AD-A085 653 SCIENCE APPLICATIONS INC MONTEREY CA F/G 4/2
TROPICAL CYCLONE WIND THREAT FOR THE BAY OF BENGAL.(U)
OCT 79 J D JARRELL AID-SOD-PDC-C-0110
UNCLASSIFIED NL

1 of 1
AD A
085653

END
DATE
FILMED
7-80
DTIC

6

TROPICAL CYCLONE WIND THREAT FOR THE BAY OF BENGAL.

A085662

9

FINAL REPORT,

11

October 1979

12 46

15

Contract AID-SOD-PDC-C-0110

SAI Contract #1-042-02-219-00

10

Jerry D. Jarrell

Prepared for
Agency for International Development
State Department
Washington, DC

SCIENCE APPLICATIONS, INC.
2999 Monterey-Salinas Highway
Monterey, Ca~~lifornia~~ 93940
408/649-5242

411325

LB

8.0011, TROPICAL CYCLONE WIND THREAT ESTIMATION SYSTEM FOR THE BAY OF BENGAL

J. Jarrell, Science Applications Inc., *2999 Monterey-Salinas Hwy., Monterey, California* 93940 (AID/SOD/PDC-C-0110) Start: 09/78 End: 09/79

Disasters caused by cyclonic storm high winds and tidal surge annually threaten the countries surrounding the Bay of Bengal with severe human suffering and loss of life. The objective of this applied research project is to design, develop, program and test a system (computer model) suitable for automation to provide wind threat information to officials which would be useful in mitigating the disastrous effects of cyclones through improving the disaster preparedness decision process. This effort concentrates on developing and institutionalizing a real-time system based on an analysis of forecast error which is designed to provide estimate of cyclone strike probability and wind threat to specific geographic points surrounding the Bay of Bengal. The ultimate goal of this work and associated projects is to develop a casualty/damage probability estimation system based on model parameters (strike, surge, and flood probabilities), geography, and regional demography, to predict disaster extent, intensity, and relief requirements.

Action Officer: PF Krumpe
Telephone: 202-632-1834

SUPPORTED BY Agency for International Development
SSIE No. GI-851 FY-78: $46,500 TOTAL COST: $46,500

80 4 15 03

TABLE OF CONTENTS

Section 1

INTRODUCTION

1.0 Background

It is the policy of the U.S. government, through the Agency for International Development to:

1. Render emergency relief, in coordination with other governments, international agencies, and voluntary organizations, to victims of natural and man-made foreign disasters. Such assistance can be provided to the people of any nation affected by disasters and must, to the greatest extent possible, reach those areas most in need of relief and rehabilitation.

2. Monitor all potential and actual disaster situations.

3. Assist in rehabilitation when such rehabilitation is beyond the capacity of local resources.

4. Encourage and participate in foreign disaster preparedness through the provision of technical assistance and international training programs.

5. Where there has been severe social and economic disruption, consider on a case-by-case basis longer term reconstruction assistance and implement the program as a development tool.

6. Support the efforts of international organizations and voluntary agencies involved in foreign disaster assistance.

7. Increase U.S. technical capacity to define disaster-prone conditions and to recommend disaster-avoidance measures.

8. Initiate, within international fora, efforts to increase other donor participation in disaster preparedness and disaster relief activities.

With regard to cyclones in the Bay of Bengal, the research reported herein supports the U.S. policy objectives above. To some extent all the above policy objectives are supported but the primary emphasis is on monitoring (objective #2), disaster preparedness (#4), and increasing technical capacity to define disaster prone conditions and to recommend disaster-avoidance measures (#7).

1.1 The Tropical Cyclone Problem

Tropical cyclones include the hurricane (in oceans bordering North America), typhoons (north western Pacific Ocean) and the cyclones of the South Pacific and Indian Oceans including the Bay of Bengal and Arabian Sea. Historically the great disasters have been in the Bay of Bengal. The November 1970 Bangledesh cyclone is estimated to have killed over 200,000 people (ESCAP, LRCS, WMO 1977) and the November 1977 Andhra Pradesh cyclone killed perhaps 20,000.

→ The problem in the Bay of Bengal is partly attributable to the distribution of population in low lying and unprotected areas along the bay, but more important is the configuration of the bay which results in large cyclone induced storm surges (often incorrectly

→ over
next page

referred to as tidal waves). These surges are an elevation of the sea surface because of the barometer effect (pushing up the water into the cyclones central low pressure) combined with the buildup of wind driven water along the coast. These are superimposed on the astronomical tides which have a 12-hourly period (two highs and two lows per day) and a large tidal range at least with some combinations of the solar-lunar cycles. An unfortunate coincidence of a large storm surge and high tide can increase the mean water level by several meters, thus inundating large coastal areas with devastating effects.

The great killer, then, is the storm surge. While this work does not deal with storm surge, it does deal with cyclone winds which directly (but not exclusively) determine the storm surge. This work also involves the introduction of probability into interpreting cyclone forecasts in time of threat.

Forecasts tell in very specific language where the cyclone will be, at what time, and describe its configuration (size and wind distribution). If it were not for inaccuracies in these forecasts, specifying the impact of a cyclone on a locale would be rather straightforward; however, inaccuracies are a fact of life even with advanced forecasting capability. Forecast errors have gradually been reduced over the past few decades, but still they persist and their reduction seems to have leveled off in the decade of the seventies (Jarrell et al 1978, Neumann 1978). The improvement was most pronounced in the regions of the world where observation improved. This was mostly post WWII aircraft reconnaissance supplemented increasingly

next [illegible]

after 1964 by meteorological satellites. In the Bay of Bengal the satellite era is just emerging, thus we may expect to see improvement in forecasting capability there.

Within a few years forecast accuracies may approach those of the Atlantic and Eastern Pacific hurricanes and the Western Pacific typhoons. What we are doing here is attempting to make current forecasts with their inherent inaccuracies more usable. Barring unforeseen dramatic improvement in forecast accuracy this will be a continuing need.

The aim of this research was to develop a reliable estimate of the probability of 40, 65 and 100 kt winds for points under threat of a tropical cyclone.

