CHAPTER 3

TECHNICAL NOTES

A. COMPARISON OF OBJECTIVE TECHNIQUES

1. GENERAL

Verification of objective forecasting techniques has been continuous since 1967 although year-to-year modifications and improvements have prevented any long period comparison of more than a few of the techniques. None of the objective forecasts used now go beyond the simple steering concept of a point vortex in a smoothed flow field with adjustments based on past movement. Development and its important relationship to movement are excluded in all objective forecasts.

TYFOON, a new statistical analog technique for Western Pacific typhoons (Jarrell and Somervell, 1970) that closely resembles HURRAN, its Atlantic counterpart (Hope, et al 1970), was first tested during the 1970 season. While designed as a forecast aid, verification is presented here along with the other objective techniques. This technique provided for the first time verifiable objective 72 hour forecasts.

2. DISCUSSION OF OBJECTIVE TECHNIQUES

a. EXTRAPOLATION - Past 24 hour movement is extrapolated to 24 and 48 hours.

b. ARAKAWA (1963) - Grid overlay values of surface pressure are entered into regression equations and hand-computed for storms 50 kts or greater.

c. HATRACK 700 mb, 500 mb (Hardie, 1967) - Point vortex advected on the 700 mb and 500 mb analysis or prognostic SR (space mean) field in six-hour time steps up to forecast period of 66 hours (without bias correction).

d. RENARD 700 mb/500 mb PROG (FWC/JTWC, 1968) - Combination of HATRACK 700 mb longitude and HATRACK 500 mb latitude.

e. TYRACK - Tropical cyclone movement forecast on FWC Pearl tropical fields (Hubert, 1968) with capability for subjective program control.

f. WEIGHTED CLIMO (Jarrell and Somervell, 1970) - Program outputs forecast positions as the centers of probability ellipses out to 72 hours based on a group of analog storms which occurred within a time/space envelope centered about the date and position of the storm being forecast. Ellipses are based on the analog population weighted according to similarity to the existing storm.

g. FIRST ANALOG - Forecast positions out to 96 hours based on the track of the most similar analog storm.

3. TESTING AND RESULTS

Verification results for 24, 48, and 72 hour forecasts appear in Table 3-1 with the techniques listed in order of accuracy based on homogeneous comparisons.

OBJECTIVE TECHNIQUE COMPARISON

24 HOUR		48 HOUR		72 HOUR	
EXTRAPOLATION	(121)	WEIGHTED CLIMO	(216)	WEIGHTED CLIMO	(310)
WEIGHTED CLIMO	(108)	EXTRAPOLATION	(273)	ANALOG	(384)
ARAKAWA	(142)	ARAKAWA	(246)		
TYRACK (BETA=2)	(143)	TYRACK (BETA=2)	(297)		
ANALOG	(127)	ANALOG	(263)		
TYRACK (BETA=5)	(151)	TYRACK (BETA=5)	(330)		
RENARD	(173)	RENARD	(370)		
HATRACK 700	(181)	HATRACK 700	(382)		
HATRACK 500	(193)	HATRACK 500	(380)		

TABLE 3-1

The number shown after each technique is the average error for all forecasts by that method. The complete set of homogeneous comparisons in Table 3-2 contains the data used for ranking the techniques. Individual errors greater than 500 N.M. for 24 hours and 1000 N.M. for 48 hours were discarded based on assumption that recording or processing errors were involved.

Comments on the performance of the objective technique for the 1970 season follow:

a. In no case, homogeneous or non-homogeneous, did the mean for any of the techniques better the official JTWC forecast mean.

b. EXTRAPOLATION continues to be superior for short range (24 hour) accuracy although only by a slight margin over WEIGHTED CLIMO. For the 48 and 72 hour forecasts, however, WEIGHTED CLIMO performed best. The substantial improvement in the longer range JTWC official forecast has been for a large part attributed to the reliable guidance of this new technique, which itself provided forecasts superior to all pre-1970 48 and 72 hour mean JTWC forecasts.

It should be remarked that the use of the analog forecast is limited to those cases with adequate historical sample sizes, thereby reducing its availability for some of the more difficult forecast situations. This shortcoming is partially reflected by the relatively low number of WEIGHTED CLIMO forecasts.

LEGEND

NUMBER OF CASES	X-AXIS TECHNIQUE ERROR
Y-AXIS TECHNIQUE ERROR	ERROR DIFFERENCE Y-X

JTWC = OFFICIAL JTWC SUBJECTIVE FORECAST
XTRP = EXTRAPOLATION
ARKW = ARAKAWA
HT7P = HATRACK 700 MB PROG
HT5P = HATRACK 500 MB PROG
TYB2 = TYRACK (BETA=2)
TYB5 = TYRACK (BETA=5)
RD57 = RENARD 500/700 MB
CLIW = WEIGHTED CLIMO
ANA1 = FIRST ANALOG

24-HOUR

	JTWC		XTRP		ARKW		HT7P		TYB2		HT5P		RD57		TYB5		CLIW		ANA1	
JTWC	413	104																		
	104	0																		
XTRP	316	103	318	121																
	121	19	121	0																
ARKW	171	98	158	123	172	142														
	141	44	146	23	142	0														
HT7P	223	103	191	119	114	134	224	181												
	181	78	182	63	186	53	181	0												
TYB2	227	102	197	118	106	136	169	177	228	143										
	142	40	142	24	143	7	144	-33	143	0										
HT5P	220	102	189	117	113	133	214	175	164	143	221	193								
	192	90	192	75	191	58	188	13	194	51	193	0								
RD57	219	103	188	119	109	134	218	177	165	143	215	190	220	173						
	172	69	170	51	162	28	170	-7	173	31	170	-20	173	0						
TYB5	257	102	223	117	134	132	192	188	206	138	187	196	188	180	258	151				
	151	49	149	32	141	9	150	-38	149	11	150	-47	149	-31	151	0				
CLIW	80	91	65	100	44	105	48	171	60	127	49	189	47	172	58	139	80	108		
	108	17	102	2	99	-6	111	-60	111	-16	109	-80	109	-63	106	-33	108	0		
ANA1	79	89	64	100	43	106	47	172	59	127	48	190	47	172	57	136	79	107	79	127
	127	38	132	32	135	29	129	-43	136	9	123	-67	129	-43	130	-6	127	20	127	0

48-HOUR

	JTWC		XTRP		ARKW		HT7P		TYB2		HT5P		RD57		TYB5		CLIW		ANA1	
JTWC	258	193																		
	193	0																		
XTRP	185	184	196	273																
	254	70	273	0																
ARKW	105	175	92	251	105	246														
	246	71	252	1	246	0														
HT7P	132	185	119	264	61	254	141	382												
	388	203	388	124	390	136	382	0												
TYB2	150	175	133	237	68	255	114	378	158	297										
	290	115	300	63	266	11	318	-60	297	0										
HT5P	127	185	113	262	64	247	130	358	109	307	136	380								
	387	202	376	114	387	140	376	17	381	74	380	0								
RD57	127	185	114	261	60	252	136	373	110	306	128	370	136	370						
	377	193	370	109	382	130	370	-3	374	68	350	-20	370	0						
TYB5	162	178	151	245	81	253	125	381	145	295	120	384	121	374	171	330				
	326	148	335	90	324	71	341	-40	315	20	333	-51	335	-39	330	0				
CLIW	70	186	57	212	39	236	41	382	52	253	42	386	39	368	53	299	71	216		
	216	30	211	-2	201	-36	230	-153	212	-41	227	-160	229	-139	213	-86	216	0		
ANA1	64	183	53	211	39	236	38	380	48	258	40	396	36	366	49	301	65	214	65	263
	264	82	278	68	283	47	268	-113	268	10	262	-134	268	-99	276	-25	263	49	263	0

72-HOUR

	JTWC		CLIW		ANA1	
JTWC	39	302				
	302	0				
CLIW	39	302	63	310		
	304	3	310	0		
ANA1	30	257	46	327	46	384
	364	108	384	57	384	0

TABLE 3-2

EXTRAPOLATION errors can be considered to be a good indicator of the difficulty of a forecast and similarly be a good measure of forecast skill. Keeping this in mind, it is noteworthy that the improvement of the JTWC official forecast over EXTRAPOLATION has increased from 5 percent in 1968 to 13 percent in 1969 to 15 percent in 1970.

c. ARAKAWA ranked third in accuracy for both 24 and 48 hour forecasts.

d. Of the computer techniques, TYRACK (BETA=2) verified with the lowest average error. Controls for adjusting tropical cyclone movement were added to the TYRACK program in 1970, but forecaster and computer time for testing was lacking.

The only control parameter tested was BETA, a variable northerly component added to the motion, and optimum results are noted for BETA=2. However, only a comprehensive testing using all combinations of the control parameters will lead to more accurate and reliable TYRACK forecasts.

e. FIRST ANALOG, although not among the top techniques, often provided useful guidance since characteristics of the analog storm and surrounding environmental conditions were available for comparison.

f. RENARD 700 mb/500 mb was again superior to HATRACK 700 mb and HATRACK 500 mb. HATRACK errors for forecasts based on analysis and prognostic fields were within 2 percent of each other for the 1970 season so their results are combined in Tables 3-1 and 3-2.

4. DISCUSSION AND PLANS FOR 1971 SEASON

Rapidly-acquired confidence in the analog technique as a reliable forecast guidance for both the short and long range has assured its continued use in 1971 with major emphasis on the climatological weighted mean positions. Verification of best analog forecasts will likely be discontinued.

A modified HATRACK technique developed by Renard et al. (1970) that corrects for recent error trends in the basic HATRACK prognostic forecast will be incorporated into the set of 1971 objective aids. This modified technique permits forecasts out to 48 hours. In addition, improvement to HATRACK is hoped for in a modification by the FWC computer section for the program to run on SL prog fields rather than SR progs.

Efforts to improve the TYRACK forecasts are also planned. A worthwhile testing of the control parameters on an operational basis is possible with the desired result of reducing the arbitrariness in assigning values to the parameters and the subsequent reduction of forecast error.

B. TYPHOON FORECASTING ERROR IMPROVEMENT

1. INTRODUCTION

Over the years a gradual improvement has been noted in mean errors for typhoon forecasts. The 1970 errors were all-time lows for WESTPAC typhoons. Since mean errors and multiples thereof are commonly used as a cushion in determining the extent of threat posed by a particular typhoon, some analysis of the present level of expected error is considered useful.

Two measures of forecast error have been tabulated and recorded. They are:

a. Vector Error: The magnitude of the vector from the forecast position to the corresponding best track position.

b. Right Angle Error: The closest distance from the forecast position to the best track. This may be considered as a measure of track forecasting skill without regard to speed or timing.

2. 1970 ERRORS:

Figure 4-1 depicts the annual mean vector errors since the 1950's. Figure 4-3 similarly depicts the annual mean right angle errors since 1965. As indicated earlier, both graphs show a gradual downward trend with the means for 1970 singularly less than corresponding means for any other year. In order to make use of this information it is necessary to ascertain the representativeness of the 1970 means as an indicator of the level of expected errors. There are two aspects of the 1970 typhoon season that cast doubt on its representativeness; first, 1970 had a record low number of typhoons and thus overtaxed neither the forecasting/analysis assets at JTWC nor the supporting reconnaissance assets, and secondly, 1970 was not characterized by difficult typhoons to forecast. There was a minimum of recurvatures and hence the rapid accelerating typhoons on a northeast track. There was an abundance of climatological rarities and loops, but this is compensated for by a large portion of relatively straight low latitude tracks.

On balance the errors of 1970 appear to be non-representative of the current capability of the Typhoon Warning Service.

3. MEASURES OF DIFFICULTY

In 1969 (FWC/JTWC, 1969) an attempt was made to gauge the difficulty of a season by normalizing mean error with mean typhoon displacement. Figure 3-1 compares the mean annual

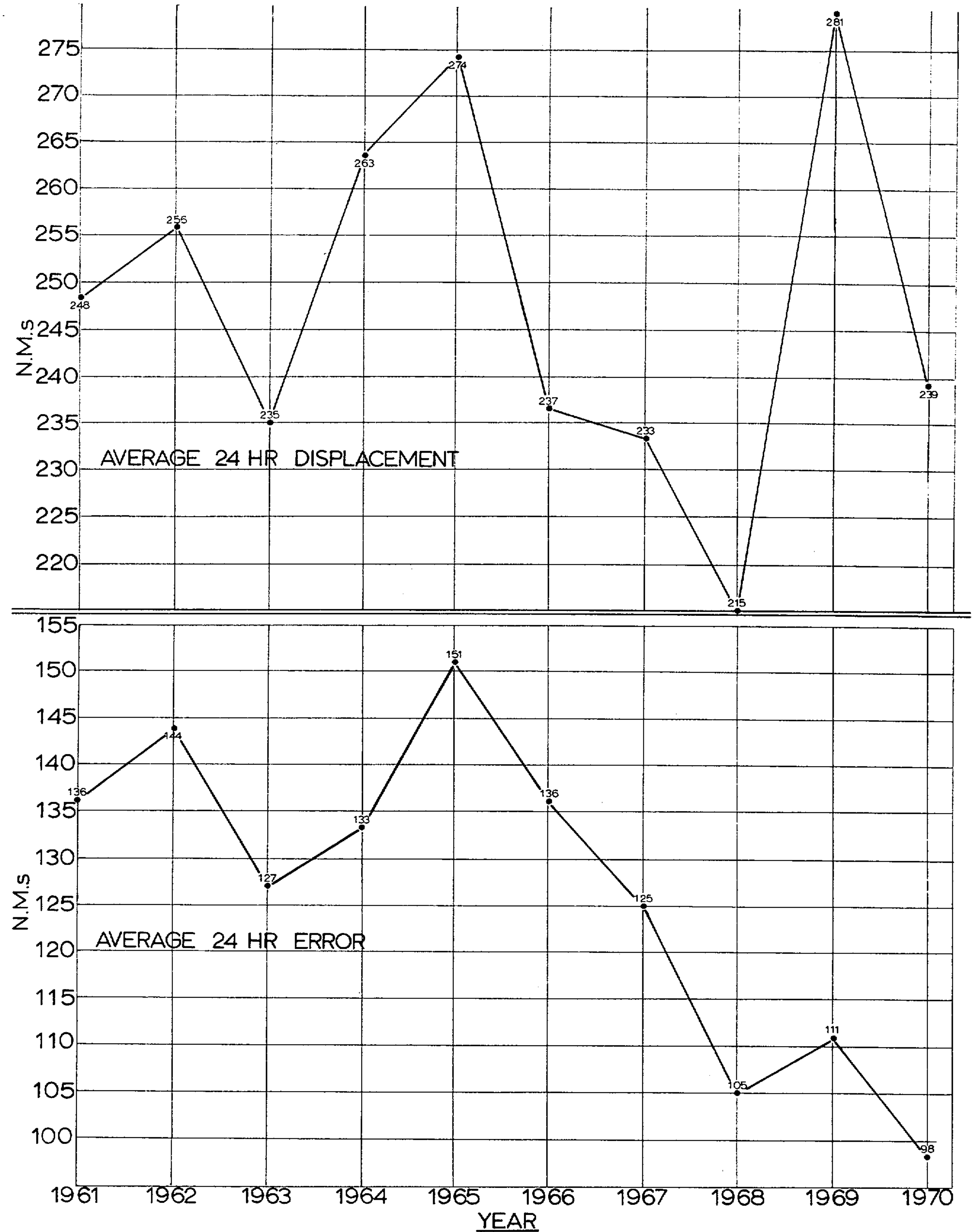

275
270
265
260
255
250
245
240
235
230
225
220
N.M.s
AVERAGE 24 HR DISPLACEMENT
248
256
235
263
274
237
233
215
281
239
155
150
145
140
135
130
125
120
115
110
105
100
N.M.s
AVERAGE 24 HR ERROR
136
144
127
133
151
136
125
105
111
98
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
YEAR

