Forecasting Tropical Cyclone Motion over the Northeastern Pacific Ocean by an Analog Scheme

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ABSTRACT

The Navy's EPANALOG (Northeastern Pacific *Analog* Tropical Cyclone Tracker) forecast program is introduced. EPANALOG selects analog tropical cyclones from a 25-year northeastern Pacific Ocean history. The selected analog tracks, statistically adjusted for position, vector motion, and date differences between them and the recent history of the tropical cyclone being forecast, are composited into a single forecast track. Verifications of EPANALOG forecasts to 96 h, as initiated from best-track positions, are shown for randomly selected historical cases with a Monte Carlo simulation of initial position inaccuracies, as well as for forecasts generated from 1973 operational cyclone positions. The latter are intercompared with a homogeneous set of objective persistence and MOHATT forecasts as well as subjective OFFICIAL forecasts for the 24, 48, and 72 h intervals. The 1973 EPANALOG accuracy is shown to generally excel that of the existent techniques for all forecast intervals tested.

. Introduction

Tropical cyclone forecasting (development, movement, intensity) is an important and time-consuming task for the operational meteorologist. Objective guidance is necessary for timely and credible results. Such guidance, at least for movement, exists in great abundance for the North Atlantic Ocean (Neumann and Hope, 1973) as well as for the western North Pacific Ocean (WESTPAC) areas (U. S. Fleet Weather Central/Joint Typhoon Warning Center, 1973). However, relatively few objective techniques are available for the eastern tropical North Pacific Ocean (EASTROPAC) area, reputed to be the region of greatest tropical cyclone density (Hansen, 1972).

Starting in 1969, objective techniques for forecasting tropical cyclone tracks, using an analog concept, were developed. One such technique, designed for WESTPAC, currently called TYFOON-73 was formulated at the National Weather Records Center[2] (Hodge and McKay, 1970) and subsequently modified by Jarrell and Somervell (1970) and by Jarrell and Wagoner (1973). A similar technique called HURRAN, was concurrently developed by Hope and Neumann (1970) for the prediction of the movement of North Atlantic tropical cyclones. Both techniques are based on identifying history cyclones with characteristics similar to the one being forecast. When the movements of all similar past cyclones are assembled, their average movement is computed and the cyclone-center positions on the average analog track are used as guidance in the issuance of forecasts. Following these earlier studies and timed by the existence of a suitable data base, this paper describes the development of an analog technique to forecast the movement of EASTROPAC cyclones for intervals to 96 h.

Wagoner (1973) observed that "a large portion of the forecaster's subjective prognosis is nothing more than an analog procedure. He simply searches his mind for situations similar to the one presently confronting him. These are then converted into a modified forecast by mentally determining the average outcome of all the situations. The similarity between the mental processes and the analog technique probably explains why the accuracies of the two approaches are comparable."

2. Climatology

In general, EASTROPAC cyclones are formed in the eastern section of the area and propagate westward and northward. The cyclone season may be defined to extend from mid-May through October; less than 1% of the tropical cyclones form out of this season. From 1965 to 1973 the annual average of named EASTROPAC cyclones is 14, of which 6 became hurricanes. Other pertinent facts, taken from Hansen (1972), follow. The average track is toward 292°, although this varies with latitude. The mean speed of EASTROPAC

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cyclones is 10 kt with a standard deviation of 3 kt. The relative incidence of recurvature is significantly less than counterparts in the North Atlantic and western North Pacific Ocean areas and the most likely time of recurvature is near the end of the season.

3. Data

Historical data, compiled for the Naval Weather Service by the National Climatic Center, Asheville, N. C., consist of best-track initial and subsequent 0000 and 1200 GMT positions for all known tropical cyclones generally having all or part of their life history in the North Pacific Ocean east of 180°. In the period 1949–73 there is a total of 2666 positions (257 cyclones) in this area.

Tropical cyclone tracks in the operational weather satellite era (1965–1973) were found to be smoother than those in the earlier years, a fact kept under consideration, but determined to be of no significance in the development of an acceptably accurate analog technique.

4. Test cases

About 500 cyclone positions (i.e., positions of cyclone centers being forecast) were randomly selected from the history file of best-track data to serve as test cases. For each case, an initial-position error was introduced to simulate operational position uncertainty. The concept used specified that a forecast for an interval of t hours, initiated at h hours after a reliable position determination, is tantamount to a forecast for an interval $(t+h)$ hours. Further, forecast errors were assumed to grow linearly in time and their frequency distributions were assumed to be similar in all oceans, given similar initial conditions. Actual errors were generated from a cumulative frequency distribution of WESTPAC tropical cyclone forecast errors at warning time (i.e., time of forecast initiation, averaging about 3 h after the most recent fix) (Jarrell, 1972) and at a forecast interval of 24 h (i.e., about 27 h after the fix position upon which the forecast is based) (U. S. Fleet Weather Central/Joint Typhoon Warning Center, 1970). Simulated forecast errors at $(t+h)$ equal to 9, 15, and 21 h were interpolated between 3 and 27 h cumulative forecast-error frequency distributions (Fig. 1).

In all cases, a Monte Carlo simulation (Hillier and Liebermann, 1967) was used. A random number between 0 and 100 (%) was generated and entered into the cumulative frequency distributions of forecast errors in order to give a basic pair of random errors at 3 and 27 h after fix time, from which intermediate values are interpolated as needed. Another random number between 0 and 2π (radians) was used to specify the bearing of the simulated erroneous position from the best-track position.