Section 2

USE OF PROBABILITY

2.0 Choice Between Two Alternatives

We use probability as a means of quantifying the risk of an event occurring. Often events can be expressed as binary outcomes, a choice of two. The event will or will not occur. In this context, for a given case the real probability (presently unknown) is either 0 (the event will not occur) or 1 (the event will occur). Any other outcome is impossible.

If we take a long term perspective of the problem then a number between 0 and 1 can represent the proportion of a large number of like cases which will result in the event occurring. It is this point of view that is usually advocated in decision theory. The techniques used are those which maximize the long term outcome, not necessarily in the immediate decision at hand. For example if evacuation is considered, all the costs, both monetary and human, must be weighed against the savings.

The following loss table illustrates the trade-off between evacuation and non-evacuation.

Preparation Actions	Outcome	
	Hit	Miss
Evacuate	Costs of Evacuation (C)	Costs of Evacuation (C)
Do not evacuate	Avoidable Losses (L)	None

CONTINGENCY LOSS TABLE

If we want to minimize probable losses we will want to evacuate only when the probable loss with evacuation is less than the probable loss without evacuation. Note that unavoidable losses are not a relevant part of the problem.

If P is the probability of a "hit" of sufficient magnitude to necessitate evacuation then the expected or probable losses with evacuation would be C and those without evacuation P x L. We want to order evacuation only if $C < P \times L$ or, rearranging, we evacuate when $P > C/L$.

To illustrate this principle, suppose a boatowner is considering moving his boat to an inland shelter. Let's say the boat is worth $10,000 and it costs $100 to move it. With $C = 100$, $L = 10{,}000$, he would not want to move it unless the probability (P) of its being lost exceeded the ratio of these numbers:

$$P > C/L = 1\%$$

Obviously in real world situations life is not that simple. We have great difficulty putting dollar values on both evacuation costs and losses because of a host of complexities. Note that it is necessary that both C and L be expressed in the same units, but not necessarily monetary units. They could, for example, be human lives although it requires some innovation to express costs of preparation in those terms. One way which has been suggested is through loss of credibility in the warning systems. That is, if evacuation is ordered unnecessarily and repeatedly ("crying wolf"), it becomes increasingly difficult to affect an evacuation because of reluctant public response. Thus evacuating uses up credibility and hence has a future loss of lives (when the real wolf appears) as its price.

The condition ($P > C/L$) is offered as a necessary condition, that is, don't act unless this condition is met. It is not sufficient, meaning when this condition has been met there are still other factors to consider before acting. For example, suppose the boatowners criteria was met in that there was a greater than one percent probability of destructive conditions occurring three days from now. If it only takes a few hours to move the boat, he should wait. Severe tropical cyclone damage is a rare event, if we have a probability of occurrence of 1%, then we have a probability of non-occurrence of 99%. If the boat owner waits a day or so, in most cases the threat will subside. Simply stated this principle is that we should put off action until we have just enough time to complete the action before the event occurs. In this connection, one must not overlook the reality of darkness and/or the onset of inclement weather ahead of the approaching cyclone as factors in slowing any action.

2.1 Choice Between Three or More Alternatives

The above extends easily to choosing between three alternate courses of action. Consider the following example of a medium sized, and hypothetical, police force which will man various emergency posts dependent upon which of 3 hurricane events is forecast. We assume the most likely (the mode) will be forecast.

Minor event requires 2 man days
Moderate event requires 10 man days
Major event requires 50 man days

There are "penalty" costs associated with either underestimation or overestimating the requirements which are given in the following cost table. The elements on the diagonal represent the cost of correct manning, and those off the diagonal represent the cost of either over or under manning.

		ACTUAL OCCURRENCE		
	ACTION OPTIONS	MINOR	MODERATE	MAJOR
1	Man for minor event	2	17	97
2	Man for moderate event	11	10	85
3	Man for major event	60	55	50

Cost contingency table for hurricane manning (man days)

A rational decision is one which minimizes the expected cost. If we can estimate the probabilities of each outcome occurring P_1, P_2, P_3 then the expected cost if we use:

$$\text{Option 1 is } C_1 = 2xP_1 + 17xP_2 + 97xP_3,$$

$$\text{Option 2 is } C_2 = 11xP_1 + 10xP_2 + 85xP_3, \text{ and}$$

$$\text{Option 3 is } C_3 = 60xP_1 + 55xP_2 + 50xP_3$$

For example suppose $P_1 = .45$, $P_2 + .35$ and $P_3 = .20$. Note that we assume no other outcome is possible (minor includes no event) $P_1 + P_2 + P_3 = 1.00$.

$$C_1 = 2x.45 + 17x.35 + 97x.20 = 26.25$$

$$C_2 = 11x.45 + 10x.35 + 85x.20 = 25.45$$

$$C_3 = 60x.45 + 55x.35 + 50x.20 = 56.25$$

Since C_2 is the course of action with minimum expected cost, it should be selected. Notice that the minor event is most likely to occur but in this case, the best bet is slight over preparation. The difference in C_1 and C_2 may be trivial, but certainly either is preferable to C_3.

Figure 1 summarizes this problem in three graphical depictions. Figure 1a shows a 1x1 graph of P_1 vs P_2. Note for any P_1, P_2 combination, a value of P_3 is determined since $P_3 = 1 - P_1 - P_2$. Thus in the lower left corner P_1 and P_2 are small, thus P_3 is near 1. The space blocked off in the lower left is the region where event 3 (major hurricane event) is more likely than either events 1 or 2, similarly the upper left and lower right represent the

