from the right angle and speed errors that the NTCM model predicts speed of translation better than direction. Compared to the eastern region cases, the decrease in forecast

Table 3. Mean error statistics for southern hemisphere JTWC cases west of 135°E.

	24h	48h	72h
Forecast error FE (km):	214	511	746
Observed distance OD (km):	266	467	728
Ratio FE/OD:	.81	.99	1.02
Right angle error (km):	155	395	616
Speed error (km):	121	237	300
Number of cases:	66	64	54

error at 24 h is associated with an improved speed error, and the poorer performance at later forecast times is due to an increased right angle error.

Almost half of the cases in the western region sample were storms which skirted along the northwest coast of Australia. One such case is presented in Fig. 4. The NTCM has a very strong bias to the left in these cases, which accounts for much of the forecast error in the sample. The poor performance of the NTCM in these cases is somewhat surprising, since the NTCM handled this track type (Table 2, category 2) very well for the storms east of Australia. If the steering motion in the model data is correct in these cases, then onshore motion of these cases should result. One would expect rapid decay of the storms in such events. In the actual cases, the storms do not move onshore, apparently because that portion of the circulation which remains over the warm ocean heat source is sustained. Thus, there may be a propagation of the circulation along the coast due to continued redevelopment over this area. The NTCM would be unable to simulate this process since it does not include such differential heating due to land/ocean effects.

C. Comparison with TYAN78

The Joint Typhoon Warning Center in Guam has used an analog method named TYFOON since 1970. The scheme has since undergone several updates and modifications, the most recent of which is called TYAN78. The scheme currently provides guidance for the northwest Pacific, northeast Pacific, southwest Pacific, southwest Indian and north Indian Ocean regions. Records of TYAN78 performance in the southwest Pacific are not available. Recent performance of the analog in the northwest Pacific region indicates average forecast errors of 240, 450 and 685 km at 24, 48 and 72 h, respectively (Annual Typhoon Report, 1979; Annual Tropical Cyclone Report, 1980-1981).

To evaluate NTCM performance versus TYAN78 in the southwest Pacific region, the analog technique was run for the cases in the NTCM sample. Because TYAN78 requires 48 h of previous positional data, some cases could not be run. These cases have been removed