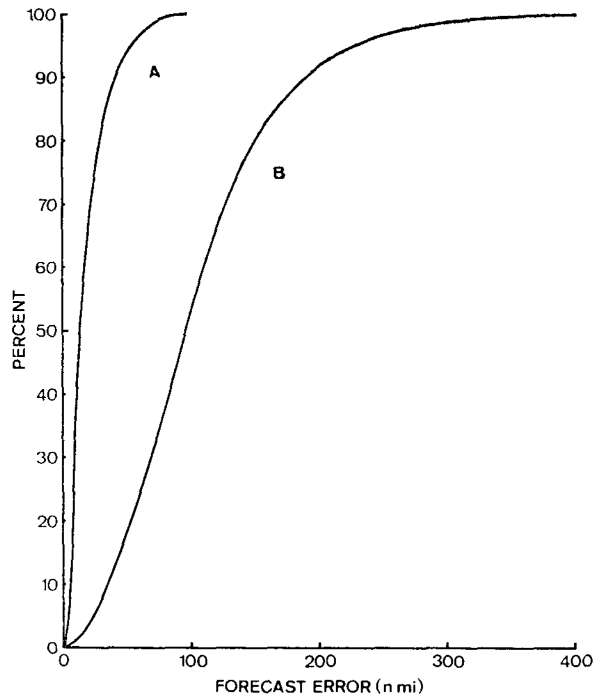

FIG. 1. Cumulative frequency distribution of warning position errors (curve A) and 24 h forecast position errors (curve B) in the western North Pacific Ocean area, 1968–1970.

5. Forecast technique development

a. Introduction

The assumption is made that a pure analog forecast scheme will not perform satisfactorily. A pure analog scheme is defined as one for which history is searched for a situation analogous to an existing situation. Such an analog is found and the subsequent behavior of this analog is used directly as a forecast. Pure analog schemes, for tropical cyclone forecasting, have failed for two reasons. First, good analog pairs (those whose future are closely parallel) are not common enough to presuppose a single good analog could be found for most forecast situations. Secondly, there are no known methods for reliably discriminating poor analogs from good or near-perfect analogs.

One solution to the dilemma is to use screening parameters to stratify the analogs into groups, ranging from the best to the worst. In a statistical sense this is possible; that is, one can separate the analogs into groups which are better (or worse) than average performers. Generally, analog schemes have tried to separate analogs into two groups: "good enough" and "not good enough." The "not good enough" group is then ignored and the "good enough" group forms the basis of the forecast. Usually these are composited into a single analog forecast using an ordinary or weighted average after each has been adjusted for any systematic and hence predictable differences between it and the cyclone being forecasted.

The variations between analog schemes fall into three areas: 1) how criteria are established to eliminate unacceptable (i.e., "not good enough") analogs; 2) how discernable differences between the existing cyclone and an acceptable analog cyclone are adjusted; and 3) how the group of adjusted "good enough" analog tracks are composited.

b. Determining an acceptable analog

The widely accepted usage of a composite analog track over a single analog track is evidence of the improvement (as demonstrated in subsection c below) in analog forecasting as the number of analogs in the composite increases, at least to a certain point. The basis for the expectation that a composite forecast would improve as the number of analog candidates increases relates to the use of the sample-average position as the forecast. There are two components of error in using the sample-average. First, there is the error between the verifying cyclone position and the true analog-population mean. This error is independent of the forecast. Secondly, there is an error between the population mean and the sample mean used as a forecast. This component approaches zero as the number of analogs being composited increases.

Since the period of retrievable history is severely limited (especially in EASTROPAC), there is an upper limit on the possible number of analogs. Within this limit, the number of analogs actually used depends upon the definition of a "good enough" analog candidate. As the criteria for "good enough" are relaxed, the number of analogs are increased, but with an undesirable percentage increase of "not good enough" analogs. Obviously, it is ideal to define the "good enough" cutoff point as that point where the improvement brought about by increasing the number of analogs exactly balances the detrimental effect of including worse analogs and beyond which the net effect is to decrease the accuracy of forecasting the cyclone track.

c. Criteria for an acceptable analog candidate

The differences in the date and location (latitude, longitude) of any two cyclone positions as well as the difference in the recent 12 h motion of the two cyclones were employed as kinematic predictor parameters relating to the future behavior of either of the cyclones. Other parameters with physical association were considered, such as sea-surface temperature, cyclone size and intensity, synoptic pattern, etc., but not used owing to their unavailability in suitable form. To establish the maximum value of each of the analog predictors (called screen setting or envelope value) which allows the best explanation of future differences in the two cyclone tracks, multiple nonlinear regression equations were developed. The parameters in Appendix A (except 24 h history predictors) were used to generate 35 date, location, and history predictors for specifying predictands defined to be the zonal and meridional differences between the two cyclones 48 h after a common starting point. (See the translation process in Fig. 3 for establishing the common starting point between the two cyclones.) The variance in the predictands (actually the sum of zonal and meridional components) not explained by the predictors is then a measure of the dissimilarity of the tracks of the cyclone pairs.

The screen parameters, whose optimal settings were determined by the regression analysis, are identical to parameters i to v in List 1, Appendix A. The selection was patterned after earlier work by Jarrell and Somervell (1970). Several hundred different combinations of symmetric cut-off values for these screens were subjected to stepwise regression analysis. Recorded for each such test were the unexplained variance and the number of cyclone pairs passing through all five screens.

Only the 1965–73 history file was used in this effort. This limited the history to 126 tropical cyclones and 1623 positions. Once the first of the pair of points was selected, all the other 1622 points (except those of the cyclone which contained the first point) were eligible to play the role of the second of the pair of points. The maximum possible number of pairs was in excess of one million. By use of a random selection, the number of pairs was restricted to a few percent of the total possible (usually 10 000 to 50 000).