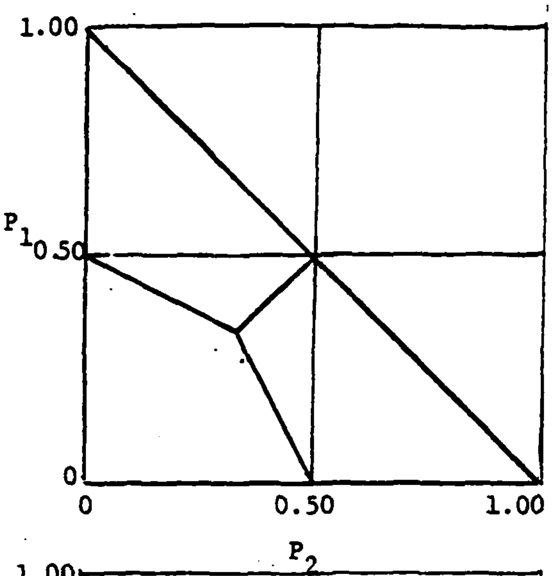

Figure 1a. Illustrates sections of a 1x1 probability square wherein events 1, 2 or 3 are the mostlikely of the three mutually exclusive events which are also exhaustive ($P_1+P_2+P_3 = 1.0$)

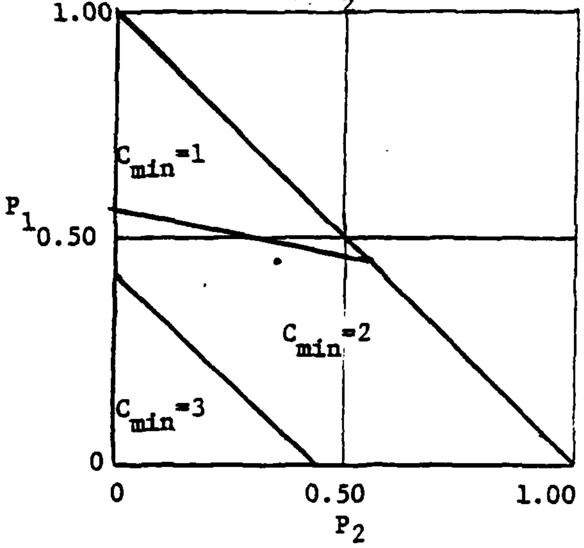

Figure 1b. Illustrates sections of a 1x1 probability square wherein the expected cost is minimized by planning for events 1, 2 or 3.

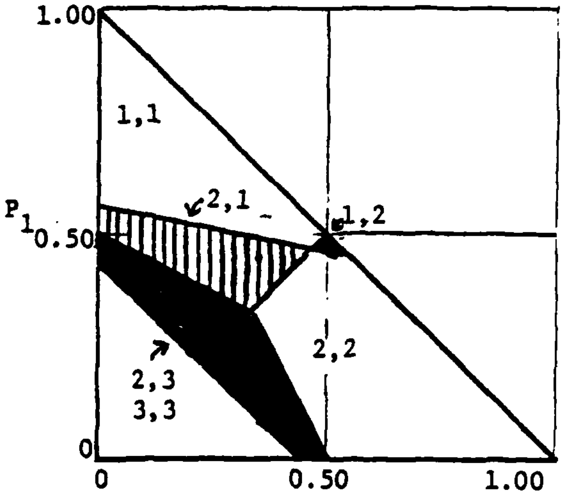

Figure 1c. Combines figures 1a and b. Illustrates conditions under which overpreparation (vertical hatching) and underpreparation (black) minimizes expected cost. Number pairs (N_1, N_2) are minimum expected cost event, most likely event.

combinations wherein events 1 and 2 respectively are the most likely outcome. Notice that combination of P_1, P_2 in the upper right triangle do not exist since $P_1 + P_2 \leq 1$.

Figure 1b is a graphical representation of all possible combinations of P_1, P_2 and the minimum expected cost of each for the police department problem. Note there is a similarity between figures 1a and 1b. Near the corners where the outcome is fairly certain, the most likely outcome is the best one to plan on; however, in the middle region that is not true.

Figure 1c combines figures 1a and 1b. In the area with vertical cross-hatching, the most likely event to occur is one, a minor event; however the expected cost is less in this region if we provide more manpower than that which is most likely required. In the shaded regions, the least expected cost occurs when we underman.

This type argument can be extended to any number of possible courses of action, although the computations become laborious. Graphical solution (of the type illustrated here) is restricted to 3 or less. A programmable calculator can nicely handle up to 5 or 6 options.

The difficult part of applying such methods is obtaining the probabilities. Providing the probabilities is the subject matter of this research.

2.2 Basis for Probabilities

In the Bay of Bengal probabilities are available based on climatology. For example, Neumann and Mandal (1978) describe an analog scheme which models such a probability. This probability is solely based on climatology biased to persistence. To the extent that the forecaster can improve on climatology, probabilities based on his forecast will be an improvement over climatological probabilities. By improvement we mean probabilities followed by the events actual occurrence will be larger and those followed by actual non-occurrence will be smaller, with diminished occurrence of those in the middle. This means the users critical probability ($P_c = C/L$, see section 2.0) will be exceeded less often in non-hit cases. Since the forecaster can take into account not only climatology and persistence, but also synoptic factors and the analog scheme itself, he should ususally beat the analog.

Section 3

THE MODEL

3.0 Statistical Model Basis

The probability estimation model is based on a study of tropical cyclone forecasts issued by the Joint Typhoon Warning Center (JTWC) on Guam during the 7 years beginning with 1971. That was the year when the JTWC began forecasting in the Bay of Bengal.

The particular forecasts were 205 motion and maximum wind forecasts for cyclones in the north Indian Ocean; however, there were only 137 forecasts where the nowcast position was actually in the Bay of Bengal. This number of forecasts is barely adequate to support a statistical study. In a similar motion forecast study for Western Pacific typhoons, Nicklin (1977) had over 5000 cases. Jarrell (1979) studied wind forecast errors also in the western Pacific and had a sample of over 2000 cases. The large difference in sample size is somewhat reduced because the Bay of Bengal forecasts were issued at 12-hour intervals vs 6-hour in the Western Pacific, thus consecutive forecasts are more nearly independent. Additionally, the general characteristics of the error distributions are known to a good approximation from these and other earlier studies. This study was more to confirm similarity rather than break new ground.