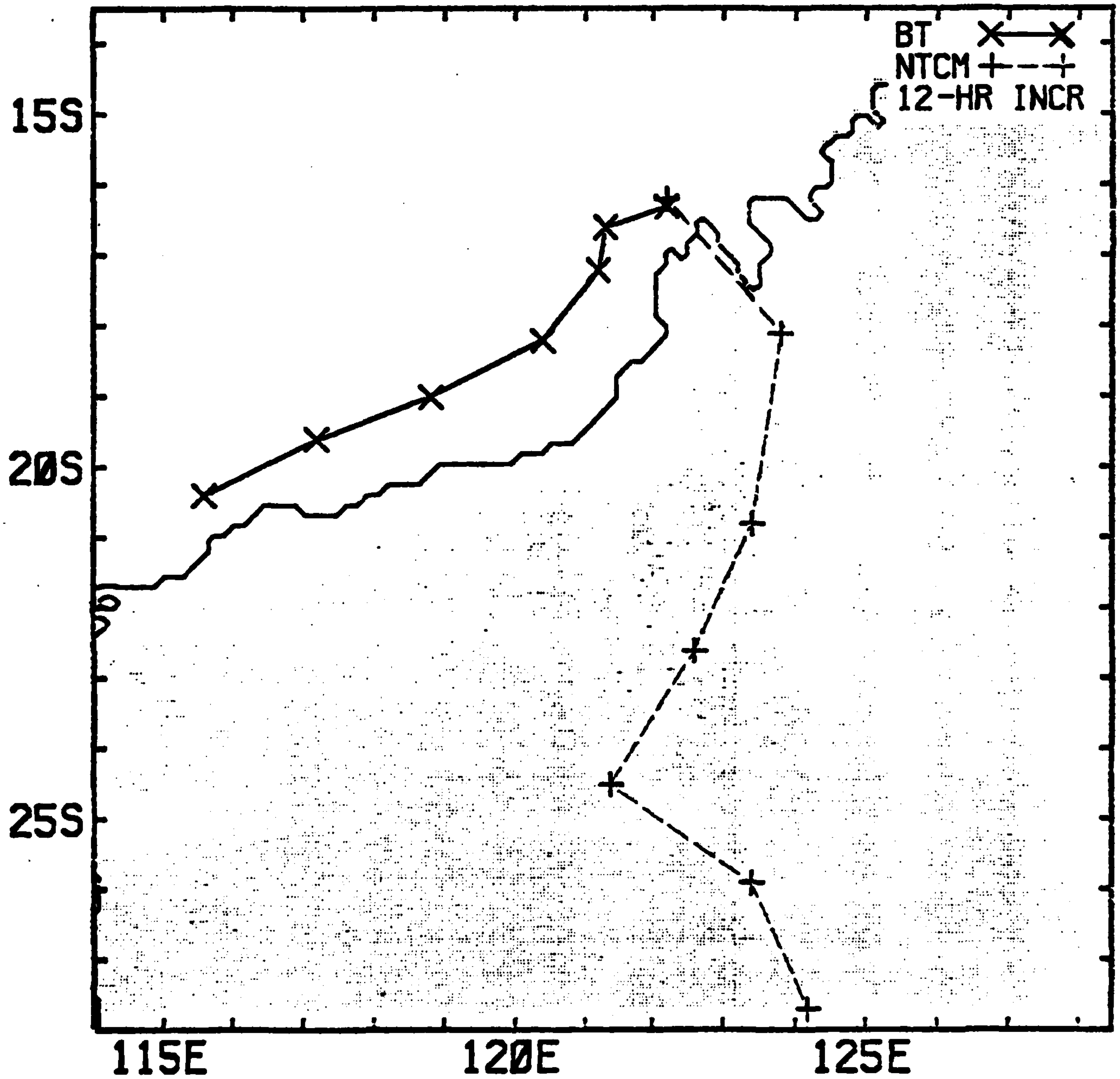

Fig. 4. NTCM forecast for cyclone Trixie at 00 GMT 16 Feb 1978.

from the NTCM sample, as were cases for which analogs could not be found on the record tapes. Thus, the following comparisons are for a homogeneous sample.

The mean error statistics for the NTCM and TYAN78 cases east of 135°E are presented in Table 4. The number of cases available for comparison is considerably smaller than for the original sample, especially at 72 h. The NTCM error statistics are similar to those of the total sample (Table 1) despite the smaller sample size. The analog method performs better in terms of the forecast error and FE/OD ratio than the NTCM at 24 h, about the same at 48 h, and worse at 72 h (Table 4). Thus, the analog method performs progressively worse as the forecasts move farther from the initial and 48 h history positions upon which they are based.

The mean NTCM and TYAN78 error statistics for a homogeneous set of cases west of 135°E are presented in Table 5. Again, the number of cases in the homogeneous sample is much smaller than in Table 3. The NTCM error statistics are somewhat degraded relative to those of the total sample (Table 3) especially at 48 and 72 h. Furthermore, the TYAN78 results are much better than the NTCM in terms of the forecast error and FE/OD ratios at all forecast times (Table 5). Thus, the TYAN78 performs as well on the western region cases as did the CYCLOGUE and SWPAC analog techniques.

The southern hemisphere TYAN78 performs much better on the western region cases than it generally did in the northern hemisphere. This may be due to the more uniform behavior of the western region cases as mentioned earlier, or else that the sample is too small for valid comparisons.

D. Comparison with TCWC official forecasts.

Records of official forecasts made by the Australian Bureau of Meterology Tropical Cyclone Warning Centres (TCWC) are not readily available. Annette (1978) included official and CYCLOGUE forecast error statistics for five storms during 1976-1977. Table 6 summarizes the NTCM preformance on these storms (minus tropical cyclone Ted, for which FNOC data were unavailable) versus the TCWC official forecasts and CYCLOGUE forecasts.

Table 4. Mean error statistics for a homogeneous sample of southern hemisphere NTCM and TYAN73 cases east of 135° E. NTCM statistics are to the left of the slash; TYAN73 to the right.

	24h	48h	72h
	---	---	---
Forecast error FE (km):	247/206	452/443	679/747
Observed distance OD (km):	335	611	875
Ratio FE/OD:	.74/.62	.74/.73	.78/.85
Right angle error (km):	149/139	310/334	439/573
Speed error (km):	173/129	272/256	436/408
Number of cases:	73	63	56

Table 5. Similar to Table 4 except for cases west of 135°E.

	24h	48h	72h
Forecast error FE (km):	213/197	543/397	767/626
Observed distance OD (km):	273	535	817
Ratio FE/OD:	.78/.72	1.01/.74	.94/.77
Right angle error (km):	148/126	462/276	[illegible]
Speed error (km):	126/125	195/235	231/349
Number of cases:	42	33	28

Table 6. Comparison of mean forecast errors (km) for 4 storms from 1977 (number of forecasts in parentheses). Statistics for the Tropical Cyclone Warning Centers (TCWC) and CYCLOGUE forecasts are from Annette (1978).