FIGURE 3-1

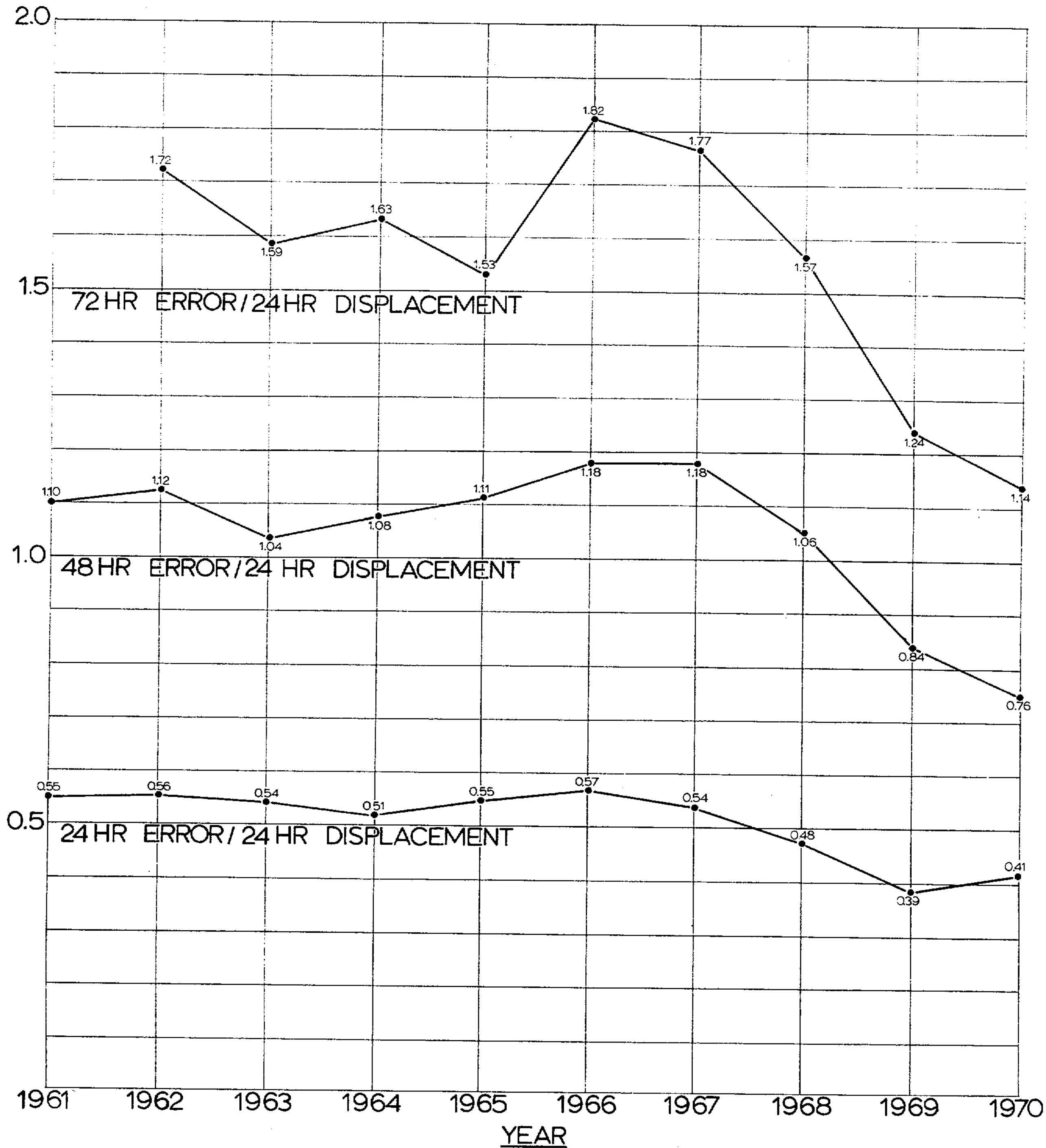

2.0
1.5
1.0
0.5
72 HR ERROR/24 HR DISPLACEMENT
48 HR ERROR/24 HR DISPLACEMENT
24 HR ERROR/24 HR DISPLACEMENT
1.72
1.59
1.63
1.53
1.82
1.77
1.57
1.24
1.14
1.10
1.12
1.04
1.08
1.11
1.18
1.18
1.06
0.84
0.76
0.55
0.56
0.54
0.51
0.55
0.57
0.54
0.48
0.39
0.41
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
YEAR

FIGURE 3-2

24 hour forecast errors to annual mean 24 hour typhoon displacement. The implication here is that as displacement per 24 hours, or speed of movement, increases so does forecast error. The validity of this implication is supported by the remarkable similarity in the two curves. Figure 3-2 presents 24, 48, and 72 hour mean errors normalized by dividing mean error by mean 24 hour displacement. This depiction reveals that little real improvement occurred until 1968 when a modest improvement was initially noted in 24 hour errors as well as the beginning of a dramatic improvement in 48 and 72 hour outlook errors.

Another method of estimating the difficulty of a year (or a forecast) is to normalize the error by the error made by any of the objective techniques.

The 1969 Annual Typhoon Report (FWC/JTWC, 1969) suggested using an objective extrapolation as the normalizing vehicle. Unfortunately a homogeneous comparison of extrapolative errors versus official errors is available only for 1968, -69, and -70, thus prohibiting a long term comparison of errors normalized in this fashion.

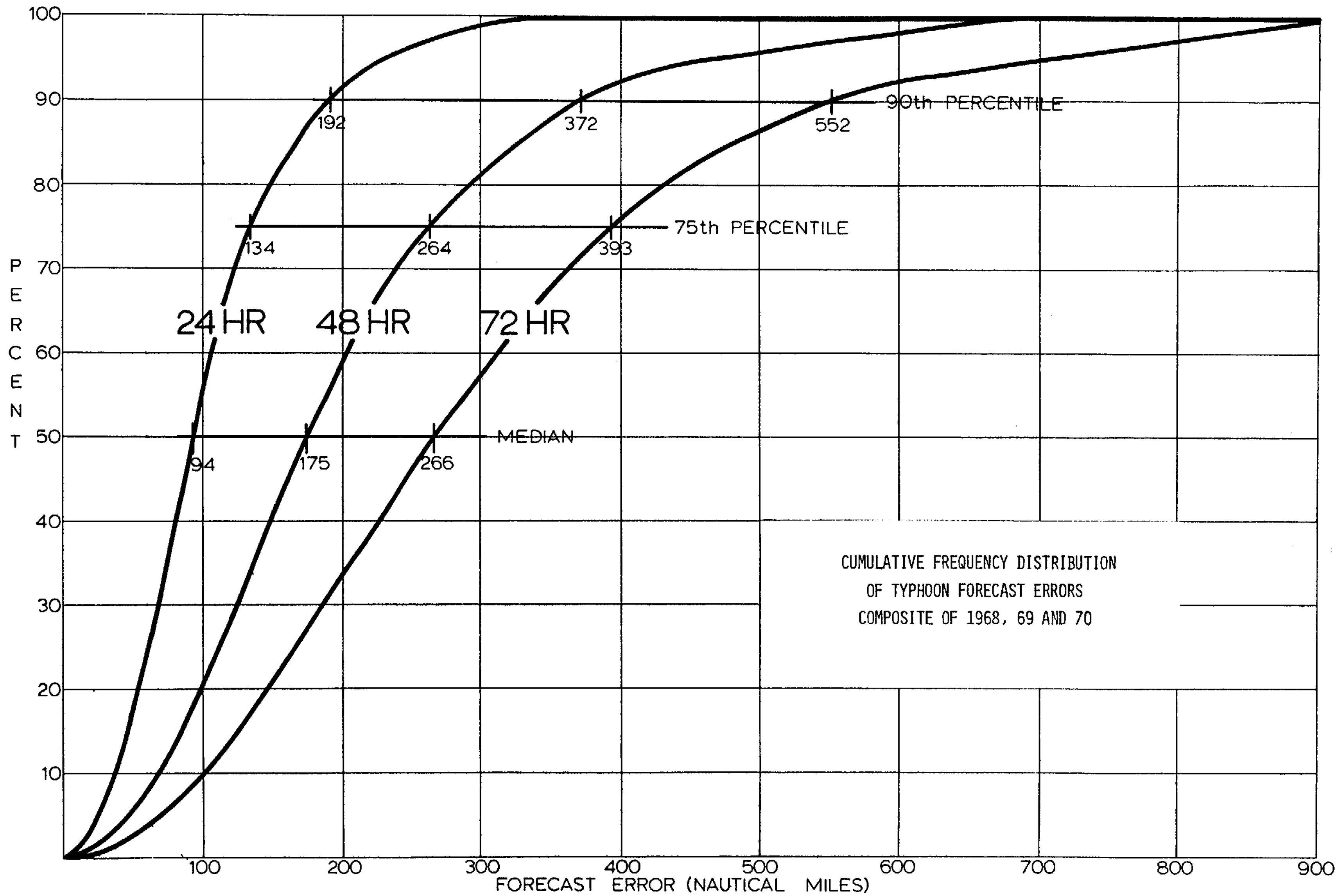
	1968	1969	1970
EXTRAPOLATION ERROR (N.M.)	108	131	121
OFFICIAL ERROR (N.M.)	103	121	103
NORMALIZED ERROR (%)	95.2	92.2	85.1

4. A SUGGESTED ERROR STANDARD

It is considered that a conservative estimate of the present level of forecasting capability can be made by combining the forecast errors made over the past three years which includes the period of apparent improved capability depicted in Figure 3-2.

Figure 3-3 is a cumulative frequency distribution of composited 1968, -69, and -70 forecast errors at 24, 48, and 72 hours. From this presentation an estimate of error confidence limits or percentiles can be deduced.

Mean vector and right angle or track errors for this combined period are given in Table 3-3.



CUMULATIVE FREQUENCY DISTRIBUTION
OF TYPHOON FORECAST ERRORS
COMPOSITE OF 1968, 69 AND 70
PERCENT
FORECAST ERROR (NAUTICAL MILES)
24 HR
48 HR
72 HR
90th PERCENTILE
75th PERCENTILE
MEDIAN
192
372
552
134
264
393
94
175
266

FIGURE 3-3

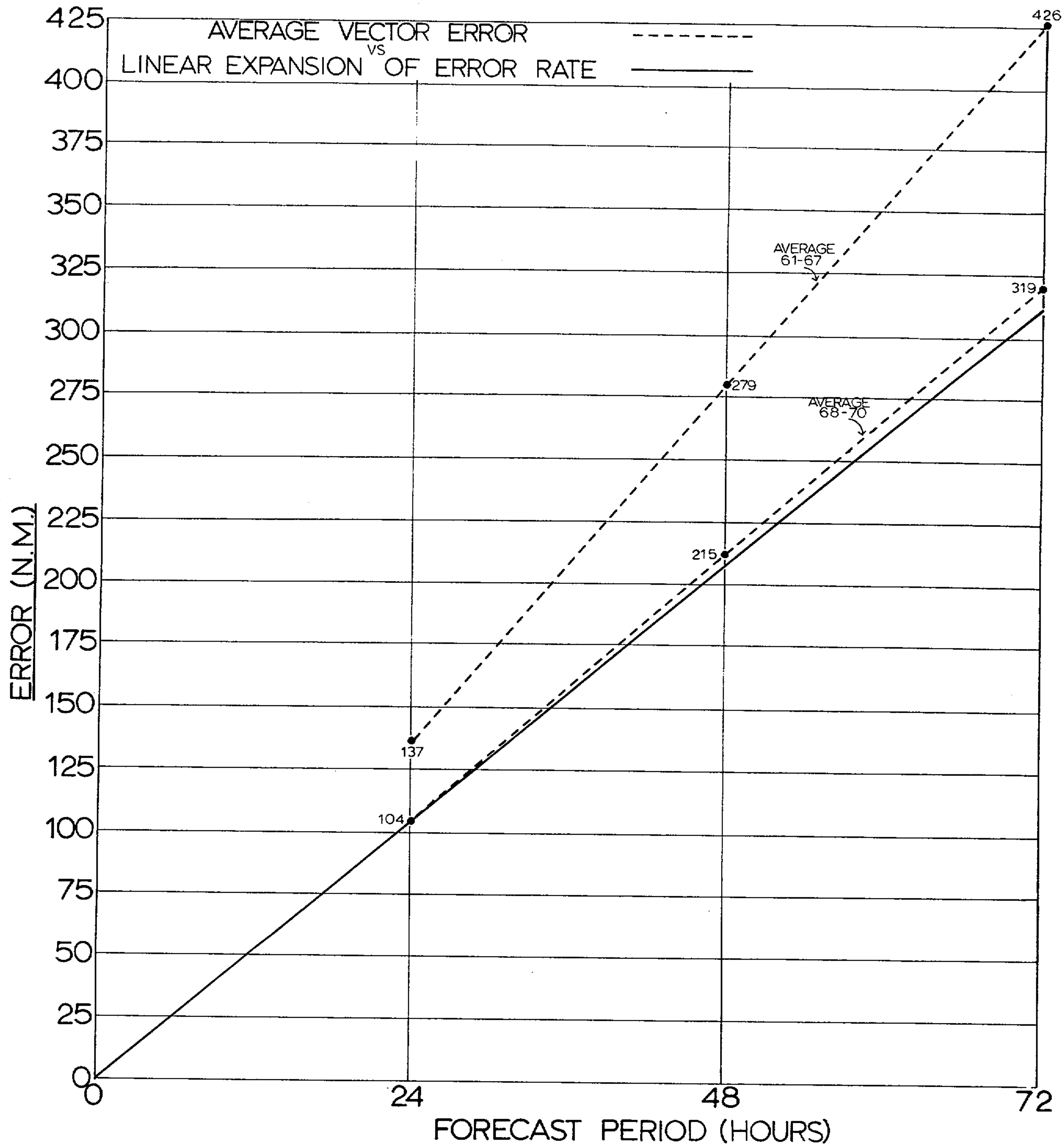

AVERAGE VECTOR ERROR
VS
LINEAR EXPANSION OF ERROR RATE
ERROR (N.M.)
425
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
426
AVERAGE 61-67
319
279
AVERAGE 68-70
215
137
104
0
24
48
72
FORECAST PERIOD (HOURS)

FIGURE 3-4

	MEAN Vector Error	MEAN Track Error
24 Hour	104 N.M.	64 N.M.
48 Hour	215 N.M.	131 N.M.
72 Hour	319 N.M.	200 N.M.