An attempt was made to stratify forecasts into difficulty classes. The most successful stratification was on the basis of forecast direction of motion. Errors are usually smaller for cyclones moving west and larger for cyclones moving northeast. These directions represent typical tracks before and after recurvature. Recurvature is a term signifying a transfer from control by the near equator easterly air currents to the westerly currents of the mid-latitudes. Prerecurvature tracks in the easterlies are typically westnorthwest while post recurvature tracks are typically toward the northeast. The westerlies are much stronger and hence cyclone forward speeds after recurvature are much greater. Larger errors are associated with larger forward speeds. The best directional separation occurred at about 340° (northnorthwest), i.e., directions from 340° to 180° appeared to behave differently from the remainder of the cyclones. Some statistical summary results are shown in Table 1. The group with headings 340° clockwise to 180° consists mainly of post recurvature cases and is shown as Sector 1 in Table 1. Sector 2 forecasts (pre-recurvature- headings 180° to 340°) are the most common forecasts. In Sector 1 the mean W-E error is somewhat positive (east) while the mean S-N error is significantly positive (north), since these forecasts are typically for north to northeast motion, this represents a speed over-forecast. For Sector 2, the W-E mean error is significantly negative (west), while the mean S-N error is slightly positive (north). Again these are over forecasts in speed along the track. These speed errors may in part be attributable to the lack of a good climatology for the area and hence the Guam forecaster relies on his experience with faster moving Pacific typhoons. For this sample, the average forward speed was 5.4 kts, if we add the average 24 hour speed error (2.9 kts) to that, we arrive very close

	Sector 1			Sector 2			Combined		
ERROR MAGNITUDE	0 HR	24 HR	48 HR	0 HR	24 HR	48 HR	0 HR	24 HR	48 HR
Mean (nmi)	54	173	251	54	151	280	54	160	271
Std Dev (nmi)	41	99	114	48	98	148	45	99	138
S-N ERROR (En)									
Mean (nmi)	17	21	72	11	15	10	13*	17*	30*
Std Dev (nmi)	45	124	197	38	107	194	41	114	195
W-E ERROR (Ee)									
Mean (nmi)	6	41	2	-27	-85	-175	-14*	-34*	-117*
Std Dev (nmi)	47	153	187	55	119	184	52	134	185
WIND ERROR (Ew)									
Mean (kt)	0	8	12	-1	-2	2	-1	2	5
Dev (kt)	9	16	22	8	13	22	8	15	23
CORRELATIONS									
Ee to En	0.40	0.37	0.22	-0.06	0.17	0.15	0.07	0.26	0.22
Ee to Ew	-0.16	-0.25	-0.51	-0.25	-0.00	0.19	0.02*	0.00*	0.04*
En to Ew	0.03	-0.18	-0.23	0.09	-0.16	-0.05	0.01*	-0.15*	-0.10*
CASE COUNT	56	55	26	81	81	54	137	136	80

*assumed to equal zero on the model

Table 1. Summary of results of a statistical study of errors in JTWC forecasts for the Bay of Bengal.

to the average typhoon forward speed of nine kts. This appears to be a correctable bias. Without this bias, there appears to be no significant difference in the difficulty classes, hence an artificial set of statistics based upon the removal of this bias is used in the model and the directional discrimination is eliminated.

This permits the pooling of cases for maximum statistical stability. The correlation coefficients are of some passing interest. The correlation between the error components is small but comparable to those found in the western Pacific by Nicklin (1977) and in various studies (see for example Neumann, 1975, and 1978). Notice the small correlation between the error in maximum winds and displacement error components. Since none of these in the pooled sample are significantly non-zero, these errors will be treated as independent in the model.

While we are satisfied with the stability of the forecast error statistics, we would have preferred a longer period of record. We have also seen a rather severe bias in the Guam forecasts which we assume will be corrected. The presence of this bias serves to flag the risk in applying statistics derived from forecasts from one source to forecasts of another source. For this reason we recommend that the statistical package be derived from and tailored for the driving forecasts. For example, if one of the nations on the Bay chooses to adapt this model relative to their own forecasts, a statistical package derived from their forecasts should be substituted for the Guam statistics. In some cases this may also provide a more extensive basis.

3.1 Model Operation

Like most models the wind threat model can be thought of in three stages: Input, computation and output. Input and output are perhaps of most concern to the user because of their visibility, but the important work goes on in the computation stage. It is there that the underlying mathematical relationships are expressed and exercised and it is there that any simplifying assumptions are made. The latter, together with the input, determine the validity of the output. The following description provides information which the user needs to understand in order to fully appreciate the output information.

3.1.1 Input

The input is taken exclusively from the JTWC cyclone warnings. It consists of cyclone identification information, used for output labelling, and forecasts of latitude, longitude and maximum wind at 0, 24 and 48 hours after forecast valid time. Figure 2 illustrates an actual forecast of tropical cyclone 17-79 originated by the JTWC at 0800 GMT on 11 May 1979. The bottom line in figure 2 is the necessary input information extracted from the warning. The information (except the second entry, month: 5 = May) is underlined in the warning. This cyclone warning will be used again as an output example.