		12h FORECASTS			24h FORECASTS			36h FORECASTS	
Storm	Life-Span	TCWC	NTCM	CYCLOGUE	TCWC	NTCM	CYCLOGUE	NRM	CYCLOGUE
Irene	8-12/1/77	169(11)	103(6)	168(4)	262(7)	264(6)	205(4)	444(6)	292(3)
Keith	30/1-1/2/77	50(6)	121(3)	109(2)	58(2)	210(3)	201(2)	419(2)	248(1)
Karen	3-9/3/77	96(24)	97(10)	80(9)	208(8)	168(10)	150(8)	314(10)	217(8)
Leo	24-27/3/77	93(13)	123(7)	100(4)	212(4)	216(7)	154(3)	364(7)	126(2)
Total		105(54)	108(26)	106(19)	212(21)	204(26)	170(17)	368(25)	222(14)

The NTCM does as well as the analog technique at 12 h. However, CYCLOGUE performs progressively better at later forecast times, with especially noteworthy performance at 36 h for Karen and Leo. It should be noticed that all of these cases are in the proximity of the coast. Even so, the NTCM forecast errors are about the same as the official forecast errors at 12 and 24 h.

4. Post-Processing of Model Forecasts

Elsberry and Frill (1980) proposed a statistical technique for post-processing the tropical cyclone tracks of the FNOC Tropical Cyclone Model (TCM). The technique uses multiple linear regression equations to remove systematic bias in the TCM track forecasts. The predictors used in the equations are the storms' initial latitude and longitude plus various zonal and meridional components of the model-predicted storm displacement and velocity. The most important predictors are those which result from comparison of the best track with the forecast found by integration of the model backward in time.

Peak and Elsberry (1981) applied the same technique to the northern hemisphere version of the NTCM, but with backward extrapolation positions instead of backward integration positions. The technique decreased the NTCM 72 h forecast error by 110km. If systematic bias does exist in the southern hemisphere tracks, the same technique should improve the forecasts.

A. East of 135°E.

The error bias characteristics of the southern hemisphere NTCM forecasts east of 135°E are shown in Table 7. The number of cases is slightly smaller because those cases without a 36 h history are inappropriate for the postprocessing scheme and were removed. Thus, the forecast error for these cases is also slightly different from those of the total sample (Table 1). The zonal error bias (Table 7) indicates that the forecasts have a strong bias to the east of the best track, especially at 72 h. The meridional error bias indicates a slight southward bias at 36 and

Table 7. Means ($\overline{X}$) and standard deviations (σ) (km) of forecast error and zonal and meridional error biases of all southern hemisphere NTCM cases east of 135°E.

Forecast Time (h)	Number of Cases	Forecast Error	NTCM ERROR BIAS Zonal $\overline{X}$	Zonal σ	Meridional $\overline{X}$	Meridional σ
12	110	137	-36	113	0	97
24	110	249	-53	213	-4	168
36	110	367	-71	306	20	268
48	110	473	-59	402	29	342
60	110	581	-57	509	-5	403
72	110	700	-95	628	-54	439

48 h and a northward bias at 72 h. This is similar to the bias of the northern hemisphere version, although the zonal errors are larger, as is the 72 h meridional bias.

The 110 cases are randomly divided into a 73-case dependent sample and a 37-case independent sample. It can be seen in Fig. 5 that the systematic zonal and meridional bias trends are similar between the samples, although the zonal error is larger in the dependent sample and the 36-48 h meridional errors of the independent sample are positive. These differences may indicate the necessity of a larger sample.

Zonal and meridional regression equations were derived for the dependent sample. The reduction in variance by the regression equations ranged from 29% to 62% and averaged 47%. This reduction in variance is considerably greater than that of the regression equations derived for the northern hemisphere version (Peak and Elsberry, 1981). The regression scheme generally reduces both the means and standard deviations of the zonal and meridional error biases in the independent sample (Table 8). Some slight increases in bias result from the different bias characteristics of the samples.

The mean NTCM forecast errors of the independent sample with and without the regression adjustment are about the same as the comparable errors from the dependent sample (Table 9). The post-processing decreases the mean forecast error of the dependent sample by 63 km at 12 h to a maximum of 152 km at 72 h. The same error decrease occurs on the independent sample except for a smaller 122 km decrease at 72 h. Thus, the NTCM forecast errors with statistical post-processing are considerably less than for the TYAN78, SWPAC and CYCLOGUE analogs. The improvement in forecast error reduces the FE/OD ratio to .63, .62 and .69 at 24, 48 and 72 h. An example of the forecast improvement made by the regression scheme is presented in Fig. 6.