Composite mean errors for 1968 through 1970.

TABLE 3-3

A comparison of the means of Table 3-3 with the cumulative frequency distribution curves of Figure 3-3 indicate that the mean errors approximate the 60% confidence level. This combined period is considered to be representative of the present level of capability of typhoon forecasting.

Figure 3-4 compares the average errors for the period 1968-70 with those of 1961-67. This comparison reveals an average error reduction of about 25% or some 34 miles per 24 hour forecast interval. Figure 3-4 also illustrates the near linear expansion of forecast error with time. It is considered unlikely that a sub-linear expansion of errors can be achieved because the nature of forecast techniques tends to compound errors in the time-step process.

5. THE FUTURE

There are no dramatic schemes pending which would lead to significant reduction in forecast errors. There is some expectation that some of the larger errors can be reduced by judicious application of climatological probabilities. Simpson (1971) has indicated that Atlantic hurricane forecasts are kept within the HURRAN 50% probability ellipses. This would probably tend to reduce the large error cases. Such ellipses are output by the similar Pacific TYFOON program (Jarrell and Somervell, 1970) and this will be used in much the same way (although not likely as a hard and fast rule).

C. CLASSIC EXAMPLE OF FUJIWHARA INTERACTION

During early September 1970 tropical storms Ellen and Fran provided many anxious moments for the forecasters at JTWC and for the people on Okinawa because of their apparently strange and definitely unpredictable behavior. In fact, the forecast errors on Ellen and Fran were the highest of all the 1970 named storms. (See error statistics, Chapter 4.) After the dust had settled and their respective tracks were superimposed in post analysis it became evident that the explanation of their fickle maneuvers lies mainly in an extreme interaction between the two vortices a la Fujiwhara (1921 and 1923).

The best tracks of the two cyclones are depicted in Figure 3-5. The intersection of the tracks is southern Okinawa. Ellen passed across the island first followed by Fran some 15 hours later. Both tracks were well documented by numerous aerial reconnaissance and land radar fixes during most of their life time. Neither storm ever became very strong. Ellen hit a maximum of 45 knot sustained winds at point 5 on the best track and weakened thereafter. Fran attained 50 knot maximum sustained winds at point 4 on the best track and maintained this intensity through point 8.

To obtain the most vivid depiction of the interaction of the storm pair the steering flow was subtracted from the resultant movement in order to show the motion of the two relative to each other. The steering flow was assumed to be reflected by the track of the computed centers of rotation of the cyclone pair. A weighted center of rotation (center of mass) was located along the axis connecting the two storms at six hourly intervals using the following equation as suggested by Brand (1968):

$$d_1 = \frac{DV_2}{V_1+V_2}$$

where

d_1 is the distance to the center of rotation from cyclone 1

D is the total separation distance of the two cyclones

V_2 is the maximum wind speed of cyclone 2

V_1 is the maximum wind speed of cyclone 1

The resultant track of the centers of rotation is shown as the dashed line in Figure 3-5. In general the track is

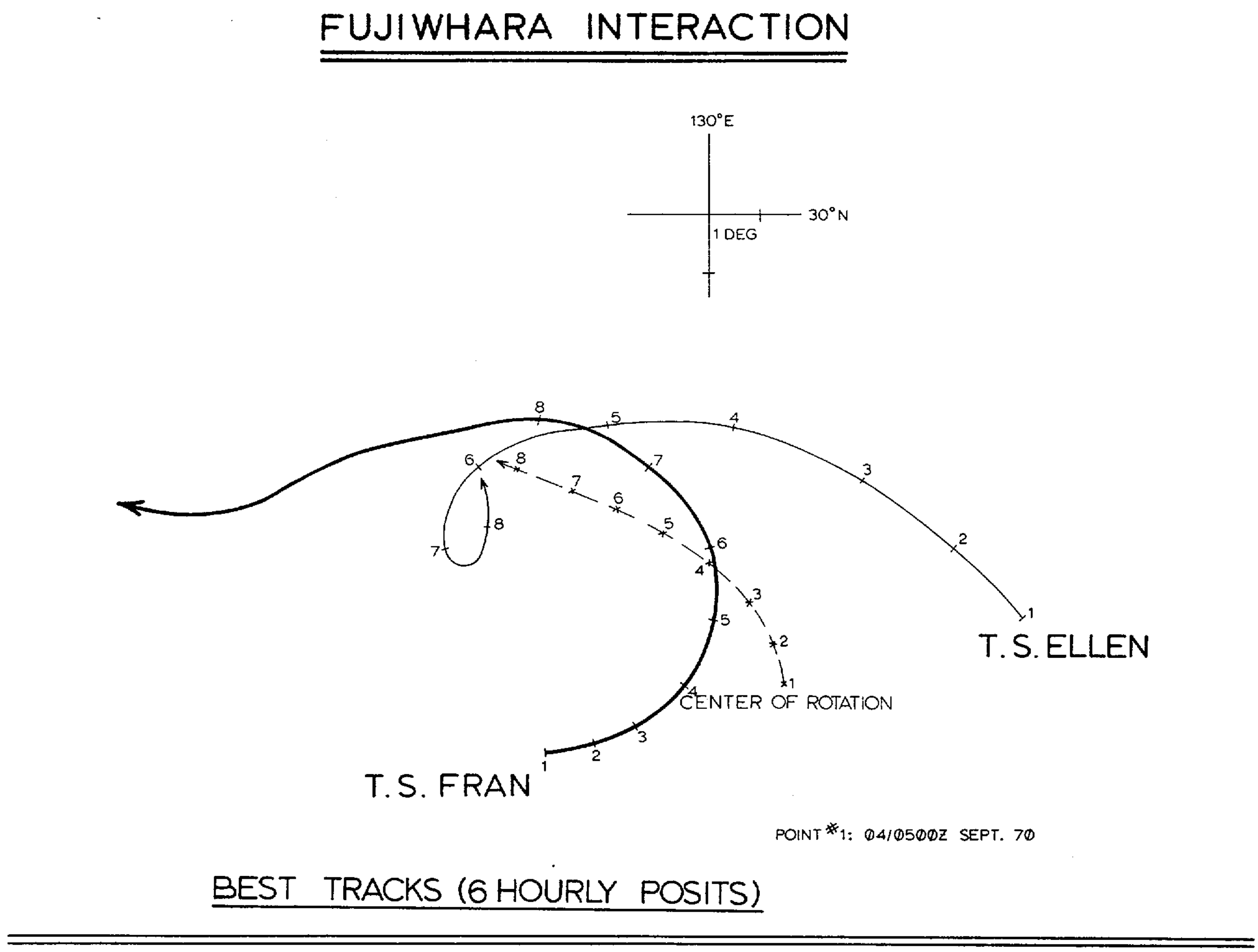


FIGURE 3-5

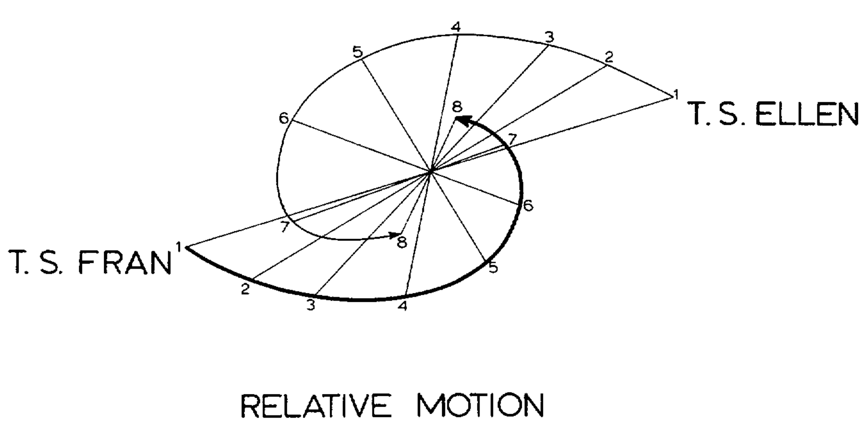


FIGURE 3-6

northwesterly at 10 knots, with some cyclonic curvature. This agrees closely with observed middle level steering during this period.

After subtracting this steering flow from the resultant movement of each storm the relative motion of the cyclone pair shows the interaction quite dramatically as can be seen in Figure 3-6. Riehl (1954) made a similar plot for a 1945 typhoon pair. See his Figure 11.44 for comparison.

The interaction of Ellen and Fran was a classic example of the Fujiwhara effect. In simple terms this effect can be explained as follows: When two cyclones are close enough to interact, the relative motion of the two is manifest in cyclonically convergent paths wherein the rate of rotation increases as the distance between the two storms decreases. During the 42 hours of interaction between Ellen and Fran, depicted in Figure 3-6, the two storms cyclonically rotated 220° about each other and converged from a distance 450 N.M. apart at point 1 to 140 N.M. at point 8. In reality, the effect was observed to have progressed even further with the likely possibility that Ellen was completely absorbed near the center of Fran. The last fix on Ellen was made at 06/0130Z, two and one half hours after point 8, at which time she was about 30 N.M. from the center of Fran at a location denoting a total rotation of 280° from the beginning of their interaction.

Brand (1968) plotted the 12-hour angular changes of binary systems versus the average separation distance between them during the period for numerous cases. He found a good correlation in support of the theory. See his Figure 2. Similar changes for the Ellen-Fran pair follow:

12 Hr Interval Between Points	Angular Change	Average Separation Distance
1-3	+31°	430 N.M.
3-5	+71°	290 N.M.
5-7	+80°	260 N.M.

These values plotted on the graph in his Figure 2 closely fit the regression equation computed from his data.

In retrospect, one notes a clear cut case of irony in the Ellen-Fran episode. Even though the data indicate that the Ellen and Fran interaction to be, to our knowledge, the most extensive example of the Fujiwhara effect ever documented, nevertheless it was unrecognizable during most of the period it was occurring.

D. AN EVALUATION OF AERIAL RECONNAISSANCE FIX ACCURACIES

1. INTRODUCTION:

The Joint Typhoon Warning Center (JTWC), in the course of following tropical cyclones, is dependent on aerial reconnaissance fixes. These include penetration fixes near the surface (usually done by the Navy's VW-1) and at the 700 mb level (normally done by the USAF's 54WRS) and aircraft radar fixes taken from outside the eye. It is helpful for the typhoon duty officer to have some idea of relative fix accuracy. Since most methods of predicting typhoon motion depend on the cyclone's movement during the previous 12 hours, "In some instances an error of as little as 10-15 degrees in computed direction of vortex motion based upon the position 12 hours previous and the present location can produce variations in the predicted displacement of 75-100 miles in 24 hours and 400 miles in 72 hours," (Simpson, 1971). Diagnoses are presented that compare deviations of penetration versus radar fixes and surface versus 700 mb level penetration fixes from the post-analyses best track (BT) as a reference. A further comparison is made between deviations right and left of BT at both the 700 mb level and the surface.

2. PROCEDURES:

A total of 911 fixes were used: 235 by surface penetration, 446 by 700 mb penetration, and 230 by radar. Table 3-4 gives a summary of the data.

SUMMARY OF DATA USED

Surface fixes (1967 through T. Georgia, 1970)	235
700 mb fixes (1967 through T. Georgia, 1970)	446
Total penetration fixes	681
Total radar fixes (1967-1969)	230
Total fixes used	911

TABLE 3-4

Fix deviations from BT were measured at right angles in nautical miles. Data were taken only from the time the storm reached 64 kts or greater to the time it degenerated to less than 64 kts.

Mention should be made of possible errors that exist in the data. It should be understood that the BT is a subjectively drawn track. Best Track Officers change from year to year and a bias possibly arises as one best tracker may give more emphasis to a fix of one type/level over another. It should be expected that, by using nearly four years of data, this bias has been minimized.

Nonrepresentative comparisons might also be introduced when a storm moves erratically since the best track is heavily smoothed in these situations. Therefore, areas of extreme track curvature and loops were neglected and those fix data were not considered.

Three comparisons were made, as listed below:

(1) The magnitude of deviations from BT at the surface and at 700 mb level were compared.

(2) The magnitude of deviation from BT of all penetration and radar fixes were compared.

(3) Comparisons between deviations to the right and to the left of BT at the surface and at the 700 mb level were made.

Statistical tabulations of the data used in each study are shown in Tables 3-5 and 3-6.

DEVIATION FROM BEST TRACK

CLASS INTERVAL	FREQUENCY OF FIXES			
(N.M.)	SURFACE	700MB	ALL PENETRATIONS	RADAR FIXES
0- 2.9	107	221	328	86
3- 6.9	70	138	208	49
7-10.9	24	38	62	35
11-14.9	13	29	42	26
15-18.9	12	10	22	9
19-22.9	2	6	8	19
23-26.9	5	2	7	3
27-30.9	0	1	1	0
31-34.9	1	0	1	2
35-38.9	0	0	0	0
39-42.9	0	1	1	0
43-46.9	1	0	1	0
55-58.9	0	0	0	1
MEAN (N.M.)	5.72	4.84	5.14	7.73

TABLE 3-5

DEVIATION FROM BEST TRACK (N.M.)	SURFACE LEFT	SURFACE RIGHT	700 MB LEFT	700 MB RIGHT
2- 4	37	42	73	80
6- 8	19	26	52	42
10-12	7	7	11	12
14-16	5	8	14	10
18-20	3	5	3	2
22-24	1	4	3	2
26-28	0	0	0	0
30-32	0	0	0	1
34-36	1	0	0	0
38-40	0	0	1	0
42-44	1	0	0	0
MEAN (N.M.)	7.49	7.52	6.87	6.25

DEVIATION LEFT AND RIGHT OF BEST TRACK
FREQUENCY OF FIXES

TABLE 3-6

3. RESULTS:

A summary of statistical results of the study is contained in Table 3-7.