3.1.2 Computations

The actual computations are carried out on a grid of points spaced at 60 nmi intervals along the periphery of the Bay of Bengal and along the Andaman Island

```
WTXX31 PGTW 111000
TROPICAL CYCLONE 17-79 WRNG NR 20
POSIT 13.2N6 082.3E3 at 110800Z
ACCURATE WITHIN 40 NM
BASED ON EYE FIXED AT 13.3N7 082.7E7
AT 110615Z BY SATELLITE
PRESENT MOVEMENT: WEST-NORTHWEST AT 05 KTS
PRESENT WIND DISTRIBUTION:
MAX SUSTAINED WINDS 90 KTS NEAR CENTER WITH GUSTS TO 110 KTS
RADIUS OF OVER 50 KT WINDS 75 NM
RADIUS OF OVER 30 KT WINDS 150 NM OVER WATER
REPEAT POSIT 13.2N6 082.3E3 at 110800Z
FORECASTS:
12 HRS VALID 112000Z 13.8N2 081.5E4
MAX WINDS 100 KTS WITH GUSTS TO 125 KTS
RADIUS OF OVER 50 KT WINDS 80 NM
24 HRS VALID 120800Z 14.2N7 080.5E3
MAX WINDS 105 KTS WITH GUSTS TO 130 KTS
RADIUS OF OVER 50 KT WINDS 90 NM OVER WATER
RADIUS OF OVER 30 KT WINDS 175 NM OVER WATER
EXTENDED OUTLOOK:
48 HRS VALID 130800Z 14.7N2 078.9E4
MAX WINDS 30 KTS WITH GUSTS TO 45 KTS
DISSIPATING OVER LAND
NEXT WARNINGS AT 111600Z, 112200Z, 120400Z and 121000Z
REMARKS: LATEST SATELLITE DATA INDICATES TC 17-79 HAS CONTINUED
TO INTENSIFY OVER THE PAST 12-24 HOURS, WITH SLOW INTENSIFICATION
EXPECTED UNTIL LANDFALL.  TC 17-79 HAS SLOWED TO 05 KTS, HENCE, AN
ADDITIONAL 06 HOURS WAS ADDED TO THE WARNINGS VALID PERIOD. TC17-79
CONTINUES TO OSCILLATE ABOUT AN OVERALL WEST-NORTHWEST TRACK, HENCE,
THE FIX POSITION WAS NOT USED VERBATIM.
BT

      "17-79", 5, 1108, 132, 823, 90, 138, 815, 100, 147, 789,
               30, 48
```

Figure 2. An actual cyclone warning issued by the Joint Typhoon Warning Center on Guam for Cyclone 17-79 on 110800 GMT May 1979. The added line across the bottom is the extracted model input.

Chain. These computations are executed at 3-hour time steps from forecast valie (nowcast) time to 48 hours hence. The following assumptions are implicit in the computations.

(a) That the forecast represents the mean of all possible outcomes, that the deviation of the actual position from this mean is a random variable pair described by a bivariate normal frequency distribution whose parameters are given in Table 1.

(b) That the actual maximum wind is a normally distributed random variable about the forecast, with parameters given in Table 1.

(c) When landfall is forecast, the accompanying reduction in the maximum wind forecast is solely attributable to land influence, otherwise, a trend established prior to landfall would have continued. If no trend can be inferred from the forecast, it is assumed the nowcast wind would have continued in the absence of landfall.

(d) That probabilities can be adequately interpolated in space between representative points spaced 60 nmi apart.

(e) That the forecast positions and the statistical parameters valid for 0, 24 and 48 hours can be interpolated to 3-hour time steps and further that linear interpolation of probabilities between 3-hour time steps is valid.

(f) That probabilities can be summed over time, i.e., the probability of an event occurring within a three-hour timestep is the sum of the probabilities at the two end points less the probability of an occurrence at both times. That the probability of an occurrence at both times can be determined from a geometric parameterization of probability along the forecast track.

(g) That wind errors and forecast position errors, not withstanding the landfall case in (c) above, are independent.

(h) That the shape of the mean wind radial profile is similar to that of Western Pacific typhoons and is realted to maximum wind speed.

3.1.2.1 Validity of Assumptions

The validity of all the foregoing assumptions has not been established herein, nevertheless there is considerable evidence to support most of them.

The concepts expressed in assumptions a and b have been firmly established in the development of the U.S. Navy Pacific typhoon STRIKP and WINDP programs (Jarrell, 1979). The actual values of the statistical parameters in Table 1 are subject to error. This can reasonably be as great as 10% in the important standard deviations. As an illustrative example of the impact of a 10% error, we first estimated, for comparison, the probability that a cyclone, after 24 hours, would actually be within circles of radius 50 and 100 nmi centered on a 24 hour forecast.

The probabilities of the cyclone actually being within these circles (where it is supposed to be) are 11 and 36% respectively. To demonstrate that these are reasonable, we examined the 24 hour forecast errors for 1978 (independent data) for comparison. There were only 28 such forecasts, but of those 14 and 39% actually verified within 50 and 100 nmi respectively of the 24-hour forecast point. We estimate that <u>any</u> point 100 miles removed from the forecast point has 2/3 the chance of being struck as does the forecast point and a point 200 miles away has 1/5 as great a chance. It is not true (as has been stated) that the forecast point is the safest place to be, but it is also clear that a great many other points are also threatened. Being able to quantify that threat is the unique capability of this model.

To simulate the effect of a 10% error in the standard deviations we computed several probabilities using standard deviations of 90%, 100% and 110% of those in Table 1. The probabilities estimated are for a cyclone being within circles of radius 50 and 100 nmi centered on the forecast point (as before) and removed to the Northwest distances of 100, 200 and 300 nmi. These estimates are given in Table 2.

	Distance of circle center NW of forecast point			
CIRCLE RADIUS	0 nmi	100 nmi	200 nmi	300 nmi
50 nmi	13-11-9.3	7.8-7.1-6.5	1.8-2.1-2.4	.15-.29-.43
100 nmi	42-36-31	28-25-23	8.2-9.0-9.6	1.0-1.6-2.1

Table 2. Probabilities (%) of cyclone being within various circles in the vicinity of the 24 hour forecast

The first number is that based on the smaller standard deviations, the second number uses standard deviations given in Table 1 and the third is associated with the larger standard deviations. This should give the reader some sense of the limits on the accuracy of our probability estimates. It is doubtful that the uncertainity introduced by imperfect knowledge of the statistical parameters is great enough to be important for most purposes.

The above simulation also provides some insight into what happens to probabilities when forecast accuracy improves (and the standard deviation of the errors decrease). Those probabilities near the track (distance zero) increase while those far from the track (distance large) decrease. For perfect forecasting, those along the forecast track would be 1.0 while those far from the track would be zero.

Assumption c is based upon the author's knowledge of the practicalities of forecasting and is a rather straightforward mechanism for removing a foreseeable bias.

Assumptions d and e are the result of testing and are considered to represent the minimum time and space model resolution without significant distortion of the results. Finer resolution would not materially affect the output, but for purposes other than the present (e.g., storm surge) a finer resolution in both time and space may be required.