Scatterplots of the unmodified independent sample forecast errors (Fig. 7) reveal that the regression scheme improves the forecasts of almost 75% of the cases at 24, 48 and 72 h. Different bias characteristics between the dependent and

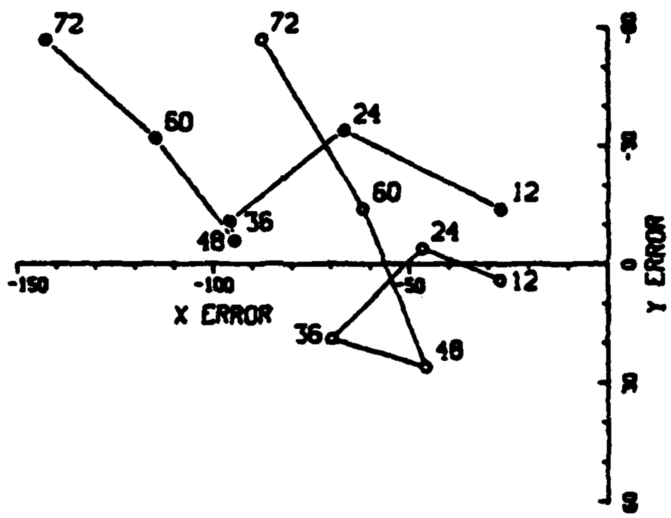

Fig. 5. Mean zonal (Δx) and meridional (Δy) errors (km) of NTCM dependent (○) and indepedent (●) samples for cases east of 135°E.

Table 8. Means ($\bar{x}$) and standard deviations (σ) (km) of southern hemisphere NTCM independent sample zonal and meridional error biases before and after regression modification for cases east of 135^{o}E.

Forecast Time(h)	Number of Cases	NTCM Zonal $\bar{x}$	NTCM Zonal σ	NTCM Meridional $\bar{y}$	NTCM Meridional σ	REGRESSION Zonal $\bar{x}$	REGRESSION Zonal σ	REGRESSION Meridional $\bar{y}$	REGRESSION Meridional σ
12	37	-27	123	-14	104	-2	59	-9	62
24	37	-67	229	-34	173	-30	161	-19	117
36	37	-96	330	-11	266	-33	260	-10	195
48	37	-95	432	-5	327	-47	353	[illegible]	230
60	37	-115	561	-32	374	-74	444	-25	26[illegible]
72	37	-143	701	-57	436	-41	579	-13	353

Table 9. Means ($\bar{x}$) and standard deviations (σ) (km) of southern hemisphere NTCM forecast errors before and after regression modification for cases east of 135°E.

DEPENDENT SAMPLE

Forecast Time(h)	Number of Cases	NTCM $\bar{x}$	NTCM σ	REGRESSION $\bar{x}$	REGRESSION σ
12	74	139	76	76	43
24	74	253	125	179	93
36	74	376	193	277	154
48	74	474	254	352	210
60	74	582	317	447	260
72	74	703	403	551	316

INDEPENDENT SAMPLE

Forecast Time(h)	Number of Cases	NTCM $\bar{x}$	NTCM σ	REGRESSION $\bar{x}$	REGRESSION σ
12	37	145	75	75	41
24	37	263	131	178	91
36	37	370	220	274	175
48	37	463	233	343	244
60	37	584	345	440	295
72	37	699	451	577	354