SUMMARY OF RESULTS OF STUDY

Mean Deviation from Best Track			
Radar	7.73 N.M.		
Penetration	5.14 N.M.		
Mean Deviation from Best Track			
Surface	5.72 N.M.		
700 mb	4.84 N.M.		
Mean Right and Left Deviation from Best Track			
Surface	Left of Best Track	7.49 N.M.	
	Right of Best Track	7.52 N.M.	
700 mb	Left of Best Track	6.87 N.M.	
	Right of Best Track	6.25 N.M.	

TABLE 3-7

Comparing first the accuracies of total penetrations against those fixes made by radar, it can be seen that the mean deviation of radar fixes from BT was greater than that for all penetrations (surface plus 700 mb fixes) by 2.59 N.M. The statistical significance of these results were tested using the χ^2 test. Making the assumption that the radar fixes were a sample of the population (penetrations), it was found that at the .01 and .05 levels of confidence, the radar fixes were not representative of that population.

This same approach was used in comparing the surface fixes and 700 mb fixes. The surface fixes deviated more from BT than the 700 mb fixes by 0.88 N.M. Since there was nearly twice as many upper level fixes (446 at 700 mb and 235 at the surface), the 700 mb fixes were assumed to be the population. At both levels of confidence, .01 and .05, the surface fixes were statistically unrepresentative of the assumed population.

Comparing the mean deviations right and left of BT, it can be seen that there was virtually no difference (0.03 N.M.) at the surface. The 0.03 N.M. bias was to the right of BT. At the upper level, however, there was just over a half a mile (0.62 N.M.) greater mean deviation to the left of BT.

A probability test was used in both the above comparisons. At the surface and 700 mb level, it was hypothesized that there was an equal chance that the fixes would occur on either side of BT. The results (at both the .05 and .01 levels of confidence) indicated that this could be true--that there may have been an even probability that a fix could occur on either side of BT at either level, and the difference in means occurred by chance.

4. CONCLUSIONS:

If one regarded the plotted BT as representative of the mean path of the storm, then it appears that the radar fixes show a greater deviation than aircraft penetrations.

Figure 3-7 was constructed to show the cumulative percentage of fixes for penetrations and radar fixes as a function of deviation from BT. For instance, fifty percent of the penetrations are within ±3 N.M. of BT as compared to ±5 N.M. of BT for radar fixes. The greater deviation of an aircraft radar fix is not surprising as ranging and azimuth errors within the radar coupled with beam width distortion of the target must also be combined with possible navigation error of aircraft position (see Jordan, 1963 and Holliday, 1966). In updating typhoon position, the forecaster should note these accuracy statistics for considering possible biases in past motion that could affect his projected track. Results of this study also show that surface fixes

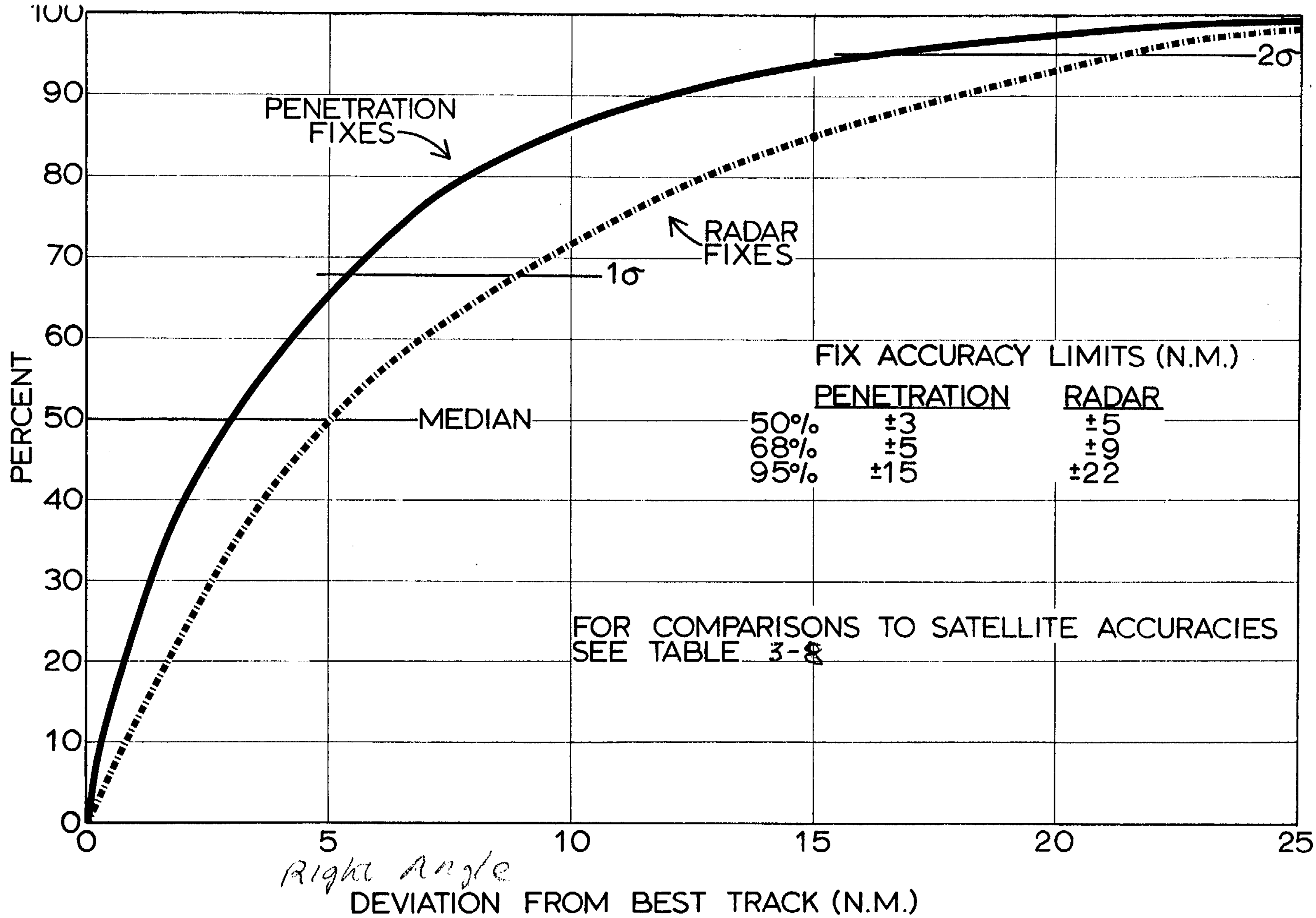

PERCENT
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
20
25
Right Angle
DEVIATION FROM BEST TRACK (N.M.)
PENETRATION FIXES
RADAR FIXES
1σ
2σ
MEDIAN
FIX ACCURACY LIMITS (N.M.)
PENETRATION RADAR
50% ±3 ±5
68% ±5 ±9
95% ±15 ±22
FOR COMPARISONS TO SATELLITE ACCURACIES
SEE TABLE 3-8

FIGURE 3-7

deviate more than the upper level (700 mb) fixes. These measured deviations from the mean path (BT) could possibly be a function of fix accuracy (navigation), discontinuity of parameters measured to determine fix location, and physical abnormalities such as transitory changes to storm structure and internal oscillatory motions. Since the data indicate the lower position of the storm shows more deviation than the middle level, it is quite possible either one or more of these influences decrease with altitude. More data need to be gathered in this area; unfortunately, no multi-aircraft penetrations are available in Pacific typhoons.

Attempting to summarize the data relative to right and left deviation is difficult. If the deviations are considered significant, there appears to be a slope within the lower portion of the typhoon (surface to 700 mb). This may be an influence of cases in the population which are near a more baroclinic environment or have been influenced by terrain such as passage of the Philippine Islands where the vertical profile is disrupted. This is not to imply there is a slope in the wall cloud but a difference in location of centers (i.e. cloud, wind and pressure centers) within the eye. If this slope does exist, it appears that it is from right to left with height relative to its direction of movement.

Three points in summary are noted: (1) radar fixes show a greater deviation than penetration fixes; (2) surface fixes appear to deviate more than 700 mb fixes, however, data are inconclusive; and (3) there is a suggestion of a vertical slope to the typhoon center, if only transitory, toward the left relative to the storm's movement.

E. MISCELLANEOUS SATELLITE BULLETIN (MSB) DATA

The Analysis Branch of NESS at Suitland, Maryland reviews daily Advanced Vidicon Camera System (AVCS) pictures for surveillance of tropical disturbances. (Pictures are stored with readout at a Command Data Acquisition Station then microwaved to NESS.) Upon detection, a bulletin is issued based on a description system of stages and categories of development. A total of 150 MSB's on tropical systems was issued for the Central and Western Pacific during 1970 as depicted in ESSA-9 and later ITOS-1 satellite pictures.

Verification of the position and intensity indicated by the MSB's was made on named storms in WESTPAC based on best tracks prepared at JTWC. Data were stratified by stage (Dvorak, 1968) and further classified into category intervals for intensity verification (Hubert and Timchalk, 1969).

Verification summation data are presented in Table 3-8.

MSB VERIFICATION VS. JTWC BEST TRACK

POSITION (all tropical storm tracks)

RIGHT ANGLE ERROR (N.M.)

Stage	B	C	C+	X
Cases	27	15	10	80
Mean	33	25	23	24
Standard Deviation	35	23	21	20

VECTOR ERROR (N.M.)

Stage	B	C	C+	X
Cases	27	15	10	80
Mean	66	52	71	39
Standard Deviation	60	30	63	25

INTENSITY ERRORS (KTS) (typhoon tracks)

	ALL				CATEGORY X				
Stage	B	C	C+	X	2	2.5	3.0	3.5	4
Cases	5	4	4	75	20	7	21	7	20
Algebraic Mean	-11	-14	-11	-8	-1	-7	-13	-14	-7
Absolute Mean	11	14	16	14	12	20	16	23	11
Standard Deviation	11	10	16	17	14	25	14	24	13

TABLE 3-8

F. NOTE ON OPTIMUM ALTITUDE FOR RECON OF TROPICAL DISTURBANCES

The utilization of APT from meteorological satellites over the past five years at FWC/JTWC Guam has been a significant tool in monitoring the vast data-void areas of the West Pacific for initial detection of tropical cyclones. The daily satellite view affords early surveillance of convective systems which may eventually act as a potential storm embryo.

The indication of a development tendency in the cloud pattern from the satellite picture has allowed early aircraft investigation of the suspect area often before the disturbance has reached the depression category. At this early stage, the perturbation is usually weakly defined in both surface wind and pressure fields since much of the relative vorticity is expressed in terms of cyclonic horizontal shear while the pressure gradient is relatively weak except in the disturbance's northern periphery. Due to the lack of identifiable pattern at this stage, the standard low level investigative (500-1500 ft.) often encounters difficulty describing significant features in the wind and pressure fields that can mark the system as an entity.

The task which faces the typhoon forecaster is to identify and determine a synoptic feature which may tab or tag the state of development of these suspect tropical disturbances and use this to monitor its continuity for signs of further intensification. It would therefore be advantageous that the most descriptive information on the system be provided by the investigating aircraft.

A study prepared by Williams (1970) conducted on the occurrence of cloud clusters in the West Pacific (October 1966-October 1968) showed a distinguishing feature in vertical profiles of relative vorticity at cluster centers between the pre-storm and non-developing types (Figure 3-8). A distinct maximum of relative vorticity was shown for the pre-storm cluster occurring at the 700-500 mb interval.

Since vorticity is expressed mostly in terms of curvature in this layer of the trades (due to the decrease in strength of the basic flow with height; see LaSeur, 1966) it would be likely from the peak of relative vorticity noted by Williams that a marked curvature would be present and also a tendency for a circulation to first form in this layer. The classic model set forth by Riehl (1954) of the wave in the easterlies shows a distinct curvature appearing between the 850-500 mb layer with the existence of a closed vortex at 15,000 feet. Evidence that the maximum amplitude of Atlantic wave disturbances occurs between 5000-15000 feet has also been well documented by Frank (1969).

VERTICAL PROFILES OF 4° -SQUARE AREA

AVERAGE RELATIVE VORTICITY AT CLUSTER CENTERS

(From Atmospheric Science Paper No. 161, Colorado State University, Williams, 1970)