The validity of assumption f, (time summation) has been thoroughly demonstrated in the U.S. Navy models, over a wide range of probabilities and circumstances.

Assumption h is perhaps the weakest of the attendent assumptions. Unlike the Atlantic and North Pacific, there are virtually no real wind measurements available in and around the Bay of Bengal cyclones. For this reason there is little choice but to assume a maximum wind determined profile. Maximum wind itself is likewise not measured, but is estimated from satellite imagery. Since maximum wind is treated as a random variable (about the forecast) then too is the wind profile. There is little doubt that real data could improve this aspect, and hence the wind probability estimates in general. The absence of this data, however, is a more serious problem with deterministic forecasts since they do not anticipate inaccuracies in this or any other forecasts.

An appropriate measure of the impact of all of these assumptions would be to test the model on independent data. A meaningful test would require a few hundred cases which would take years to acquire. There appears to be sufficient substantiation of the validity of the probabilities. The utility of this information was demonstrated in a case study of Cyclone 17-79 (revised).

3.1.3 Output

The wind threat output is in two forms, an area-threat form and a point-threat form. These are illustrated for cyclone 17-79 from 0800 GMT 11 May 1979 in figure 3.

3.1.3.1 Darkness

For planning purposes a simple darkness scale has been included in the output (see figure 3). This defines darkness as 1800 to 0600 LST and uses a -6 time zone. Each print position represents two hours.

3.1.3.2 Area Threat

The area threat is provided to serve the alerting function of government where certain preparatory actions can be taken regardless of the actual location of a disaster within a political jurisdiction. Here the threat of 40, 65 and 100 kt winds now and within 12, 24, 36 and 48 hours is provided. In figure 3 the 48-hour threat of 65 kt winds to Andhra Pradesh is 0.528. This can be read as follows: "The probability of at least 65 kt winds being observed at some point on the Andhra Pradesh coast between 0800 GMT 11 May and 0800 GMT 13 May is estimated to be 53%."

```
FOR CYCLONE 17-79 FROM 1108007
PROBABILITIES OF EVENTS WITHIN  0HRS 12HRS 24HRS 36HRS 48HRS
               HOURS OF DARKNESS  +  *****    +  ***++    +  ***

  STRIKE WITHIN SRI LANKA       0.000  .000  .001  .005  .014
   WINDS OF AT LEAST  40KNOTS 0.000  .000  .004  .014  .032
   WINDS OF AT LEAST  65KNOTS 0.000  .000  .002  .009  .018
   WINDS OF AT LEAST 100KNOTS 0.000  .000  .001  .003  .008

  STRIKE WITHIN TAMIL NADU       .003  .062  .125  .172  .209
   WINDS OF AT LEAST  40KNOTS  .009  .182  .336  .431  .504
   WINDS OF AT LEAST  65KNOTS  .004  .098  .170  .228  .273
   WINDS OF AT LEAST 100KNOTS  .000  .019  .053  .091  .116

  STRIKE WITHIN AN PRADESH       .006  .132  .289  .343  .446
   WINDS OF AT LEAST  40KNOTS  .009  .195  .414  .553  .642
   WINDS OF AT LEAST  65KNOTS  .009  .169  .349  .463  .528
   WINDS OF AT LEAST 100KNOTS  .001  .042  .138  .209  .248

  STRIKE WITHIN ORSA+W.BEN     0.000 0.000  .001  .008  .017
   WINDS OF AT LEAST  40KNOTS 0.000 0.000  .019  .052  .079
   WINDS OF AT LEAST  65KNOTS 0.000 0.000  .002  .011  .023
   WINDS OF AT LEAST 100KNOTS 0.000 0.000  .001  .005  .010

  STRIKE WITHIN EAST INDIA       .009  .193  .415  .567  .671
   WINDS OF AT LEAST  40KNOTS  .009  .193  .416  .573  .687
   WINDS OF AT LEAST  65KNOTS  .009  .192  .413  .565  .669
   WINDS OF AT LEAST 100KNOTS  .001  .061  .195  .302  .370
```

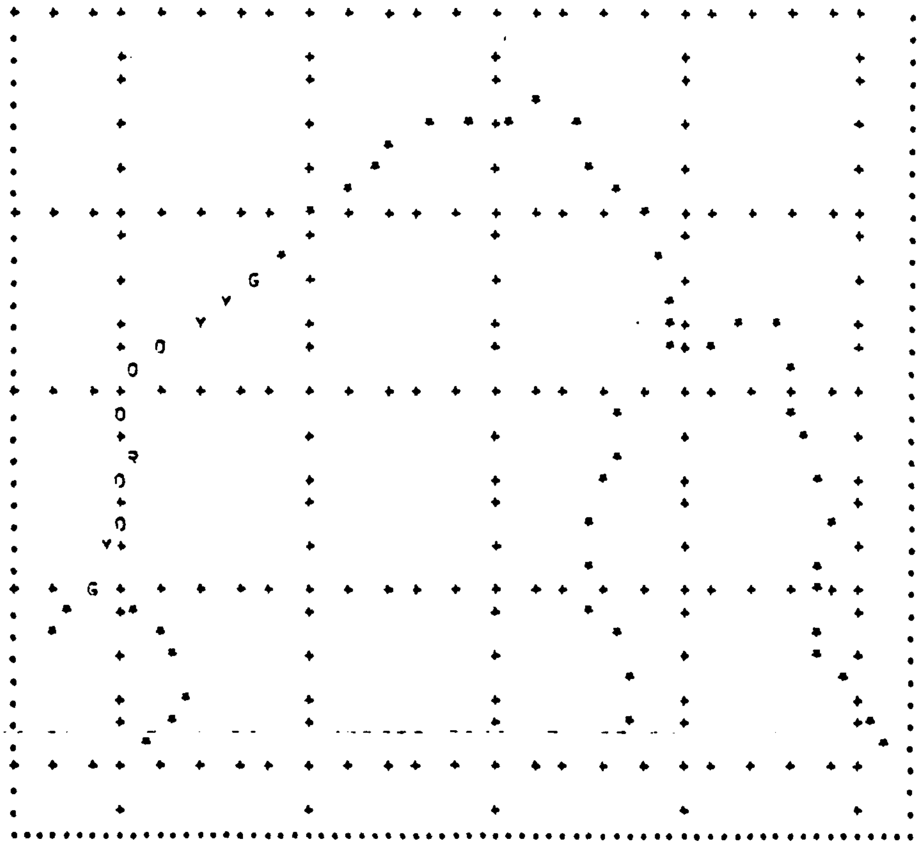

Figure 3. Wind Threat Model Output for Cyclone 17-79, 0800 GMT 11 May 1979.