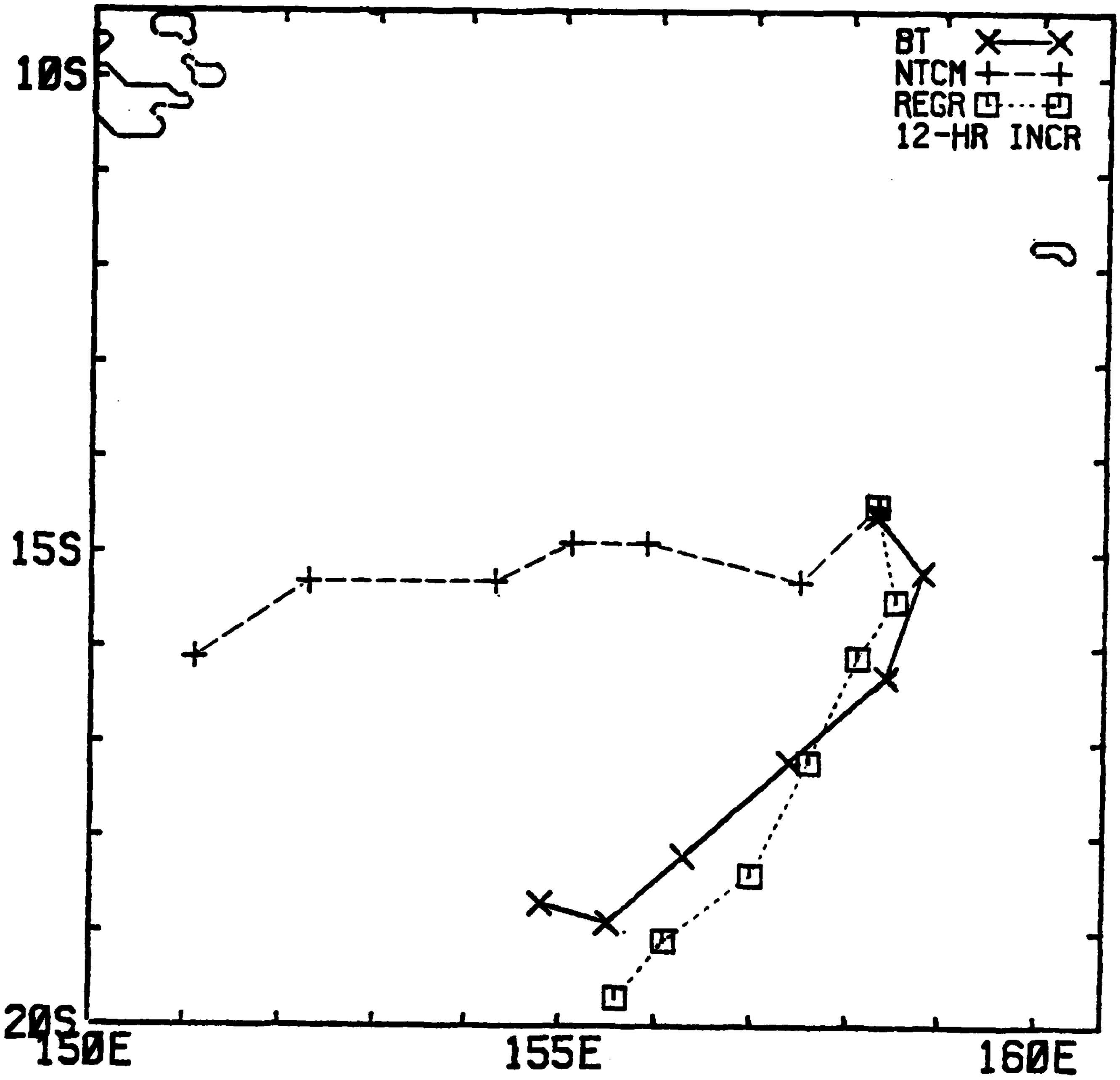

Fig. 6. Nested model (NTCM) and regression modified (REGR) forecasts for cyclone Kerry at 12 GMT 17 Feb. 1979.

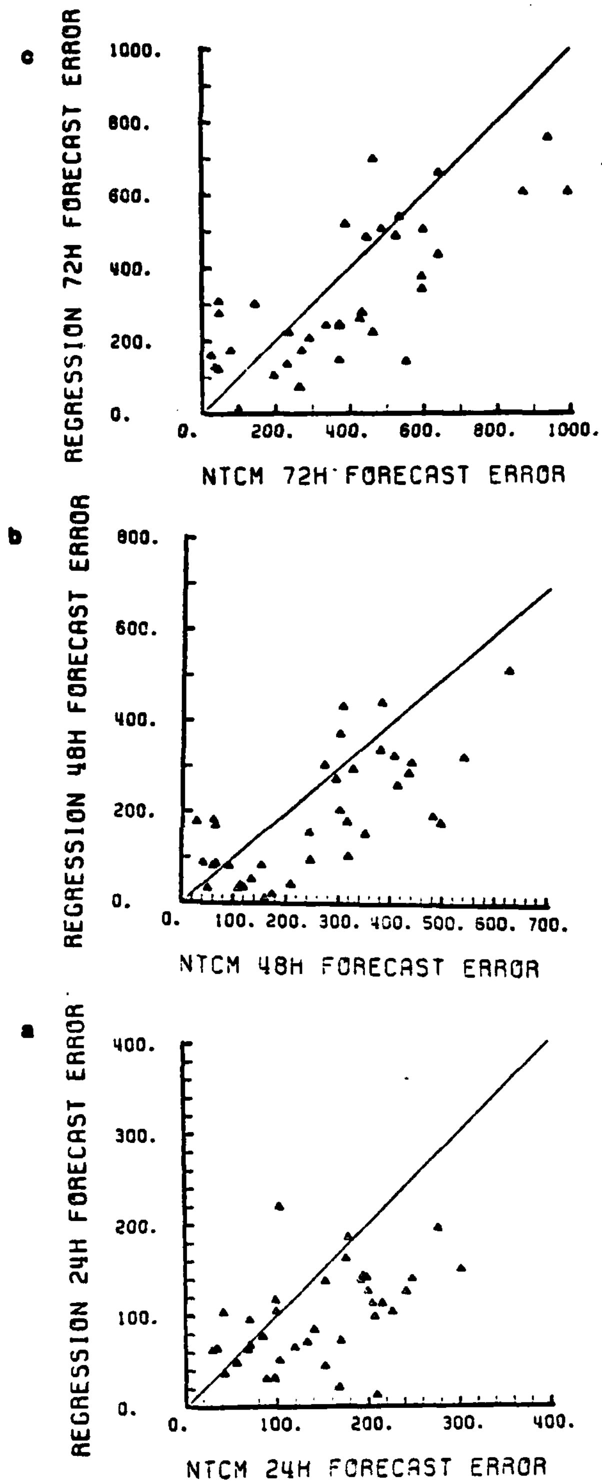

Fig. 7. Scatterplots of NTCM independent sample forecast errors (km) versus regression modified independent sample forecast errors for cases east of 135° E for a. 24 h forecast, b. 48 h forecast and c. 72 h forecast.

independent samples accounts for the slight degradation of 25% of the cases.