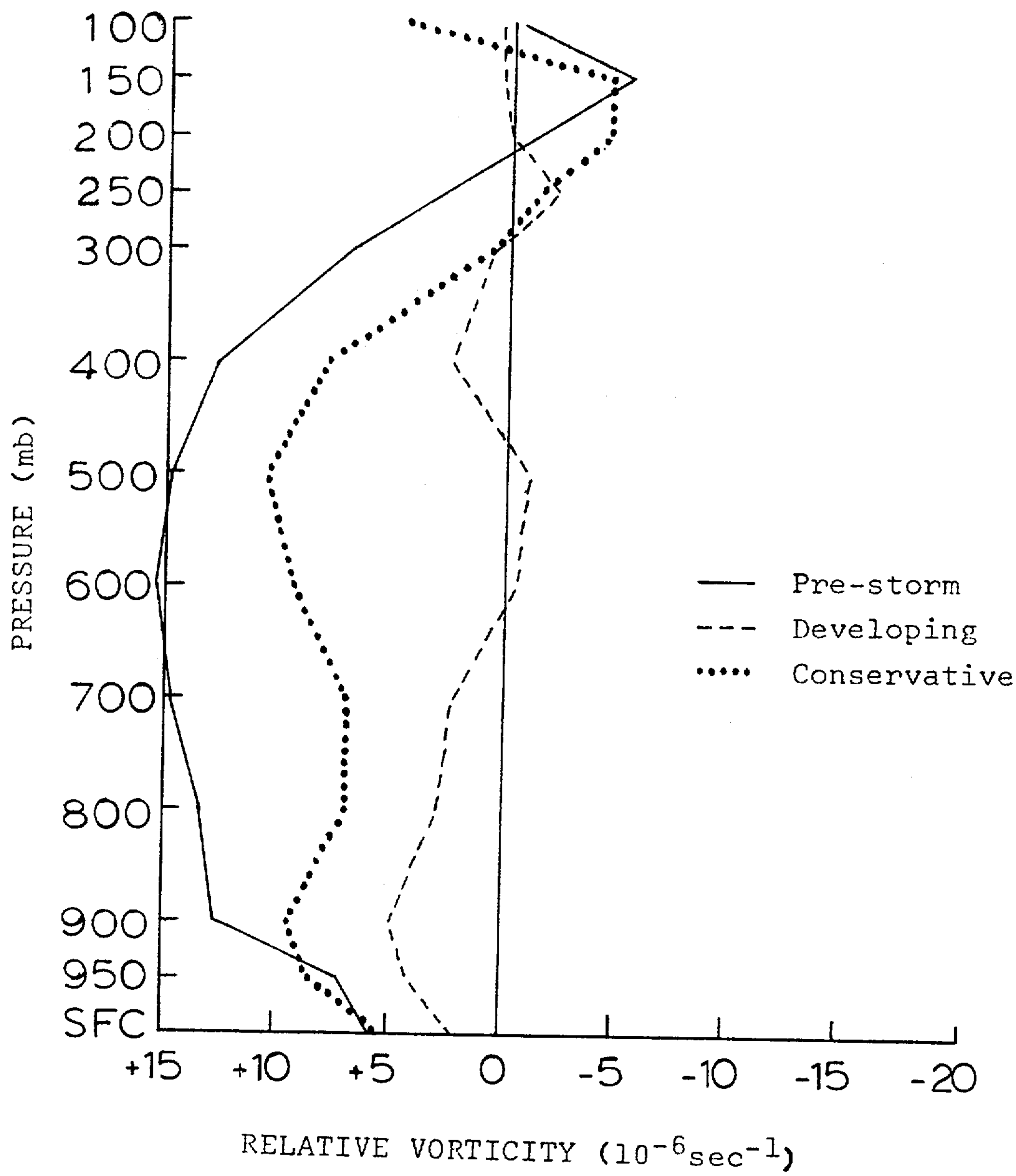


FIGURE 3-8

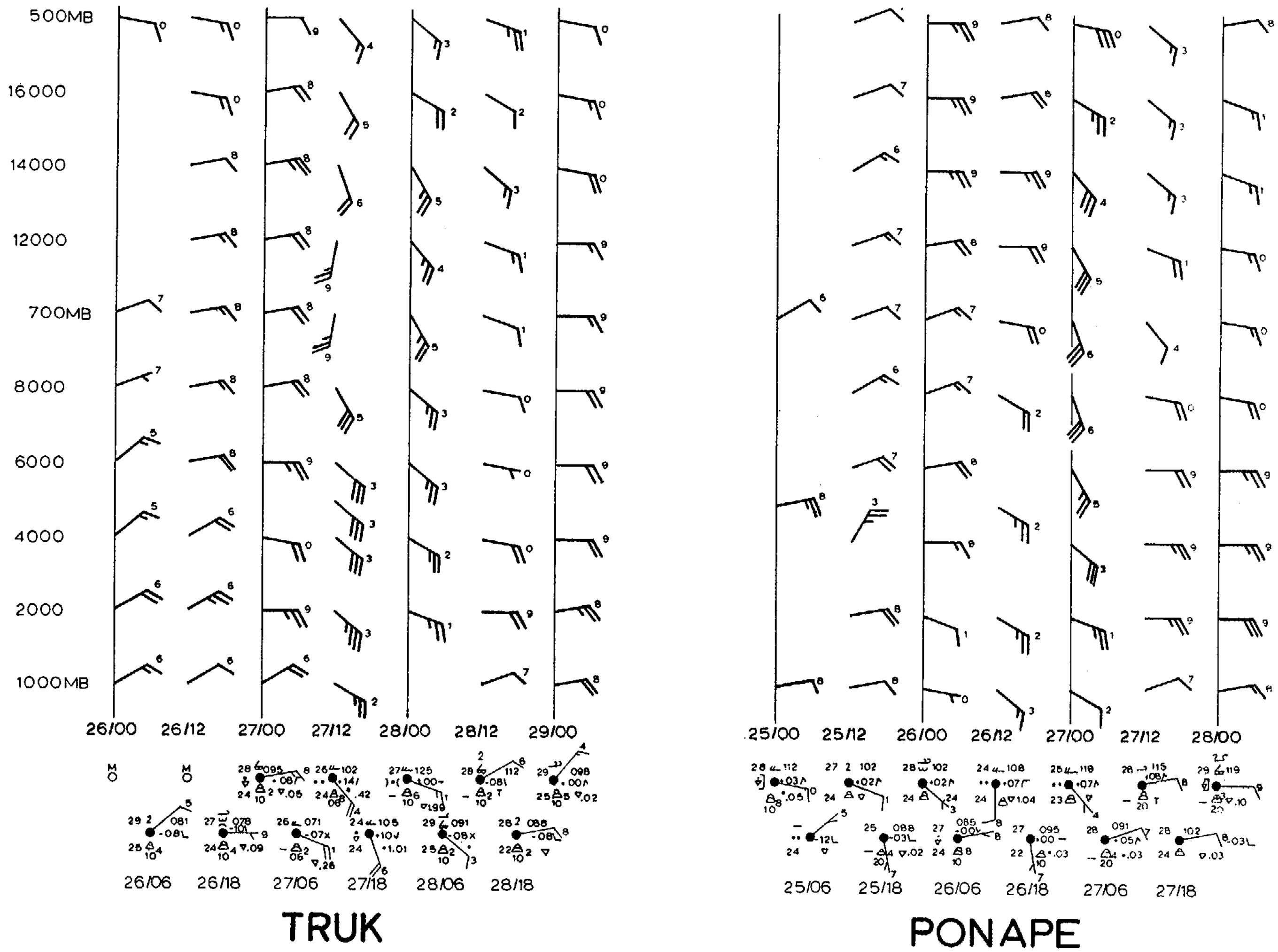
An example for illustration in the West Pacific would be the pre-storm disturbance passing through the Central Caroline Islands during late June 1970. Its early track placed it within the rawinsonde network of the Trust Territories giving an early view of its wind distribution in the vertical. The disturbance initially appeared as a cloud cluster system in the Marshalls on the 24th, tracked westward at 15 kts and moved into the Central Carolines on the 26th with satellite views depicting an extensive increase in convective activity by this time.

The time cross section for Ponape Island's rawin indicated a strong cyclonic shift from 6000-14000 feet between the period 26/00Z and 27/00Z with passage of the perturbation (Figure 3-9). Later Truk (360 N.M. east of Ponape) showed an increase in amplitude of the system as a sharp shift at 10-12,000 feet to a westerly component was detected in its rawin. Although it was evident that a vortex had developed in the lower troposphere, surface data in the vicinity indicated only a weak reflection in the wind field and pressure across the area ranged from 1008 to 1010 mb. Satellite DRIR view by this time (Figure 3-10) showed an organized character to the disturbance cloudiness at least of a stage B classification (Dvorak, 1968).

The suspect area was investigated the following morning (28th) by a recon aircraft at low levels (1,500 ft.) southeast of Guam near Satawal Atoll. Circulation at the surface could not be detected after extensive search of the area. However, the presence of a vortex at 700 mb was indicated as the aircraft passed through the disturbance and encountered a wind shift at this altitude before returning to Guam. With exception of a band of strong easterlies in the system's northern region, the pre-storm system remained weakly reflected in the surface wind field while a flat pressure gradient existed in the general area with values ranging from 1005 to 1007 mb (Figure 3-11). The cloud pattern depicted by the afternoon satellite view revealed a continued organized pattern appearing close to a stage C classification (Figure 3-12).

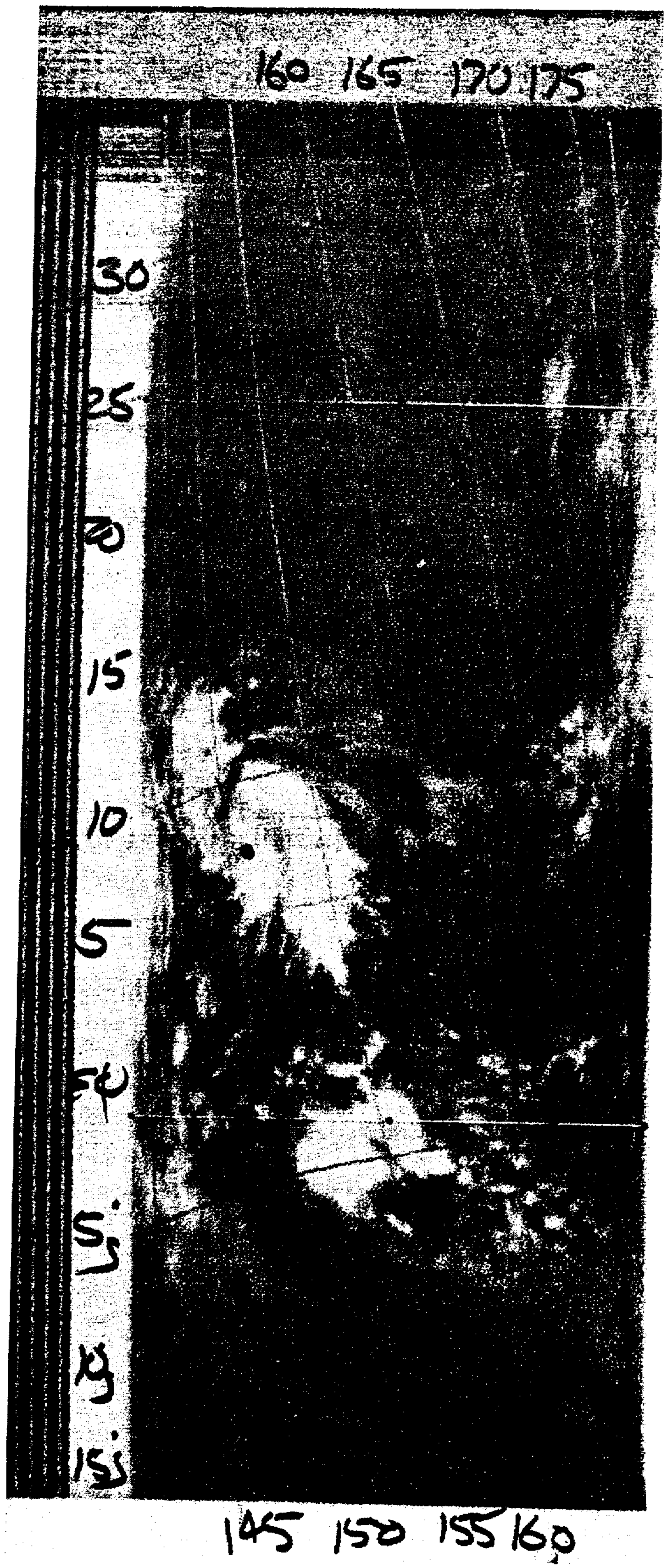
The disturbance passed south of Guam that evening with a follow up aircraft locating Tropical Storm Olga the following morning (29th) north of Ulithi Island with a definite surface circulation, a forming wall cloud, and a 993 mb central pressure.

A complete recon investigation at the 700 mb level the previous day probably would have enabled the detection of a clear-cut perturbation in the wind field providing a more meaningful description of the potential storm embryo than could have been determined from the low level investigation.



TIME CROSS SECTIONS OF RAWIN PROFILES
FOR TRUK AND PONAPE ISLANDS DURING
PASSAGE OF THE PRE-OLGA DISTURBANCE
LATE JUNE 1970

FIGURE 3-9



NIMBUS III DIRECT READOUT INFRA-RED (DRIR)
27 JUNE 1970 1247GMT

(Dot in Cloud Mass is Approximate Location of Truk Island.)