The probability that a single analog will pass all screens can be varied by adjusting the screen limit. For instance, all screens set at ± 0 (perfect analogs only) would allow the acceptance of a near-zero percentage of analog candidates while screen settings with essentially no limitations would have an acceptance rate close to 100%.

From hundreds of test runs, screen settings were determined which provided an acceptance rate of a predetermined value with minimum unexplained total variance in the test cyclone. Table 1 lists optimal screen settings for acceptance rates of 5 to 50%. It is to be noted that the latitude difference (TY) and past 12 h relative motion (BY and BX) parameters are sensitive screens, i.e., large changes in longitude difference (TX) are preferable to slight changes in these sensitive parameters. Date difference was so insensitive that total abandonment of date-difference screening was preferable for all but the smallest movements of the other parameters away from zero. Unexplained variance (not shown) increases steadily with the acceptance rate. Also shown in Table 1 are average and root mean square (rms) errors, for acceptance rates up to 30%, for a sample of 371 forty-eight hour forecasts, as a function of selected screen settings on date, location, and 12 h history motion differences between the two cyclones. An acceptance rate near 15%

Table 1. Optimum screen settings for each of five parameters obtained by changing the percentage of positions selected as analog candidates. The 48 h forecast test results for 371 forecasts are included for those percentages between five and thirty. Failures indicate the forecasts not made because of insufficient number of analogs.

Average acceptance rate (%)	Parameter TY (° lat)	TX (° lat)	BY (° lat)	BX (° lat)	DD (days)	48 h forecast test results Avg. error (n mi)	RMS error (n mi)	Failures No. (%)
5	0.8	12.0	0.1	0.6	180	171	196	132 (36)
10	1.2	12.0	0.5	0.8	180	161	184	42 (11)
15	1.5	12.0	0.5	1.6	180	159	181	34 (9)
20	1.5	12.0	0.6	1.6	180	163	189	29 (8)
25	1.5	21.0	0.6	1.6	180	164	188	23 (6)
30	1.5	72.0	0.6	1.8	180	173	199	8 (2)
35	1.8	72.0	0.7	1.8	180	—	—	—
40	1.8	72.0	0.8	1.8	180	—	—	—
45	1.8	72.0	0.9	2.0	180	—	—	—
50	1.8	72.0	1.1	2.4	180	—	—	—

appears to be the point of optimum trade-off between increasing the number of analogs and accepting poorer analogs.

The column labeled "Failures" in Table 1 indicates the number of cases in which an insufficient number of analogs were found to support a reliable forecast. Here, the minimum number of analog cyclones was arbitrarily set at three. Later this cut off was reset at a more realistic value of ten. The number of failures at an acceptance rate of 15% was deemed to be excessive, considering it would drastically increase when the cut off minimum was increased. For this reason, an acceptance rate of 30% was selected. A system of weighting discussed in subsection *e* below has the effect of reducing the screen dimensions back toward the 15% optimum.

Figure 2 relates the standard error of a single analog to that of a composite of analogs as a function of acceptance rate. The two curves would intersect where the acceptance rate is equivalent to one analog cyclone.

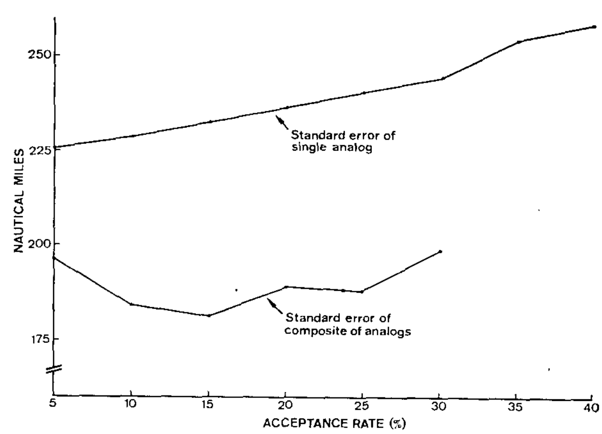

Fig. 2. A comparison of the standard errors, from 48 h forecasts, based on 1) a single analog track and 2) a composite of analog tracks as a function of the acceptance rate.

d. Adjusting the analog cyclone for best comparison to the existing cyclone

Once the acceptance region (envelope) is set in accordance with the optimum screen settings, it is necessary to solve the problem of adjusting the accepted analog tracks to remove the discernable differences between them and the cyclone to be forecasted.

The obvious first difference is that of tropical cyclone position, which is the basis of two of the screens. To account for this difference, all the points (past, present, and future) on the analog track are "translated" or adjusted (Fig. 3) by the amount of the vector from the analog's origin position to the origin of the current cyclone (magnitude $=[(TY)^2+(TX)^2]^{\frac{1}{2}}$). After this adjustment has been made, the next obvious difference in the tracks is the past movement. (Recall that past 12 h motion differences are screen parameters.) In

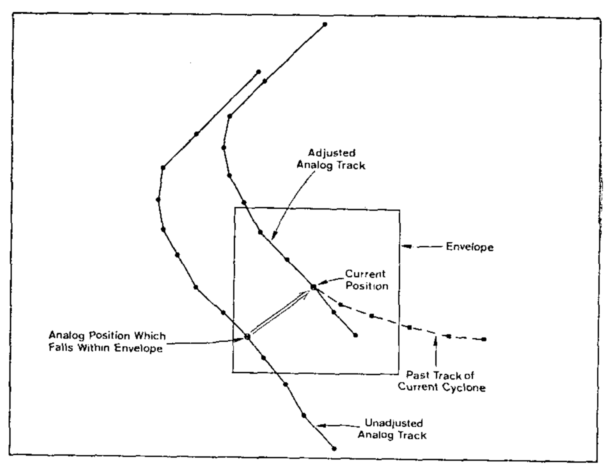

Fig. 3. Example of translation adjustment to an analog track. The translation vector is directed from the acceptable analog position to the position of a cyclone (current position) whose track is to be forecast. This adjustment is applied to 12 and 24 h history and all future positions of the analog cyclone.