B. West of 135°E.

The error bias characteristics of the applicable southern hemisphere NTCM forecasts west of 135°E are shown in Table 10. There is an eastward bias from 24-48 h and a very large westward bias at 72 h. The meridional bias indicates a very large southward bias that increases with time. Cases with such strong bias should be improved by the postprocessing; however, the small sample size in the western region may hinder the performance of the scheme with independent data.

The 52 cases are divided into a 35 case dependent sample and a 17 case independent sample. The systematic zonal and meridional bias trends of the samples (Fig. 8) are similar up to 48 h. There is a smaller independent sample meridional bias at 60 and 72 h and a smaller 72 h zonal bias. The 60 h zonal biases are of opposite sign. These differences are probably due to the small sample size.

Zonal and meridional regression equations were derived for the dependent sample. The reduction in variance by the equations ranged from 26% to 90% and averaged 57%. This reduction in variance is larger than that for the eastern region cases, possibly due to the extreme systematic bias in the meridional direction.

The regression scheme is generally successful at reducing the means and standard deviations of the independent sample biases (Table 11). The scheme performs poorly where there is a bias difference between the dependent and independent samples, which again indicates the need for a larger sample.

The mean forecast errors of the independent sample are about the same as for the dependent sample from 12 to 36 h but grow considerably smaller from 48 to 72 h (Table 12). The post-processing decreases the forecast error in the dependent sample by 40km at 12 h up to 560km at 72 h. The independent sample

Table 10. Similar to Table 7 except for cases west of 135°E.

Forecast Time (h)	Number of Cases	Forecast Error	NTCM ERROR BIAS Zonal $\bar{x}$	Zonal σ	Meridional $\bar{x}$	Meridional σ
12	52	101	11	91	22	71
24	52	205	-20	162	125	111
36	52	359	-10	253	238	174
48	52	530	-55	361	344	271
60	52	691	1	526	444	319
72	52	768	64	592	439	243

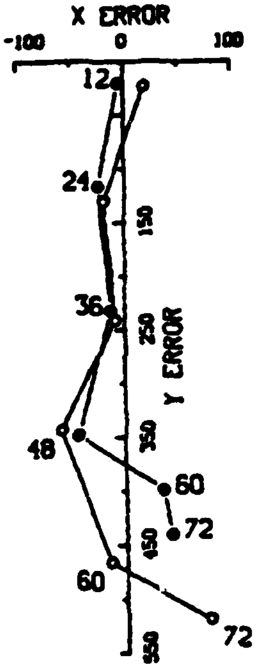

Fig. 8. Similar to Fig. 5 except for cases west of 135°E.

Table 11. Similar to Table 8 except for cases west of 135°E.

Forecast Time (h)	Number of Cases	NTCM Zonal $\bar{x}$	NTCM Zonal σ	NTCM Meridional $\bar{y}$	NTCM Meridional σ	REGRESSION Zonal $\bar{x}$	REGRESSION Zonal σ	REGRESSION Meridional $\bar{y}$	REGRESSION Meridional σ
12	17	-5	99	20	71	-22	73	1	32
24	17	-24	166	115	104	-5	136	-12	55
36	17	-13	268	232	150	-12	260	-23	154
48	17	-44	349	348	198	-74	351	-29	116
60	17	34	442	399	274	-32	435	-30	214
72	17	42	555	440	420	-133	561	-82	417

Table 12. Similar to Table 9 except for cases west of 135°E.

DEPENDENT SAMPLE

Forecast Time(h)	Number of Cases	NTCM $\bar{x}$	NTCM σ	REGRESSION $\bar{x}$	REGRESSION σ
12	35	99	60	59	27
24	35	208	114	122	64
36	35	305	140	196	101
48	35	550	202	214	122
60	31	739	314	293	176
72	25	791	340	231	121

INDEPENDENT SAMPLE

Forecast Time(h)	Number of Cases	NTCM $\bar{x}$	NTCM σ	REGRESSION $\bar{x}$	REGRESSION σ
12	17	105	51	65	55
24	17	198	108	116	96
36	17	347	154	257	123
48	15	483	208	316	169
60	15	592	258	443	[illegible]
72	15	729	334	591	377

forecast error are reductions are 40km at 12 h and increasing to 167km at 48 h. The error reduction then decreases to 138km at 72 h. The forecast errors are reduced by the post-processing to values smaller than the TYAN78, SWPAC and CYCLOGUE analogues. The improvement in forecast error reduces the FE/OD ratio to .40, .58 and .73 at 24, 48 and 72 h. An example of the forecast improvement made by the regression scheme is in Fig. 9.