FIGURE 3-10

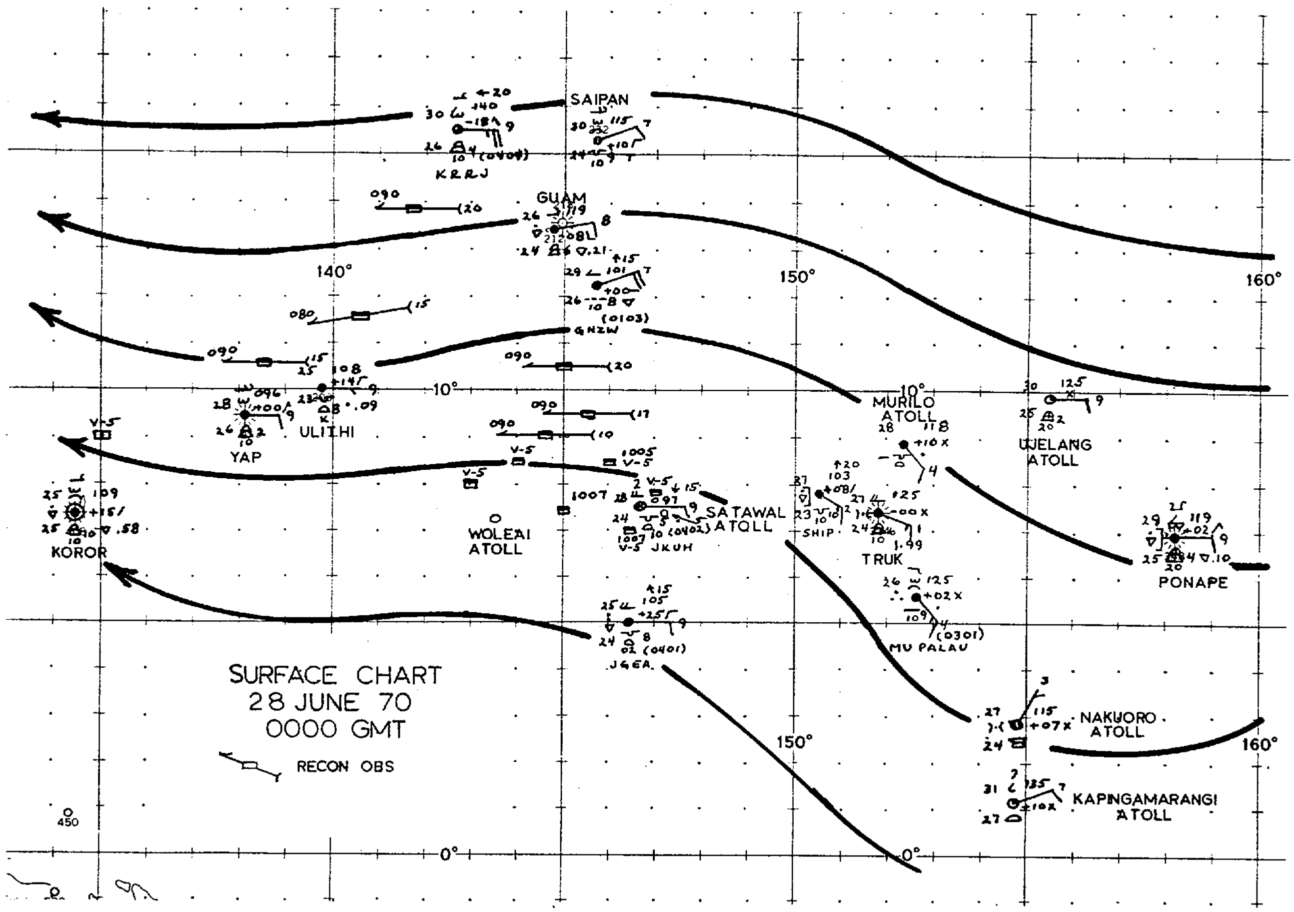


FIGURE 3-11

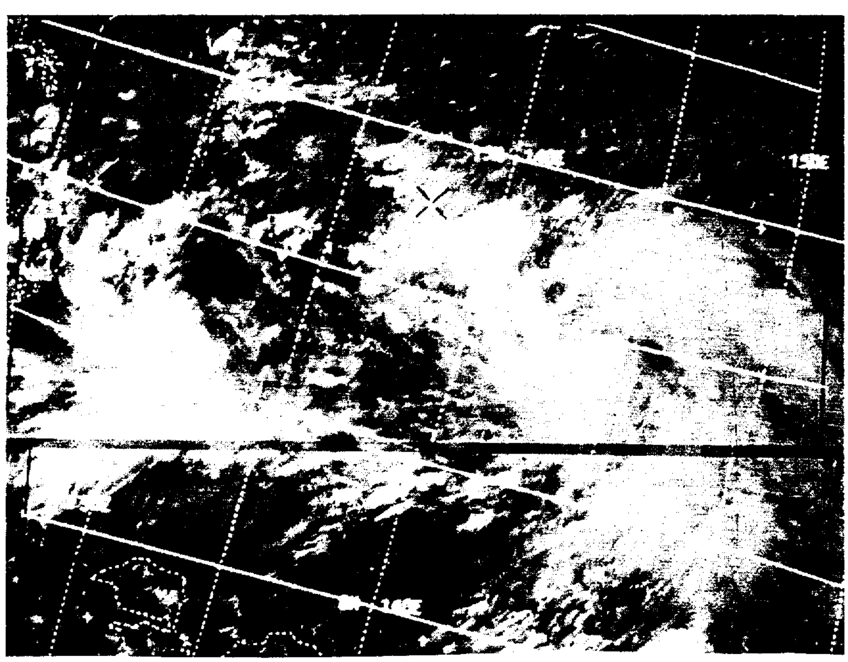


FIGURE 3-12

ITOS-1 VIEW OF
PRE-OLGA DISTURBANCE
28 JUNE 1970 0528GMT

The significance of an intermediate level investigation then is to label a conservative synoptic feature that could be tied to these suspect systems. Thus the forecaster may have some way to best evaluate the disturbance and determine to what state the development process has progressed.

It should be pointed out that the assumption that all significant disturbed weather over tropical oceans can be tied to moving perturbation of the wind field is not valid (see Zipser, 1971 and Simpson et al, 1967). The object of this note is to place emphasis on disturbances suspect of further development and how to best mark the system as an entity by aircraft recon.

The optimum compromise level for recon investigation in the early stages would appear to be the standard 700 mb level.* Several flights were conducted at the 700 mb level during the 1970 season with encouraging results. It is hoped more data will become available during the 1971 season for further evaluation.

*Obviously the low levels must eventually be investigated to provide definite evidence of the birth of a tropical cyclone.

G. TROPICAL CYCLONE INTENSITY VERIFICATION

1. INTRODUCTION:

Intensity forecasting is recognized as one of the more difficult typhoon forecasting problems, yet the literature on the subject is relatively sparce. This is probably due to the overwhelming role played by the prog track which must be good before an intensity forecast is meaningful (regardless of its accuracy) in adapting the typhoon warning to the local forecast. Since track forecasts have gradually improved over the years, the emphasis on intensity has increased.

Prior to 1969 there was no attempt at JTWC to verify forecasts of intensity. The 1969 verification consisted of a comparison of mean intensity errors and the bias in intensity forecasts at various time intervals. This is useful and will be continued for comparison, but it gives equal weight to a given error on a super typhoon and the same error on a minimal tropical storm. In the former case a 20 knot error is of little significance whereas in the latter it would be very important. It is felt that this deficiency can be overcome by describing errors as a fraction of the observed wind; this type verification is presented later.

2. INTENSITY FORECASTING AND VERIFICATION:

As pointed out in Chapter 1 the basic intensity forecasting technique is a linear extrapolation of past rate of intensification subjectively modified by expected conditions along the predicted track (FWC/JTWC, 1969). Thus there are two independent phases of the forecast, the first requires the determination of the current and recent past intensity and the second involves a synoptic evaluation along a predicted track. The errors incurred in the latter are reasonably random; they are caused by track errors, deficiencies in forecasting the environment along the track and lack of adequate methods to relate the predicted environment quantitatively to intensity changes. Progress in improving this aspect of the problem has been slow although some relationships are known. Synoptic conditions for maximum intensity of tropical cyclones were discussed by Miller (1957). The geographical location of the principal feeder band of the storm as determined by radar and satellite is weighted by the NHC, Miami (Simpson, 1971) in assessing development; this has been enhanced by the acquisition of near real time film loops from the ATS III geostationary satellite. These, of course, are not available for WESTPAC. The Navy Weather Research Facility (1970) has developed rules for evaluating the reintensification potential of tropical cyclones which have crossed the Republic of the Philippines and entered the South China Sea.

The problems in linear extrapolation of intensity as a first guess are obvious and relate to difficulty in ascertaining the instantaneous intensity of the storm at two or more recent points along the track. Reconnaissance estimates cloud the issue (Jordan and Fortner 1960 and 1961) since there is a bias introduced by the fact that penetration is necessarily made in the weakest quadrant, also areas of strongest winds are often obscured by clouds and heavy precipitation. To overcome these problems, a wind/pressure relationship is commonly used and the extrapolation is made on minimum pressures rather than maximum winds. Clearly, if one of two estimates of intensity is in error, the rate of intensification will be deduced incorrectly and the forecast intensities will suffer in like manner, but this type error should be random. When both estimates are off by about the same amount in the same direction, the forecasts may be expected to be in error by nearly a constant. This type error might be expected from an inadequate pressure-wind relationship, and a part of the bias evident in 1969-1970 verification can be attributed to this problem. The 1968 Annual Typhoon Report introduced a wind-pressure relationship which was a modification of a similar relationship presented in 1963 by JTWC. During the past two years confidence in that relationship gradually lessened until in mid-1970, it was virtually abandoned altogether. As a result the typhoons of the first half of 1970 were forecast using one relationship and verified against a post-analysis based on a combination of other relationships, mainly the Takahashi equation (1939). As a result, the mean errors for both halves of the year are about the same but the bias diminished significantly in the latter half. (See Table 3-10.) The bias for both halves of 1970 as well as 1969 was consistantly on the low side (under forecasts), that part not explained by the inadequate pressure-wind relationship is largely attributed to the inability of forecasters to anticipate periods of maximum deepening. These surges of deepening are typically of short duration, 12 to 36 hours, and are usually followed by a plateau, so that maximum underforecasting bias (in terms of knots of error per forecast hour) occurs near 24 hours since extrapolation tends to hit the plateau at longer periods.

Table 3-9 compares intensity forecasts of 1970 to 1969.

	ABSOLUTE MEAN ERROR (KTS)					ALGEBRAIC MEAN ERROR (KTS)				
	WARNING	12HR	24HR	48HR	72HR	WARNING	12HR	24HR	48HR	72HR
1969	4.9	9.0	13.7	22.9	30.2	-1.9	-1.4	-4.2	-6.8	-13.3
1970	6.6	12.1	16.7	21.2	21.7	-3.3	-5.3	-8.6	-8.9	-11.0

TABLE 3-9

Notice the apparent degradation in 1970 when a different standard was used for verification than was used for forecasting as opposed to 1969 when the same standard was used throughout.

Table 3-10 compares the first half of 1970 to the last half. (The season is divided after Typhoon Clara which marked the point after which the 1968 relationship was abandoned.)

	ABSOLUTE MEAN ERROR (KTS)					ALGEBRAIC MEAN ERROR (KTS)				
	WARNING	12HR	24HR	48HR	72HR	WARNING	12HR	24HR	48HR	72HR
EARLY 1970	7.7	12.4	16.2	20.0	23.4	-5.3	-8.0	-10.8	-10.2	-18.0
LATE 1970	5.6	11.8	17.2	22.2	20.3	-1.4	-2.7	-6.5	-7.9	-5.4

TABLE 3-10

While no significant difference is apparent in the absolute mean errors, the low side bias was markedly reduced.

3. A MEASURE OF ACCEPTABILITY:

As mentioned earlier an analysis of intensity errors as a fraction of observed winds was made. This concept implies that as wind speed increases, so does the acceptable error in wind forecasts. With this implication in mind, some acceptability criteria were established (from the viewpoint of adequacy for disaster control planning) as follows:

	12 Or 24 Hours	48 Or 72 Hours
Accurate to within measurement error	Error $\leq$ 10%	Error $\leq$ 10%
Adequate	Error $\leq$ 20%	Error $\leq$ 30%
Useful	Error $\leq$ 30%	Error $\leq$ 40%
Inadequate	Error > 30%	Error > 40%

Note the criteria become less stringent at longer time intervals since changing the degree of readiness is still possible.

Figure 3-13 shows the cumulative distribution of intensity forecast errors as a percent of observed wind for 24 and 48 hours. Envelopes of 10, 20, and 30% errors are shown. Based on Figure 3-13 and above criteria, the distribution of

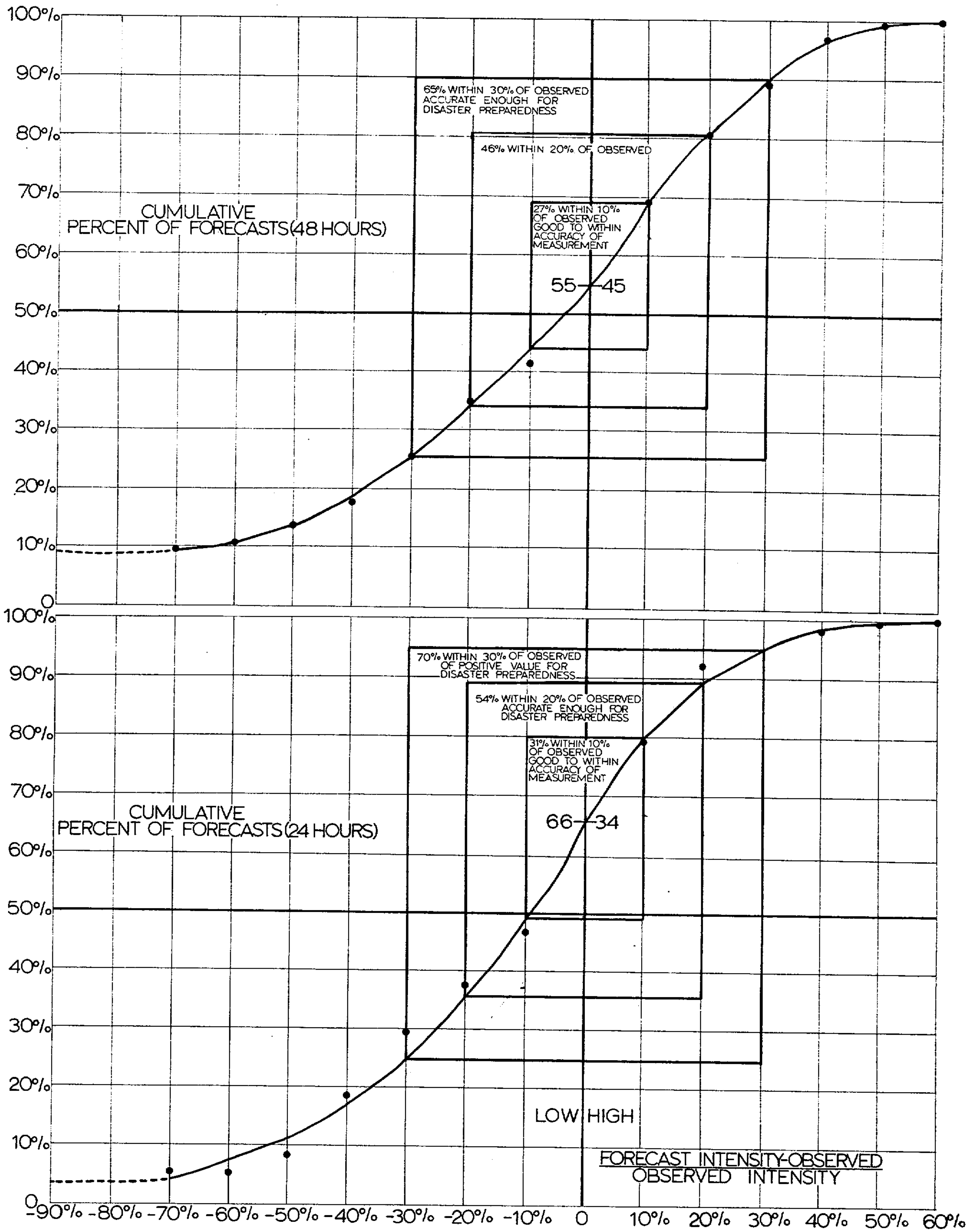

CUMULATIVE PERCENT OF FORECASTS(48 HOURS)
65% WITHIN 30% OF OBSERVED ACCURATE ENOUGH FOR DISASTER PREPAREDNESS
46% WITHIN 20% OF OBSERVED
27% WITHIN 10% OF OBSERVED GOOD TO WITHIN ACCURACY OF MEASUREMENT
55 45
CUMULATIVE PERCENT OF FORECASTS (24 HOURS)
70% WITHIN 30% OF OBSERVED OF POSITIVE VALUE FOR DISASTER PREPAREDNESS
54% WITHIN 20% OF OBSERVED ACCURATE ENOUGH FOR DISASTER PREPAREDNESS
31% WITHIN 10% OF OBSERVED GOOD TO WITHIN ACCURACY OF MEASUREMENT
66 34
LOW HIGH
FORECAST INTENSITY-OBSERVED / OBSERVED INTENSITY
0 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
-90% -80% -70% -60% -50% -40% -30% -20% -10% 0 10% 20% 30% 40% 50% 60%

FIGURE 3-13

acceptable intensity forecasts during 1970 is as follows:

	24 Hour	48 Hour
Accurate to within measurement error	31%	27%
Adequate	54%	65%
Useful	70%	79%
Inadequate	30%	21%

Notice from Figure 3-13 that these acceptable percentages could be significantly enhanced if the low side bias can be reduced.