The reason for the selection of 40, 65 and 100 kt winds are these:

40 kts: This is about the point where it becomes extremely difficult to perform outdoor tasks, hence when 40 kt winds arrive any physical preparations that will be required should be completed.

65 kts: This is about the wind force where significant wind damage begins to occur and where storm surge first begins to be a problem.

100 kts: Under ordinary circumstances, winds in excess of 100 kts can signal a major disaster. The intent here is to treat the probability of winds in excess of 100 kts as the probability of a major disaster occurring. Obviously there are a great many other contributing factors but this is a satisfactory first approximation.

3.1.3.3 Point Threat

The wind threat to a point is handled somewhat arbitrarily in a way which combines the level of the threat with the urgency of that threat. The threat used here is the probability of at least 65 kt winds, T(65). To avoid confusion with established warning/watch/readiness conditions in use in parts of the world a system of color codes is used. Red represents the greatest, and the most imminent, threat and green represents a more remote threat, with orange and yellow in between. The definitions used herein are as follow:

Symbol	Color	T(65)	Time
R	RED	$\geq$ 20%	24 hours
O	ORANGE	$\geq$ 10%	36 hours
Y	YELLOW	$\geq$ 5%	48 hours
G	GREEN	$\geq$ 2.5%	48 hours
*	NONE	$\geq$ 2.5%	No limitation

These are illustrated for points on the Bay in figure 3 for Cyclone 17-79 on 11 May 1979 at 0800 GMT.

Section 4

RECOMMENDATIONS

4.1 Operational Implementation

The wind threat estimation model was designed as an iterim step in a system to assist AID in anticipating disasters. It would be useful in its present state as a method of alerting AID to impending disasters. In effect, SAI used the model in this way during the fall of 1978 and spring of 1979, SAI in turn, passed the information to AID for evaluation. The weakness is that it is currently necessary to be aware of the cyclone before the program can be run. One possible solution to this problem is to automate the running of the program within an operational weather system when a cyclone is present in the Bay of Bengal. Informally a member of the staff of the Commander-in Chief, U.S. Forces Pacific (CINCPAC) has expressed an interest in obtaining the information. If this interest continues, the navy system which supports CINCPAC might be tasked to provide the information to both AID and CINCPAC.

4.2 Foreign Export

It should be noted that the only thing which ties this model to Guam Warnings is the statistical package (Table 1). With a simple substitution, this model could be adapted to any other forecast. Since the program is rather modest in time/memory requirements, it could be adapted to a small computer for export. Thus it appears to be completely adaptable for use in any of the countries on the Bay of Bengal. Technical assistance in this adaptation can be provided by SAI at the request of AID. It is recommended that this information be made available to foreign governments.

Section 5

BIBLIOGRAPHY

ESCAP, LRCS, WMO - Guidelines for disaster prevention and preparedness in tropical cyclone areas. Geneva 1977.

Nicklin, D.S., "A statistical analysis of Western North Pacific tropical cyclone forecast errors", Naval Postgraduate School MS Thesis, 1977.

Jarrell, J.D., "Tropical Cyclone Wind Probability Forecasting", Science Applications, Inc. contract report to Naval Environmental Prediction Research Facility, 1979 (under review).

Neumann, C.J., "A statistical study of tropical cyclone positioning errors with economic applications". NOAA technical memorandum NWS SR-82, 1975.

Neumann, C.J., "Verification of Tropical Cyclone Forecasts", (Excerpt from proposed manual on tropical cyclone forecasting for the WMO) 1978.

Reprinted from MONTHLY WEATHER REVIEW, Vol. 106, No. 7, July 1978
American Meteorological Society
Printed in U. S. A.

An Analysis of Western North Pacific Tropical Cyclone Forecast Errors

JERRY D. JARRELL[1]
Naval Postgraduate School, Monterey, CA 93940

SAMSON BRAND
Naval Environmental Prediction Research Facility, Monterey, CA 93940

DONALD S. NICKLIN[2]
Naval Postgraduate School, Monterey, CA 93940

(Manuscript received 13 February 1978, in final form 15 April 1978)

ABSTRACT

Western North Pacific tropical cyclone position forecast errors for 10 years (1966–75) are statistically analyzed. Variations of errors versus a number of parameters are examined. It is shown that a small number of readily available parameters, such as location, maximum wind and components of motion, can, with reasonable effectiveness, classify a tropical cyclone forecast as representing a group with either markedly above or below average errors. The annual variations of forecast errors are also discussed and an attempt is made to explain those variations.

1. Introduction

Operational military decision makers in the western North Pacific routinely use information on average tropical cyclone forecast errors in order to determine actions required for evacuation, evasion or protection. Resulting recommendations impact aircraft, ships and other military assets. Because of the 35 tropical cyclones traversing the western North Pacific in an average year, and the large number of military installations, decisions are made frequently.

More refined information than simple average forecast errors would be valuable to decision makers. This study attempts to provide such information by:

1) Developing a tropical cyclone forecast error data set to provide a basis for statistical analysis of past errors and provide a benchmark for future forecast improvements.

2) Providing algorithms for an estimate of the errors in forecasts in order to assist western Pacific commanders in operational decisions regarding the protection and evacuation of military resources.

3) Stratifying errors for 24, 48 and 72 h forecasts based on various parameters such as location, time of year and various tropical cyclone characteristics.

4) Determining if the year-to-year variations in forecast accuracies are real or random deviations about a long-term mean and, if real, determining the reasons for the variations.