Scatterplots of the unmodified independent sample forecast errors versus the regression modified forecast errors (Fig. 10) indicate that 75% of the regression modified cases have smaller forecast errors than the unmodified cases at 24, 48 and 72 h. Unfortunately, four cases of excellent 72 h NTCM forecasts are degraded by the application of the regression adjustment.

5. Summary and Conclusions

The performance of the Navy Nested Tropical Cyclone model is evaluated for southern hemisphere tropical cyclones. For storms east of Australia, the NTCM mean forecast error is generally less than the SWPAC and CYCLOGUE analog methods. In a homogeneous comparison with TYAN78, the NTCM tracks were worse at early forecast times and better at late forecast times. West of Australia, the model generally performed worse than the analog techniques. In a limited comparison of 12 and 24 h forecasts, the NTCM had errors comparable to the TCWC official forecasts.

The NTCM tends to have a poleward directional bias in the predicted tracks. This bias may be attributed to the lack of observations, which causes the analysis scheme to revert to climatological values. The NTCM also did not forecast storm tracks well near the Australia coast, especially in the western cases, presumably due to lack of consideration of land/sea effects in the model. It appears from these results that the NTCM, despite the paucity of atmospheric data, does show some skill in predicting tracks of southern hemisphere tropical cyclones, but not to the extent observed in the northern hemisphere.

Statistical post-processing of the model forecasts results in a significant reduction in mean forecast errors. In the region