4. FUTURE:

A suggestion (FWC/JTWC, 1969) to attempt to improve forecasts by studying cases of gross errors as well as climatological rate of intensification appears valid. Fung (1970) has suggested that the tropical cyclone population tends to show peak occurrence around three minimum pressure values, 970 mb, 940 mb, and 915 mb. This work and a climatology of super typhoons (FWC/JTWC, 1970) imply favored seasons and geographical locations for occurrences of tropical cyclones within these intensity categories, thus some improvement in intensity forecasting might be realized by an applied climatological approach to forecasting. Further applied climatology studies relative to tropical cyclone intensity are currently underway at Headquarters First Weather Wing, USAF in Hawaii and at the Navy Weather Research Facility in Norfolk, Virginia.

H. A CLIMATOLOGICAL STUDY OF SUPER TYPHOONS

1. INTRODUCTION:

One of the most awesome natural forces on earth is the super typhoon. The name Super Typhoon was coined to catagorize the stronger and larger typhoons of the Northwestern Pacific. By definition any typhoon that attains at least 130 knots sustained surface winds during its lifetime is recorded as a super typhoon. It is not known when this classification was first conceived. The first known reference to the term was by Kinney (1955) when he used it to describe large typhoons in general. The Glossary of Meteorology (1959) makes no mention of the term. The first official use of the term by JTWC was in their 1963 Annual Typhoon Report. Nevertheless it has attained common usage both as a technical classification and by the news media as a descriptive term for the stronger typhoons. It is quite probable that the 130 knot delineation was chosen because it is the value, to the nearest 5 kts, that is twice the 64 knot intensity adopted for classification as a typhoon.

2. PROCEDURES:

The dividing line of 130 knots can be difficult to determine since the data are either lacking or those which are observed can be highly subjective, particularly at these extreme intensities. However, since the establishment of the Pacific Command Joint Typhoon Warning Service in 1959 routine aerial reconnaissance coverage of tropical cyclones in the Western Pacific has been rather thorough and subsequent documentation of these storms by the Joint Typhoon Warning Center (JTWC) has been quite comprehensive. It is felt that the data accumulated by JTWC during the past 12 years for 231 typhoons constitute a fairly accurate base and population upon which to build a climatology of super typhoons.

The annual typhoon reports for 1959 through 1970 (FWC/JTWC, 1959-1970) were consulted. All typhoons that were best tracked at 130 knots or more were listed. Seventy-two typhoons were documented as super typhoons. The data on each of these were examined to weed out any obvious overestimations. Since observing surface winds in excess of 100 knots is highly subjective each of the storms was required to pass a minimum sea level pressure correlation test. Holliday (1969) listed most of the accepted equations in use today for correlating maximum surface winds in a tropical cyclone with the recorded minimum sea level pressure. Of the non-latitude influenced equations, Fletcher's (1955) is the most liberal wherein maximum sustained wind, in knots, $V_{max}=16\sqrt{1010-P_c}$, where P_c is the minimum sea level pressure (mb). In order to give the benefit of any doubt to the storm his equation was used to test the 72 typhoons for consistency. No attempt was made to upgrade any typhoons not

SUPER TYPHOONS
(1959-1970)

YEAR	NAME	BECAME SUPER TYPHOON DATE/TIME(Z)	LOCATION LAT (N)	LOCATION LONG (E)	LOWEST SLP DURING LIFETIME
1970	OLGA	30 JUN 2300	17.7	128.8	904
	ANITA	19 AUG 1400	25.4	136.8	912
	GEORGIA	10 SEP 1100	15.6	124.3	904
	HOPE	23 SEP 1800	20.2	148.0	895
	JOAN	12 OCT 1100	12.2	126.7	901
	KATE	18 OCT 0500	06.0	126.4	938
	PATSY	18 NOV 0500	14.4	127.3	918
1969	VIOLA	25 JUL 2300	17.6	126.3	897
	ELSIE	22 SEP 2300	18.1	145.0	890
1968	MARY	23 JUL 2300	20.8	141.1	924
	WENDY	30 AUG 1700	18.9	144.0	917
	AGNES	03 SEP 0500	17.6	141.0	904
	ELAINE	26 SEP 1800	16.0	126.0	908
	FAYE	04 OCT 1700	18.6	162.1	911
1967	OPAL	02 SEP 1800	19.4	161.0	919
	CARLA	14 OCT 0600	13.0	134.8	901
	EMMA	02 NOV 0300	10.5	131.6	908
	GILDA	13 NOV 1800	15.0	141.1	890
1966	KIT	25 JUN 1400	17.1	130.8	912
	ALICE	01 SEP 1200	25.8	128.7	937
	CORA	02 SEP 1800	22.3	131.9	917
1965	DINAH	15 JUN 1800	15.3	129.0	932
	FREDA	12 JUL 0300	14.5	127.8	922
	JEAN	04 AUG 0300	25.7	126.8	940
	LUCY	17 AUG 1200	23.6	154.5	940
	MARY	17 AUG 0100	20.9	129.3	936
	OLIVE	28 AUG 1800	21.4	148.1	936
	SHIRLEY	09 SEP 1800	31.3	132.9	936
	TRIX	14 SEP 0000	22.2	131.1	930
	BESS	29 SEP 1200	18.8	143.6	901
	CARMEN	06 OCT 1200	18.0	146.0	916
	FAYE	23 NOV 0000	14.4	130.1	925
1964	HELEN	30 JUL 0000	23.3	142.6	931
	IDA	06 AUG 0000	16.2	126.3	927
	SALLY	06 SEP 0600	14.8	138.4	894
	WILDA	20 SEP 1800	20.1	139.3	905
	LOUISE	17 NOV 0600	07.1	132.7	914
	OPAL	11 DEC 1200	08.3	135.9	903
1963	SHIRLEY	15 JUN 1200	16.3	130.9	935
	WENDY	12 JUL 1200	15.9	139.8	928
	BESS	04 AUG 1200	20.7	136.8	930
	GLORIA	08 SEP 1800	21.1	128.9	921
	JUDY	02 OCT 0200	23.0	143.1	917
	KIT	09 OCT 0000	20.9	132.1	929
	LOLA	17 OCT 1200	21.1	135.8	945
	SUSAN	25 DEC 0600	14.9	143.5	932
1962	GEORGIA	20 APR 0000	14.4	141.0	936
	OPAL	04 AUG 2000	21.0	124.8	910
	RUTH	15 AUG 1800	20.2	145.8	916
	AMY	01 SEP 0900	19.0	132.9	935
	EMMA	04 OCT 1200	20.7	145.8	903
	KAREN	08 NOV 1630	09.8	152.6	897
1961	TESS	28 MAR 0600	14.1	135.5	937
	BETTY	25 MAY 1200	19.1	122.9	946
	NANCY	08 SEP 1800	09.0	156.8	882
	PAMELA	10 SEP 2300	23.6	127.5	914
	TILDA	29 SEP 1200	20.4	138.0	917
	VIOLET	06 OCT 0000	16.5	143.5	882
	DOT	09 NOV 1800	17.8	149.1	922
	ELLEN	08 DEC 1200	13.5	125.9	945
1960	SHIRLEY	30 JUL 1500	22.4	124.0	908*
	OPHELIA	30 NOV 1200	11.1	137.3	928
1959	TILDA	19 APR 0600	14.5	137.2	930*
	JOAN	28 AUG 0130	18.8	130.0	891
	SARAH	14 SEP 0200	19.9	129.3	905
	VERA	22 SEP 2200	18.0	144.2	896
	CHARLOTTE	12 OCT 1800	17.0	126.6	905
	DINAH	18 OCT 1200	11.7	143.9	913
	GILDA	16 DEC 0600	09.9	131.5	914
	HARRIET	30 DEC 0000	14.2	127.4	926

*Extrapolated from min 700 mb height

TABLE 3-11

SUPER TYPHOONS

YEAR	J	F	M	A	M	J	J	A	S	O	N	D	SUPER TYPHOONS	TYPHOONS	RATIO
						MONTH									
1959				1				1	2	2		2	8	17	.47
1960							1				1		2	19	.11
1961			1		1				3	1	1	1	8	20	.40
1962				1				2	1	1	1		6	24	.25
1963						1	1	1	1	3		1	8	19	.42
1964							1	1	2		1	1	6	26	.23
1965						1	1	4	3	1	1		11	21	.52
1966						1			2				3	20	.15
1967									1	1	2		4	20	.20
1968							1	1	2	1			5	20	.25
1969							1		1				2	13	.15
1970						1		1	2	2	1		7	12	.58
TOTAL	0	0	1	2	1	4	6	11	20	12	8	5	70	231	.30
TYPHOONS	2	1	2	9	12	13	33	53	38	39	21	8	231		
RATIO SUPER TYPHOONS TO TYPHOONS						.31	.18	.21	.53	.33	.42	.63	.30		
RATIO SUPER TYPHOONS TO TYPHOONS						.21			.42						

ANNUAL AVERAGE SUPER TYPHOONS 5.8

ANNUAL AVERAGE TYPHOONS 19.2

TABLE 3-12

best tracked as a super typhoon. Only two typhoons failed the test--Cora '64 (MSLP 967 mb) and Hope '64 (MSLP 973 mb). The complete list of the remaining 70 super typhoons is contained in Table 3-11.

3. SEASONAL DISTRIBUTION:

The month and year when each super typhoon listed attained 130 knots is tabulated in Table 3-12 along with totals by year and month. The total number of typhoons is also listed for comparison. Yearly occurrence of super typhoons range from two (1960 & 1969) to 11 (1965) with an average occurrence of 5.8 per year. The vast majority (94%) of all super typhoons occurred during the period June through December. Note the total monthly frequencies describe a rather normal distribution centered on September which recorded the maximum of 20. In comparison the typhoon data are less normally distributed with a skew toward the early part of the season around a peak of 53 in August. The maximum occurrence of super typhoons during any month was four (Aug '65). Except for 1960, September claimed at least one super typhoon formation each year.

The ratio of super typhoon occurrence to total typhoon occurrence was calculated for the super typhoon season and is shown on the bottom two lines of Table 3-12. The implied probability that a typhoon will reach super typhoon strength shows an explosive increase in September. In fact, this probability is twice as high during the period September through December than it is for the beginning of the typhoon season (June through August). On an annual basis the data indicate that 3 of every 10 typhoons reached the super typhoon threshold. The ratio of super typhoon occurrence to total typhoon occurrence was calculated for each year and is shown in the last column of Table 3-12. Super typhoon to typhoon occurrences range from about 1 in 10 (1960) to near 6 in 10 (1970). No apparent correlation stands out from these data. A graphic plot of the ratios (Figure 3-14) does show a rather interesting pattern, though. Except between 1967 and 1968 the curve shows a rather uniform sawtooth pattern with alternating relatively high and low ratio years.

RATIO OF SUPER TYPHOON OCCURRENCE TO TOTAL TYPHOON OCCURRENCE

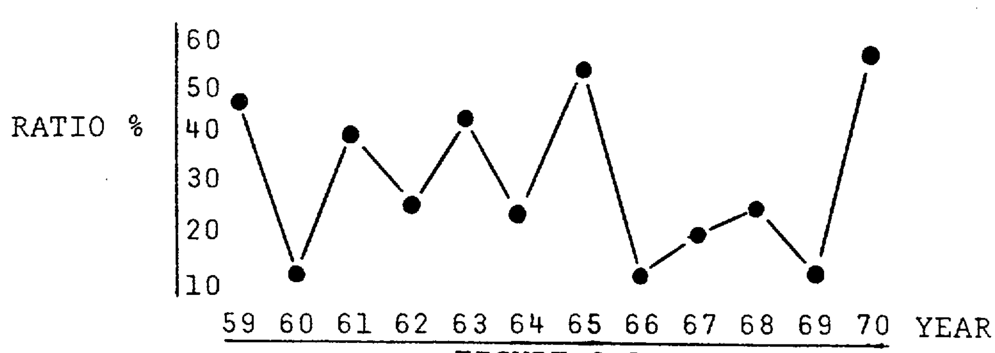


FIGURE 3-14

4. AREAL DISTRIBUTION:

The location where each super typhoon attained 130 knots sustained wind was plotted on a map (Figure 3-15). The Philippine Sea stands out as the primary genesis area. Sixty-two of the 70 super typhoons (89%) attained this distinction in that region. A large majority of all the occurrences (52 or 74%) are concentrated in the 10 degree latitude band from 14°N to 24°N. Note that none formed west of the Philippine Sea. The eastern-most formation was Fay '68 (18.6N 162.1E), the northern-most Shirley '65 (31.3N 132.9E), and the southern-most Kate '70 (6.0N 126.4E). Surprisingly only two developed southeast of Guam (Nancy '61 and Karen '62).

Another view of the areal distribution of the super typhoon genesis points is contained in Figure 3-16. The points were totalled by five degree Marsden squares and isoplethed. The areas of maximum occurrence stand out dramatically in this depiction. One is located in the western part of the Philippine Sea with another located along the eastern entrance to the Sea. A definite minima is situated between the two. This double maxima closely fits the doublet structure charted by FUNG Yat-kong (1970) of mean minimum pressure of typhoons for the period 1958-1968. His western-most minima is displaced 5 degrees north of our max occurrence area while his eastern-most minima is displaced about 400 miles northwest of our eastern maxima. This logically places the minimum pressure areas climatologically downstream from the areas of maximum super typhoon formation.

Figure 3-16 indicates the western maxima is higher than the eastern one. In reality, the eastern maxima represents a higher probability of a typhoon traversing the area becoming a super typhoon than does the western maxima. During this period (1959-1970) 51 typhoons moved through the square enclosing the western maximum super typhoon occurrence while only 33 traversed the eastern square. This indicates that 1 out of every 6 or 7 typhoons that passed through the western area intensified to super strength whereas in the eastern area about 1 out of 5 did.

5. SUMMARY:

Data for the period 1959 through 1970 indicate that super typhoons (maximum surface winds $\geq$ 130 knots) are relatively common occurrences in the Northwestern Pacific. Three of every 10 typhoons can be expected to intensify to super typhoon strength. The annual average is six with yearly extremes ranging from 2 to 11. Ninety-four percent form during the period June through December. The probability of a typhoon becoming a super typhoon during the period September through December is double the expectancy of the period June through August. September recorded the most super typhoon occurrences. During this month half of the typhoons reached super strength.