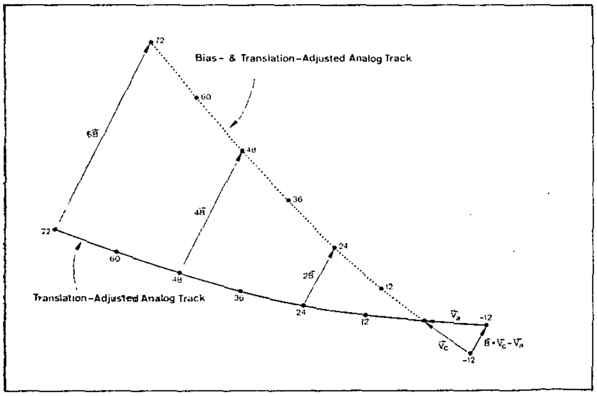

FIG. 4. The history-bias adjustment to an analog track which has been previously adjusted for translation. $\vec{V}_c$ is the previous 12 h movement of the current cyclone and $\vec{V}_a$ is the previous 12 h movement of the analog cyclone.

addition to the 12 h past movement differences (hereafter called 12 h history bias), the 24 h past movement differences were also calculated.

Various methods have been used to adjust the analog track based on past movement. TYFOON-73 vectorially adds the equivalent of the 12 h bias for each 12 h forecast interval (e.g., the 48 h forecast bias is four times the 12 h history bias, as shown in Fig. 4). In the Atlantic, HURRAN combines past motion or persistence of the current cyclone with the vector motion of the analog to form a predicted movement vector. This predicted vector is a linearly changing combination of the persistence and analog contributions, being initially all persistence and becoming all analog at 36 h and beyond.

For EASTROPAC the previously discussed stepwise regression approach was again used, this time to determine the proper history-bias correction to the translation-adjusted analog track. In this case the regression equations for the meridional and zonal components of the predictand were developed from the dependent data sample according to the time since last fix (simulated to be 3, 9, 15, and 21 h), the cyclone history positions (none, 12 or 24 h), and each of the four forecast intervals (24, 48, 72, and 96 h). Forty-nine parameters were available for entry into the regression equations. (See Appendix A.) However, only the most significant three or four were used, i.e., those which explained one percent or more of the total variance of the predictand, again defined as the difference between the translation-adjusted analog and the second of the pair of cyclones (taken as the cyclone being forecasted). Over half of these bias-correction equations were subsequently abandoned as not contributing significantly to the forecast accuracy of the analog scheme. (See Subsection *e* below.)

e. Compositing analogs in the forecast

When the history file is exhausted and all analogs have been screened and those considered "good enough" have been adjusted for position and bias, the problem of finding some method of compositing the cyclones into a single forecast remains. Previous analog schemes have composited the acceptable analog cyclone tracks in one of two ways, 1) a simple average forecast track, or 2) a weighted average forecast track. The latter method was used in EASTROPAC to compensate for the excessive dimensions of the screens. By minimally weighting those analogs far removed from the midpoint of the acceptance region, it was hypothesized that the average error would be brought more in line with the case typical of the 15% acceptance rate group. To accomplish the compositing, two types of weighting factors were multiplied to form a single weight. The first factor reflected the fact that an analog with screen parameters far removed from that of the current cyclone is more likely to produce a poor forecast than one closer. The second factor reflected the supposed lesser accuracy of analogs which have no past history (or only 12 h history).

Several parameters were tried in an effort to establish the first weight factor and all involved some measure of the empirical probability of good 48 h agreement between two translated cyclone positions (defined to be a distance less than 180 n mi) and the probability of a poor agreement (defined to be a distance greater than 240 n mi). On a test sample of 363 cases the best weighting factor (W) was

$$W=\prod_{j=1}^{5} P_{i,j}P_{Gi,j}(P_{Bi,j})^{-1}, \tag{1}$$

where $P_{Gi,j}(P_{Bi,j})$ is the probability of a good (bad) agreement given that the i, jth class has occurred and $P_{i,j}$ is the probability of that occurrence. The j reflects the five different screens and i reflects that each screen acceptance interval is divided into five equal parts. This weighting factor caused a small improvement in the total rms error. In particular, for those cases with a small number of analog cyclones (10 to 20), the forecast accuracy generally improved so that their error distribution resembles that of cases composed of large numbers of analogs.

The second weighting factor reflected the fact that better forecasts resulted from a longer history—a manifestation of a persistence contribution. Weighting factors consisted of the reciprocal of the variance of error from the nonlinear regression equations discussed above.

f. Modifications to analog program from developmental test runs

The technique, as developed to this point, was run on a set of 551 simulated test cases. A record was kept of the average error, rms error, and number of forecasts verified at each forecast interval, using varying amounts of history and simulated initial position errors. Then, proposed modifications (largely simplifications) were tested one at a time and the results compared with the above. In the end four significant modifications were made to the program. A trial modification was retained if either there were no significant increase in the errors or no significant decrease in the number of forecasts verified.