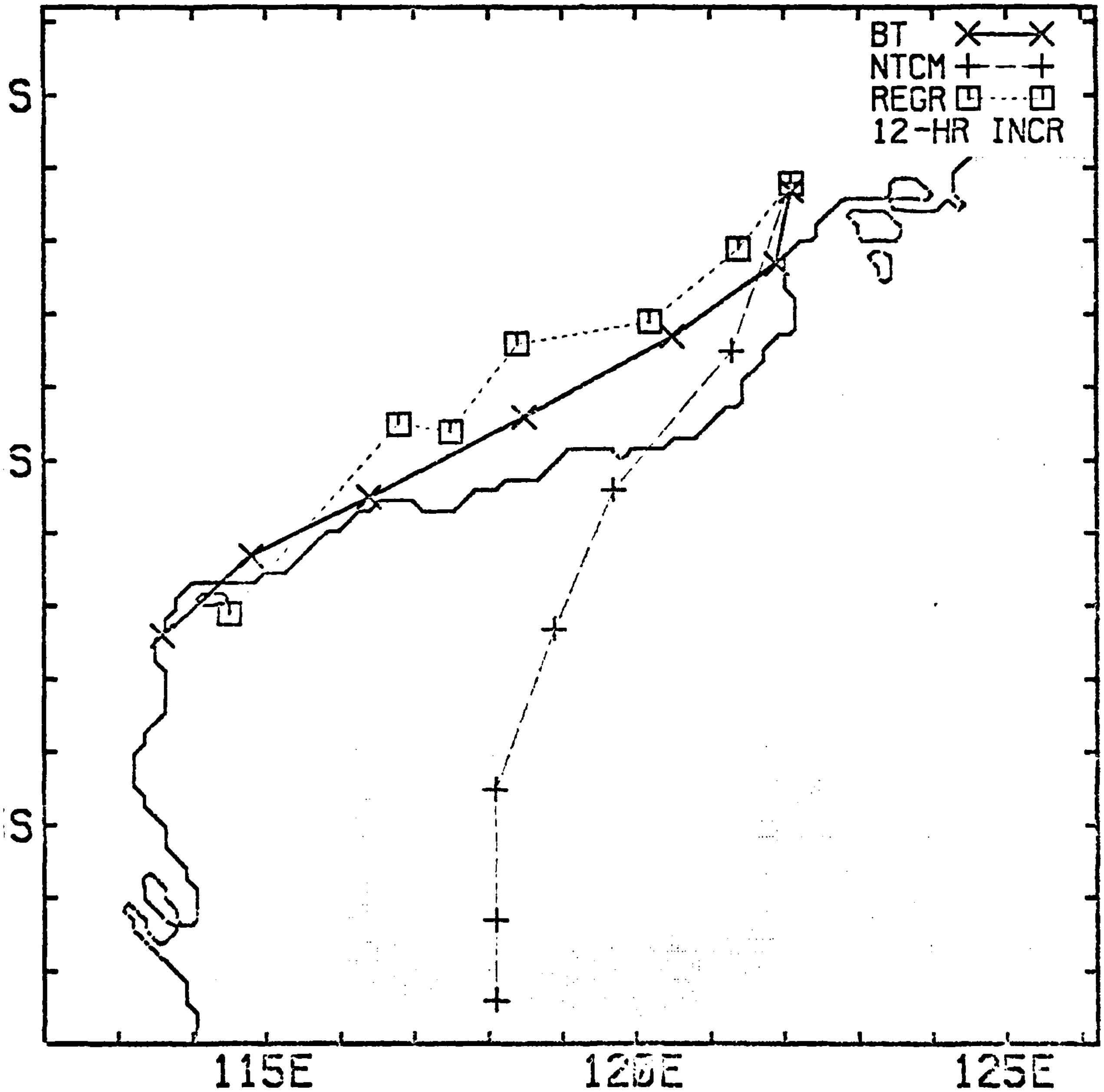

Fig. 9. Similar to Fig. 6 except for cyclone Karen at 00 GMT 5 Mar. 1977.

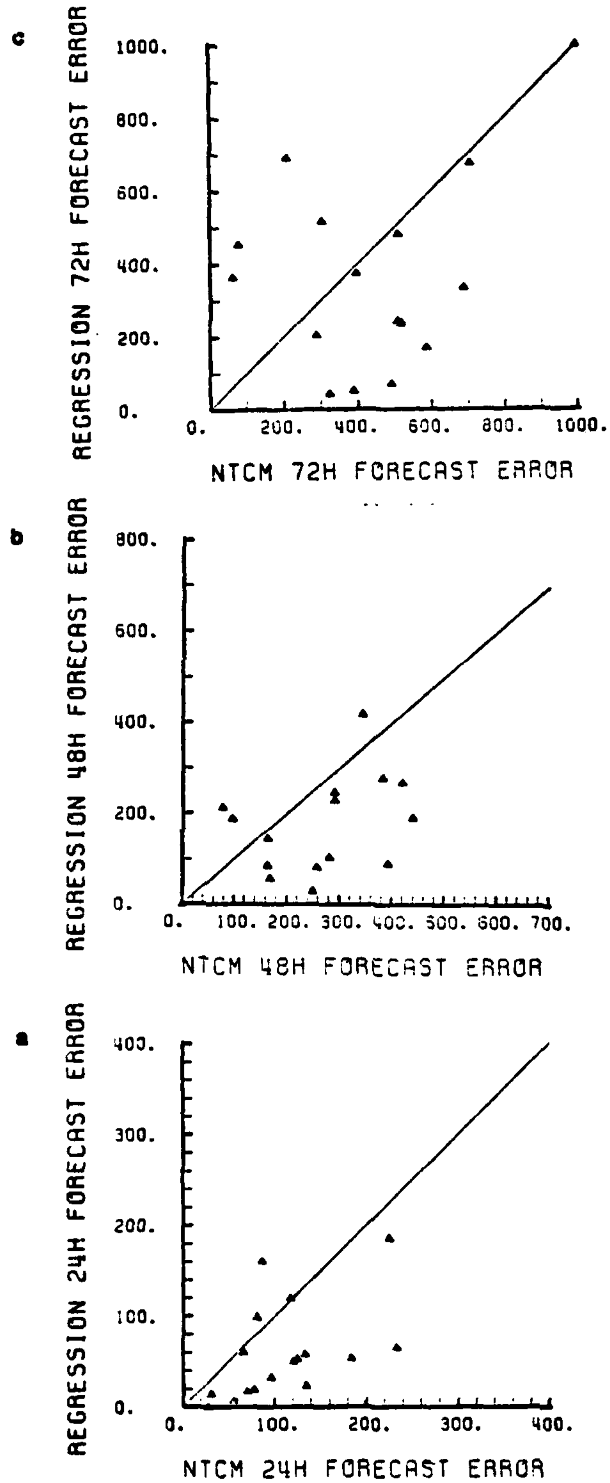

Fig. 10. Similar to Fig. 7 except for cases west of 135°E.

east of 135 E the mean errors are improved by as much as 150km at 72 h. The western region forecast improvement is even greater, such that the regression modified NTCM forecasts are superior to the analog forecasts.

It must be stressed that this evaluation is preliminary and can only be used as an indicator of the future operational performance of the model. A number of factors, including the use of less accurate warning track fixes and the use of a new global band analysis scheme will have a significant impact on the real-time NTCM forecasts. Nevertheless, the results presented here are an encouraging indication that the operational implementation of the NTCM will lead to improved southern hemisphere tropical cyclone warnings.

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