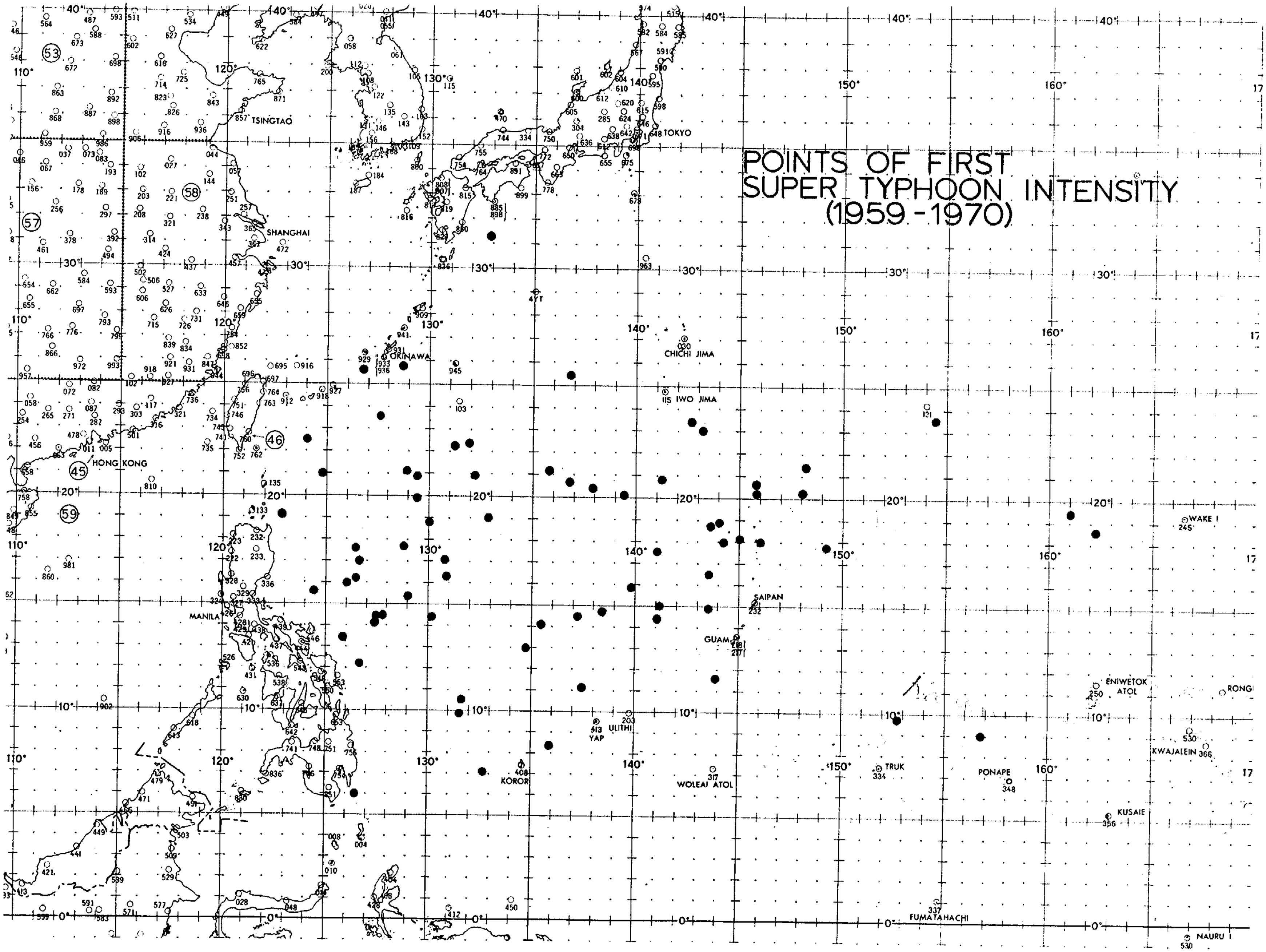

POINTS OF FIRST
SUPER TYPHOON INTENSITY
(1959-1970)
TSINGTAO
TOKYO
SHANGHAI
OKINAWA
CHICHI JIMA
IWO JIMA
HONG KONG
MANILA
SAIPAN
GUAM
WAKE I
YAP
ULITHI
KOROR
WOLEAI ATOL
TRUK
PONAPE
ENIWETOK ATOL
KWAJALEIN
KUSAIE
NAURU I
FUMATAHACHI

FIGURE 3-15

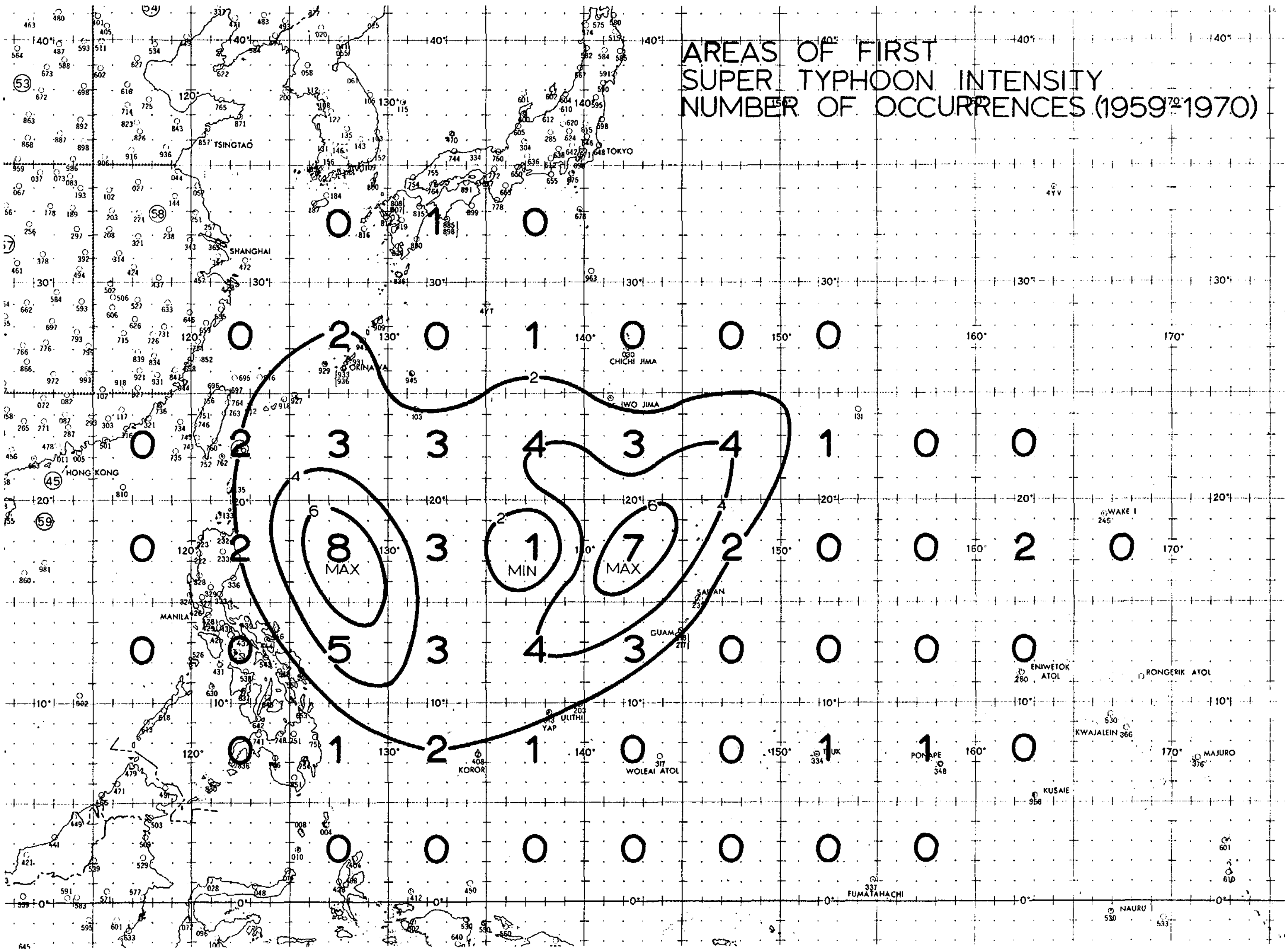

AREAS OF FIRST
SUPER TYPHOON INTENSITY
NUMBER OF OCCURRENCES (1959-1970)
MAX
MIN
MAX
TSINGTAO
SHANGHAI
HONG KONG
MANILA
TOKYO
OKINAWA
CHICHI JIMA
IWO JIMA
SAIPAN
GUAM
ULITHI
YAP
KOROR
WOLEAI ATOL
TRUK
PONAPE
KUSAIE
WAKE I
ENIWETOK ATOL
RONGERIK ATOL
KWAJALEIN
MAJURO
NAURU
FUMATAHACHI

FIGURE 3-16

I. FREQUENCY OF TROPICAL CYCLONES IN THE WESTERN PACIFIC

Not until the initial impact of aircraft reconnaissance in 1945 did a satisfactory set of statistics become available on the tropical cyclone occurrences in the West Pacific area. The Royal Observatory at Hong Kong has prepared an exhaustive study of tropical cyclone climatology from 1884-1953 data (Chin, 1958), however, it is limited to an area west of the 150th meridian. Statistics varied as different military organizations were involved in forecasting these storms. A comparison of data prepared by these sources show a fluctuation of figures prior to 1954.

In an effort to standardize the data for reference purposes at JTWC, a search has been made of available sources for the most reliable and representative set of frequency statistics. Research by the Environmental Data Service (NOAA) of figures available at the National Weather Records Center in Asheville is regarded as the most comprehensive study on the subject. This study was conducted in the preparation of the TYFOON analog program history file under NAVWEARSCHFAC sponsorship with JTWC cooperation. JTWC believes this to be the most representative set of statistics available and regards it as the official data base. These data are summarized in Tables 3-13 and 3-14.

FREQUENCY OF TROPICAL CYCLONES (INCLUDING TYPHOONS) BY MONTHS AND YEARS

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1945	0	0	0	1	1	2	5	7	6	1	3	0	26
1946	0	0	1	0	1	2	3	2	3	1	2	0	15
1947	0	0	1	0	1	1	3	3	5	6	6	1	27
1948	1	0	0	0	2	2	2	5	5	4	3	2	26
1949	1	0	0	0	0	1	5	3	6	1	3	2	22
1950	0	0	0	0	1	2	3	2	3	3	3	1	18
1951	0	0	1	2	1	1	1	2	2	4	1	2	17
1952	0	0	0	0	0	3	3	4	5	6	3	4	28
1953	0	1	0	0	1	2	2	6	3	4	3	1	23
1954	0	0	1	0	1	0	1	6	4	3	3	0	19
1955	1	0	1	1	0	1	6	3	3	4	1	1	22
1956	0	0	1	2	0	1	2	5	5	2	3	1	22
1957	2	0	0	1	1	1	1	3	5	4	3	0	21
1958	1	0	0	0	1	3	5	3	3	3	2	1	22
1959	0	1	1	1	0	0	3	6	6	4	2	2	26
1960	0	0	0	1	1	3	3	10	3	4	1	1	27
1961	1	1	1	1	3	2	5	4	6	5	1	1	31
1962	0	1	0	1	2	0	6	7	3	5	3	2	30
1963	0	0	0	1	1	3	4	3	5	5	0	3	25
1964	0	0	0	0	2	2	7	9	7	6	6	1	40
1965	2	2	1	1	2	3	5	6	7	2	2	1	34
1966	0	0	0	1	2	1	5	8	7	3	2	1	30
1967	1	0	2	1	1	1	6	8	7	4	3	1	35
1968	0	0	0	1	1	1	3	8	3	6	4	0	27
1969	1	0	1	1	0	0	3	4	3	3	2	1	19
1970	0	1	0	0	0	2	2	6	4	5	4	0	24
1971	1	0	1	3	4	[illegible]	[illegible]	[illegible]	6	[illegible]	[illegible]	[illegible]	[illegible]
Totals	11	7	12	17	26	40	94	133	119	98	69	30	656
Avg.	.42	.27	.46	.65	1.00	1.54	3.62	5.12	4.58	3.76	2.65	1.15	25.23

TABLE 3-13

FREQUENCY OF TROPICAL CYCLONES REACHING TYPHOON INTENSITY BY MONTHS AND YEARS

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1945	0	0	0	0	0	1	2	5	3	1	1	0	13
1946	0	0	1	0	1	1	3	1	3	1	2	0	13
1947	0	0	0	0	1	1	0	3	4	5	4	1	19
1948	1	0	0	0	2	0	2	2	4	1	2	1	15
1949	1	0	0	0	0	1	3	3	3	1	1	1	14
1950	0	0	0	0	1	1	1	2	1	3	2	1	12
1951	0	0	1	2	1	1	1	2	2	3	1	2	16
1952	0	0	0	0	0	3	1	3	3	4	3	2	19
1953	0	1	0	0	1	1	2	4	2	4	1	1	17
1954	0	0	0	0	1	0	1	4	4	2	3	0	15
1955	1	0	1	1	0	1	5	3	3	2	1	1	19
1956	0	0	1	1	0	0	2	4	5	1	3	1	18
1957	1	0	0	1	1	1	1	2	5	3	3	0	18
1958	1	0	0	0	1	3	4	3	3	3	1	1	20
1959	0	0	0	1	0	0	1	5	3	3	2	2	17
1960	0	0	0	1	0	2	2	8	0	4	1	1	19
1961	0	0	1	0	2	1	3	3	5	3	1	1	20
1962	0	0	0	1	2	0	5	7	2	4	3	0	24
1963	0	0	0	1	1	2	3	3	3	4	0	2	19
1964	0	0	0	0	2	2	6	3	5	3	4	1	26
1965	1	0	0	1	2	2	4	3	5	2	1	0	21
1966	0	0	0	1	2	1	3	6	4	2	0	1	20
1967	0	0	1	1	0	1	3	4	4	3	3	0	20
1968	0	0	0	1	1	1	1	4	3	5	4	0	20
1969	1	0	0	1	0	0	2	3	2	3	1	0	13
1970	0	1	0	0	0	1	0	4	2	3	1	0	12
	[illegible]	[illegible]	[illegible]	2	1	2	6	3	5	2	2	0	24
Totals	7	2	6	14 17	22 23	28 30	61 67	94 97	83 88	73 75	49 51	20	459 [illegible]
Avg.	.27	.08	.23	.54	.85	1.08	2.35	3.62	3.19	2.81	1.88	.77	17.65
	.26	.07	.22	.63	.85	1.11	2.48	3.59	3.26	2.78	1.89	.74	17.89

TABLE 3-14

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