Early in the development of the analog scheme all the forecast positions generated from a single analog cyclone were weighted and averaged. Then, the average position from each cyclone was composited for the final analog forecast. The first modification eliminated this averaging process, thus allowing each accepted point on an analog cyclone track to be weighted without regard to the number of such points. The requirement that a valid forecast must have a contribution from at least ten different cyclones was retained.

The second modification involved testing the significance of the regression equations. All the regression equations for the latitude bias correction were found to give no appreciable decrease in the error and were eliminated. This is probably because of the relatively small screen size on the 12 h latitude bias, and was expected because of the small amount of the meridional variance explained. Also eliminated were the equations for the longitude bias correction when no history was present. In any case, forecasts in the absence of history are entirely a climatological average.

The third modification made to the forecast technique concerned the latitude/longitude weighting factors. The program was run with varying combinations of weights. In the final analysis the latitude weighting factor was eliminated. Again it was felt that the relatively small north-south screen size made any weight differences insignificant.

The fourth modification was to correct a problem which sometimes results from permitting those analog cyclone positions with no history (first 0000 or 1200 GMT point on an analog track) to be considered when analog positions with history are available. In the absence of analog history, past relative motion cannot be computed; therefore, two screens (BY and BX parameters) are inactive, and a disproportionately large number of no-history points may enter the "good-enough" fold. This is particularly troublesome in the cyclone formation region if the past motion of the current cyclone is climatologically unusual and proportionally few analogs are permitted through the relative motion screens. In these cases an abnormally high percentage of analogs making up the composite are "no-history" cases. Hence, the forecast is climatology dominated in a situation where recent motion has not followed climatology. To cure this problem, a check is made to see if the number of no-history cases exceeds that upper limit of the total expected 5% of the time by chance alone. In these cases, all "no history" analogs are excluded from the forecast. This modification significantly improved a group of poor forecasts, but also had the effect of decreasing the number of valid forecasts made.

To test a possible fifth modification, the forecast technique was run again on the set of internally generated test positions in order to examine the practicality of dropping that portion of the history file prior to 1965. In this trial the cyclones occurring prior to 1965 were excluded as possible analog candidates, though they were utilized as test positions. The results indicated no appreciable change in accuracy and a sharp decrease in the percentage of forecasts made due to decreased analog population. In view of these results, it was decided to keep the history file intact.

g. *Analog forecast format*

The forecasts from this technique are output as center positions (i.e., the cyclone center) and extreme points on the minor and major axes of a 50% probability ellipse for 24, 48, 72, and 96 h. Both TYFOON-73 and HURRAN use probability ellipses. Figure 5 illustrates a typical EPANALOG input/output message along with a plot of the output and post-analysis track of Hurricane Doreen (July 1973).

6. Results

a. *Analog forecast verifications*

The final forecast technique, henceforth referred to as EPANALOG (Northeastern *P*acific *Analog* Tropical Cyclone Tracker), was subject to two types of testing. First, 551 simulated forecasts, not all of which could be verified, were made for comparative purposes. The verification results of these tests are given in Table 2. EPANALOG forecasts were made for 24, 48, 72, and 96 h under four classes of simulated initial position errors. (See Section 4.) The following results are apparent. The forecast errors appear to be acceptable by current standards, with error sensitivity to initial position inaccuracies (time since last fix) inversely related to forecast interval.

In order to further investigate the validity of the above results, the 1973 best-track data were removed from the history file and the forecast technique was run on 1973 operational positions for which official and MOHATT (Renard *et al.*, 1973) forecasts existed. The homogeneous test set consisted of warning-time positions for nine named tropical cyclones and two tropical depressions. All operational warning-time positions were ones for which at least a 24 h forecast could be verified. Tables 3 and 4 summarize the results of this test. Table 3 lists the average forecast errors stratified by forecast interval and according to cyclone stage and nature of track. Table 4 shows the average forecast

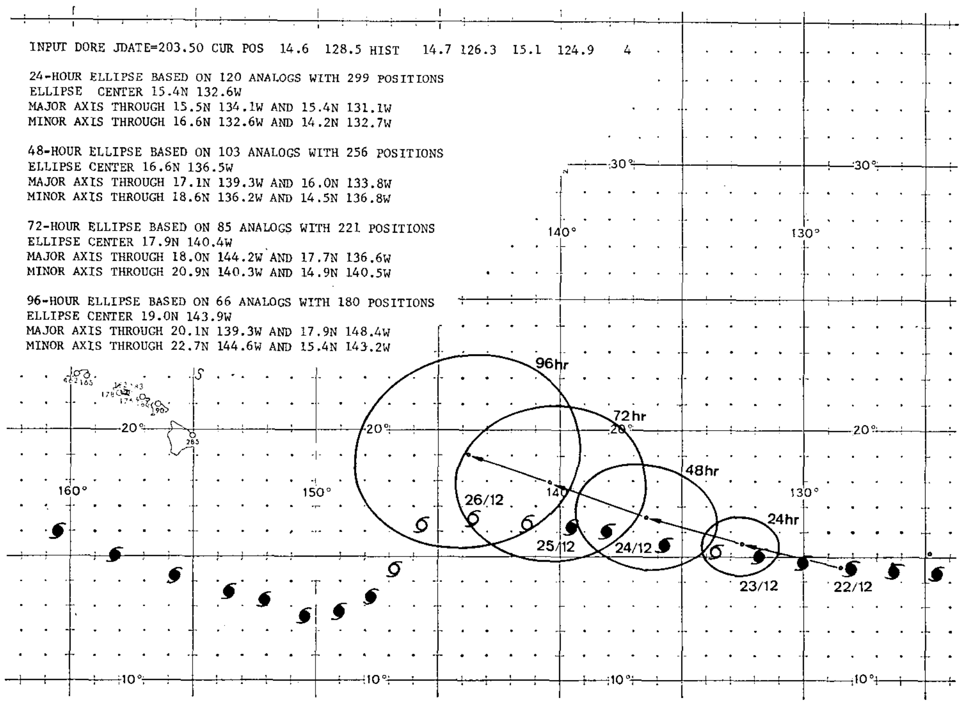

FIG. 5. The 24, 48, 72, and 96 h analog forecasts of Hurricane Doreen, starting from the operational 1200 GMT 22 July 1973 position. Most probable forecast positions are centers of 50% probability ellipses. Best-track cyclone locations at 12 h intervals, coded for stage, are shown for comparison. Insert: Associated computer-produced EPANALOG forecast message.

errors for each cyclone as well as the average initial position error.

The information of Table 3 is consistent with expectation in tropical cyclone forecasting, namely that:

TABLE 2. The results of the EPANALOG forecast technique on the randomly selected test cases incorporating a simulated initial position error.

Time since last fix (h)	Forecast interval (h)	Forecasts verified	Average error (n mi)	RMS error (n mi)
3	24	521	92	108
	48	405	172	202
	72	309	247	289
	96	219	316	365
9	24	516	107	125
	48	397	181	213
	72	307	255	297
	96	217	325	376
15	24	511	128	150
	48	396	202	239
	72	298	265	312
	96	212	333	387
21	24	495	149	174
	48	378	222	264
	72	286	274	324
	96	204	346	403

1) forecast accuracy generally improves as tropical cyclones become better developed at least through 48 h and 2) forecasts for post-recurvature verifying positions are usually less accurate than those for pre-recurvature points. The former differences may be partially attributed to poor initial positioning for formative cyclones, particularly when positioning is based on satellite pictures. The latter difference is related to the difficulty of assessing the time of recurvature and the subsequent greater speed along the track after recurvature.

b. Tropical storms Claudia and Jennifer

The average errors shown in Table 4 are fairly consistent from cyclone to cyclone with two notable

TABLE 3. EPANALOG 1973 forecast errors (n mi) by forecast interval according to cyclone stage and nature of track at verifying time. Operational position data were used to initiate forecasts. The number of forecasts is contained in parentheses.

	Forecast interval		
	24 h	48 h	72 h
Tropical depression	143 (34)	246 (22)	253 (14)
Tropical storm	129 (79)	212 (61)	285 (57)
Hurricane	80 (86)	167 (73)	251 (52)
Before recurvature	102 (189)	181 (148)	258 (119)
After recurvature	263 (10)	467 (8)	518 (4)

exceptions, tropical storms Claudia and Jennifer. Since neither attained hurricane intensity, they were particularly subject to the effects of poor initial positioning. In fact the ratio of 24 h average forecast error to initial position error for Claudia (204/76) is not unlike the ratio for the corresponding values considering all 1973 cases (110/41). Even Jennifer's errors look more reasonable from this point of view.

There are other factors involved in the anomalously poor Claudia and Jennifer forecasts. First, both tracks are brief and climatologically unusual. Claudia followed a slow northwest track at low latitudes (10–17°N) and Jennifer, starting at 13°N, described a fast northeast (i.e., post-recurvature) track after a period of being virtually stationary.

Since analog forecasting is closely related to climatological forecasting, it should not be expected to handle climatologically unusual cases well.

There is one additional factor deteriorating forecast accuracy for the recurving cyclone in the EASTROPAC area. Because of the presence of cold water to the north of the tropical cyclone area, those cyclones which recurve also dissipate rapidly; the historical tracks of such cyclones abruptly end along a relatively sharp northern boundary. If the cyclone to be forecast is stationary or moving northward slowly on a pre-recurvature track, screening is likely to include historical cyclones which subsequently tracked toward directions ranging from westward to northeastward. Of these tracks, those that persist longest are those that move westward; consequently, the mean analog forecast track becomes progressively more westward.

Table 4. The 1973 operational initial-position and EPANALOG forecast errors (n mi) by cyclone and forecast interval. Operational position data were used to initiate forecasts. The number of cases is contained in parentheses.

Cyclone	Initial	24 h	48 h	72 h
		Forecast interval		
Ava	39 (42)	125 (25)	231 (23)	323 (21)
Claudia	76 (14)	204 (7)	307 (3)	
Doreen	29 (66)	87 (46)	166 (42)	237 (38)
TD-5	55 (9)	42 (5)		
Emily	24 (30)	86 (23)	134 (19)	146 (15)
Florence	36 (24)	78 (15)	98 (11)	133 (7)
Glenda	50 (27)	108 (15)	147 (11)	152 (8)
TD-10	45 (12)	146 (6)		
Irah	29 (20)	111 (12)	230 (8)	328 (4)
Jennifer	74 (15)	347 (6)	673 (4)	1156 (1)
Katherine	30 (37)	100 (30)	235 (25)	394 (23)
Lillian	49 (20)	97 (13)	170 (10)	197 (6)
Total	41 (316)	110 (199)	196 (156)	267 (123)

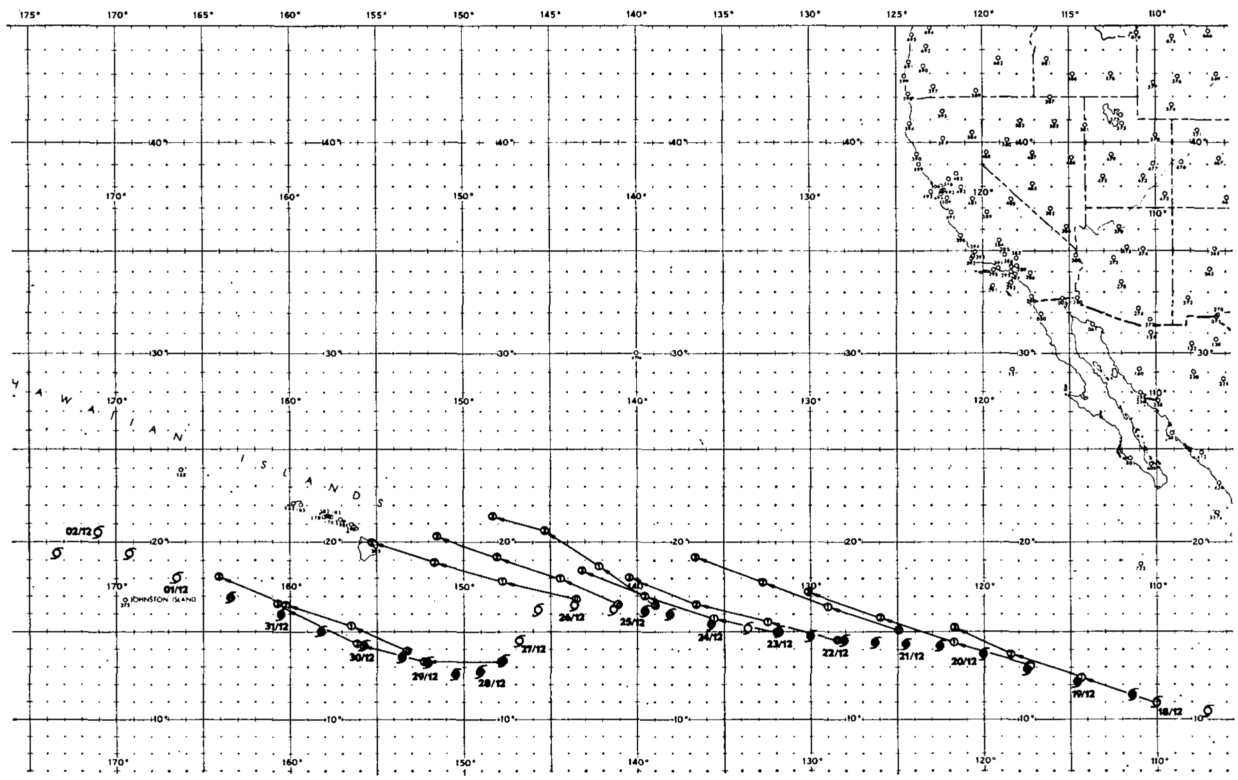

Fig. 6. Hurricane Doreen, 18 July to 3 August 1973 best-track positions at 0000 and 1200 GMT are indicated by standard hurricane (●) or tropical storm (○) symbols. Sample EPANALOG forecasts for 1-, 2-, and 3-day intervals are indicated by numbered points connected by line segments. The origin of each of these forecasts is the position specified in the operational tropical cyclone advisory.

TABLE 5. Comparison of 1973 Northeastern Pacific tropical cyclone average forecast errors (n mi) between EPANALOG, Official, Persistence, MOHATT (850 mb steering) and MOHATT (700 mb steering).

Forecast interval (h)	Verification time (GMT)	No. of forecasts	EPANALOG	Official[a]	Persistence	MH850	MH700
24	0000	48	101	104	111	120	109
	0600	47	112	108	124	145	144
	1200	53	128	139	145	151	159
	1800	51	99	106	109	154	150
	All	199	110	115	123	143	141
48	0000	36	172	203	223	213	232
	0600	36	204	202	233	270	299
	1200	41	213	234	277	282	264
	1800	33	176	219	209	305	253
	All	146	192	215	237	267	262
72	0000	29	254	278	336	312	309
	0600	27	278	299	340	356	356
	1200	30	250	337	386	398	410
	1800	24	254	271	322	485	363
	All	110	259	298	347	384	360

[a] Via Fleet Weather Central, Pearl Harbor, Hawaii.

A similar effect was explained by Jarrell and Wagoner (1973) for typhoons approaching the China mainland, an area where historical tracks had been abruptly discontinued. There the effect was forestalled through artificially extending the historical tracks by extrapolation. No attempt has been made to apply such a modification to Northeastern Pacific tracks because the frequency of recurvature and the rather striking symptoms of the problem make a subjective treatment by the forecaster rather straightforward.

c. *Hurricane Doreen*

Figure 6 illustrates some of the operational EPANALOG forecasts made on Hurricane Doreen (18 July–3 August 1973). These are not intended to be representative forecasts, but rather were selected to illustrate certain points.

Most notable along the track of Doreen is the southward motion starting on 26 July, which took her on a path well south of the Hawaiian Islands. Notable also is the lack of EPANALOG forecasts during this period. The reason for this forecast void is that screening on past motion prohibited selection of a sufficient number of analogs to support a reliable forecast. Failure to anticipate the southward move by EPANALOG is to be expected since this is a relatively unusual track. It may appear that forecast error comparisons would be inflated in EPANALOG's favor since it is unable to make forecasts when they are difficult. For this reason homogeneous comparisons with other forecast techniques have been carefully documented. Additionally, it must be noted that the large forecast errors occur in forecasts initiated *before* the unusual movement and that once such a movement is revealed in the track, forecasts again become routine.

There is clearly a bias in the forecasts of this storm as all forecasts are too far north and most are too fast. The anomaly is at least partially due to the operational positions generally being poleward of the best track.

d. *Intercomparison of forecast techniques*

The next step in the verification phase was a homogeneous comparison of EPANALOG forecast errors to those of two objective techniques, persistence and MOHATT (Renard *et al.*, 1973), and the largely subjective official[3] forecasts. The presistence forecasts are linear extrapolations of the most recent 24 or 12 h history, the latter used only when the former was not available. In the case of the MOHATT forecasts, both the 850 mb and 700 mb steering modes were evaluated. Table 5 contains the results.

The usual fix time for 1973 in EASTROPAC was near 1800 GMT. This once-per-day fix impacts on forecast errors differently for each technique. Both MOHATT modes are predictably poorest near fix time since past 6 and 12 h movements are least reliable then. Generally the other forecast approaches are best at 1800 and 0000 GMT and poorest at 1200 GMT. Without exception, EPANALOG's mean error was better than that of the other objective techniques. A comparison of EPANALOG with Official gives the edge, except for 0600 GMT, to EPANALOG. If

[3] Via Fleet Weather Central, Pearl Harbor, Hawaii.

TABLE 6. Average errors (n mi) for North Atlantic and North Pacific tropical cyclones; number of forecasts in parentheses.

Forecast interval (h)	North Atlantic Hurran[a] (1945–69)	North Atlantic NHC[b] (1973)	North Pacific West JTWC[c] (1973)	North Pacific East NWSFO[d] (1973)	North Pacific East EPANALOG[e] (1973)
12		57 (98)			
24	84 (671)	107 (84)	108 (267)	130 (NA)	110 (199)
48	235 (531)	239 (54)	197 (153)	225 (NA)	196 (156)
72	372 (394)	346 (28)	253 (97)	320 (NA)	267 (123)

[a] Initiated from historical post analysis data (Neumann and Hope, 1973).
[b] Courtesy of National Hurricane Center; 1973 Official forecasts, adjusted for initial-position error.
[c] From U. S. Fleet Weather Central/Joint Typhoon Warning Center (1973).
[d] National Weather Service forecasts estimated from Baum (1974).
[e] From Table 4.

sensitivity to errors associated with initiation time can be inferred from the difference between average errors at the poorest and best synoptic times for each technique, then EPANALOG is least sensitive to these errors. This is a highly desirable attribute in an area where inaccurate cyclone positioning is a fact of life.

Table 6 is a comparison of 1973 average errors for EPANALOG and Official tropical cyclone forecasts, the latter from both the North Atlantic and North Pacific areas. For further comparison, test results for HURRAN forecasts made from best-track positions in 1945 to 1969 are included (Neumann and Hope, 1973). Comparability among the non-homogeneous sets of forecasts is difficult to establish because of differences in initiating forecasts and methods for computing errors as well as a natural variability which exists between oceans. Nevertheless, with the exception of the HURRAN forecasts, the EPANALOG forecasts are of equal quality at 24 h and generally superior after that time.

TABLE 7. A comparison of mean EPANALOG forecast errors (n mi) for test cases with the simulated error and 1973 operational data. The number of forecasts in each sample is given in parenthesis.

	Forecast interval 24 h	48 h	72 h
Simulation: 3 h since last fix	92 (521)	172 (405)	247 (309)
Operational: from 1800 GMT position	99 (51)	176 (33)	254 (24)
Simulation: 9 h since last fix	107 (516)	181 (397)	255 (307)
Operational: from 0000 GMT position	101 (48)	172 (36)	254 (29)
Simulation: 15 h since last fix	128 (511)	202 (396)	266 (298)
Operational: from 0600 GMT position	112 (47)	194 (36)	278 (27)
Simulation: 21 h since last fix	149 (495)	222 (378)	274 (286)
Operational: from 1200 GMT position	128 (53)	213 (41)	250 (30)

7. Conclusions

Based on the results described above, it may be concluded that the EPANALOG technique is a valuable aid in forecasting the movement of EASTROPAC tropical cyclones.

Since most 1973 reconnaissance fixes were made at about 1800 GMT, it is assumed that 1800 GMT corresponds to that "time since fix" nearest to 3 h and subsequent synoptic times 0000, 0600, and 1200 GMT correspond to "time since last fix" nearest to 9, 15 and 21 h, respectively, in Table 2. With this assumption, the simulated results of Table 2 can be directly related to the operational test results of Table 5. Such a comparison is made in Table 7. If it can be assumed that 1973 was a representative year, then the similarity in average errors of forecasts from simulated test positions and actual operational positions infer that the technique outlined earlier for generating simulated positions and the usage of those positions in the program development was realistic. Such similarity also tends to confirm that the "Monte Carlo" type simulation realistically modeled the operational uncertainty in positioning.

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APPENDIX A

Predictor and Screen Parameters

The predictors used in the stepwise regression analyses described in Section 5c were obtained by multiplying each of the parameters contained in List 1 by each of those appearing in List 2. The screen parameters are numbers i to iv in List 1.

List 1

i) Longitude difference between two cyclone locations (TX)
ii) Latitude difference between two cyclone locations (TY)
iii) Relative zonal movement between the two cyclones over the 12 h prior to locations in i and ii above (BX)
iv) Relative meridional movement between the two cyclones over the 12 h prior to locations in i and ii above (BY)
v) Difference in Julian dates associated with cyclone locations in i and ii above (DD)
vi) Same as iii for 24 h (BX 24)
vii) Same as iv for 24 h (BY 24)

List 2

i) 1.0
ii) Longitude of cyclone whose position is not translated (XCO)
iii) Latitude of cyclone whose position is not translated (YCO)
iv) Julian date of cyclone whose position is not translated (D)
v) $(YCO)^2$
vi) $(XCO)^2$
vii) D^2

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