2. Data and method of analysis

The Joint Typhoon Warning Center (JTWC), Guam, provided forecast and "best track"[3] tropical cyclone information from 1966 through 1975 for the basic statistical analysis. The data set included the 24, 48 and 72 h official forecasts issued by the JTWC.[4] Some 6150 six-hourly best track positions for some 317 tropical cyclones (including depressions, tropical storms and typhoons) were examined. Storms so short lived that forecast verifications were precluded, were deleted from the data set. The dissipation of storms also accounts for the reduction of cases verified as forecast range increased. The verifying cases totaled 24 h, 4809 forecasts; 48 h, 3038 forecasts; 72 h, 1372 forecasts. The following parameters were available for each forecast initiation time:

1) Maximum wind
2) Latitude
3) Longitude

---

[1] Present affiliation: Science Applications, Inc., LaJolla, CA.

[2] Presently at Offutt Air Force Base, Omaha, NE.

[3] A post-analysis track based on all available information.

[4] It should be noted that JTWC presently incorporates a number of objective forecast techniques in the development of their forecasts, including, since 1975, preliminary results from a dynamic model forecast scheme presently under development at the Naval Environmental Prediction Research Facility and Fleet Numerical Weather Central.

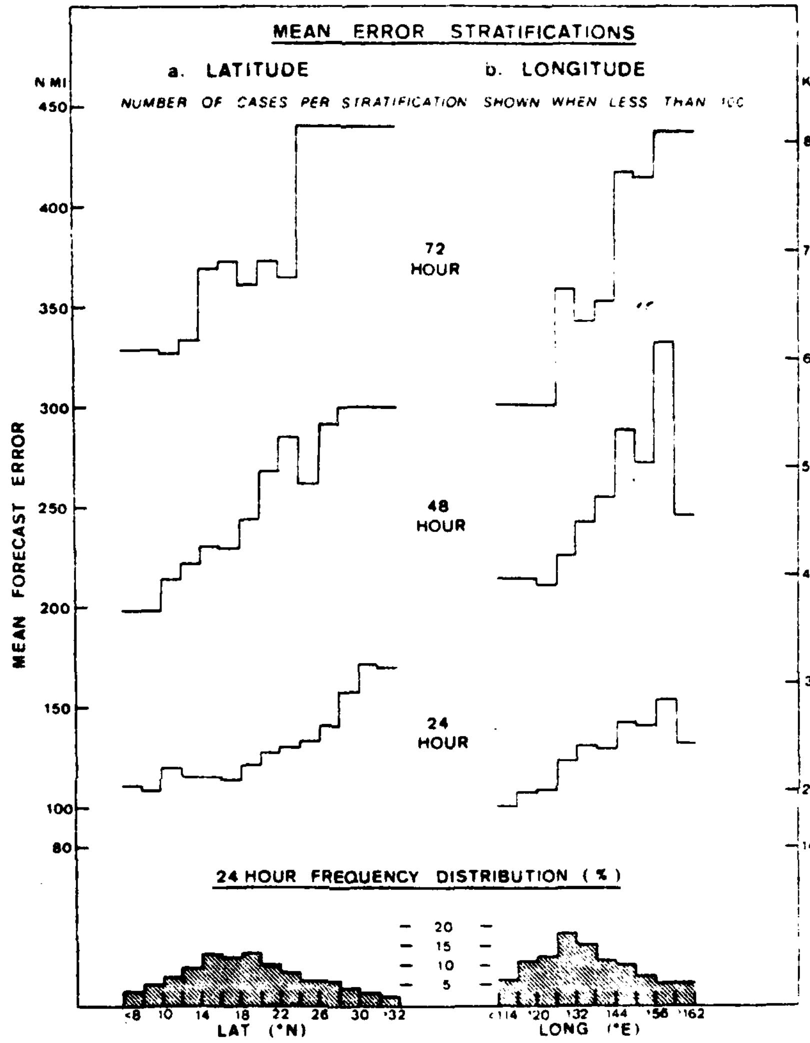

FIG. 1. Mean error stratifications by latitude and longitude

4) West–east component (positive to the east) of tropical cyclone movement
5) South–north component (positive to the north) of tropical cyclone movement
6) Position number on storm track (related to warning number or length of existence of storm)
7) Number of storms in progress at forecast time
8) Month
9) Error distance (forecast position to best track position)
10) Direction from forecast position to best track position.

Similarly, the 1976 data were provided, but retained separately for independent testing. In this data set there were 625 best track positions at six-hourly intervals for 25 tropical cyclones and the verifying cases totaled 24 h, 524 forecasts; 48 h, 424 forecasts; 72 h, 332 forecasts.

The 1966–75 basic data set was then examined by stepwise multiple linear regression and discriminant analysis techniques to determine basic statistical relationships between parameters and find parameters related to forecast errors. The results were then tested on the 1976 data set. The results of the statistical analysis were also used to examine the year-to-year variation in forecast accuracy as well as the trend during the 11-year period.

3. Statistical analysis

Table 1 summarizes the means, standard deviations, and the error variance explained by stepwise multiple linear regression of the first eight variables discussed above for the 24, 48 and 72 h forecasts. No correlation

TABLE 1. Basic statistical information of the stepwise multiple linear regression analysis (1966–75 data).

Variable	Means	Standard deviation	Variance explained (%) 24 h	48 h	72 h
Maximum wind:					
m s^{-1}	33.9	14.8	1.7	0.7	0.2
(kt)	(65.9)	(28.8)			
Latitude (°N)	18.7	6.3	4.2	1.1	0.6
Longitude (°E)	135.0	14.6	1.8	2.3	2.3
West–east movement					
m s^{-1}	−2.8	3.3	0.1	1.7	1.5
(kt)	(−5.5)	(6.4)			
South-north movement					
m s^{-1}	2.0	2.1	0.3	0.3	0.1
(kt)	(4.0)	(4.1)			
Position No.	13.5	10.6	NE*	NE	NE
Number of storms	1.5	0.7	0.3	0.2	NE
Month	8.7	2.3	NE	NE	0.1
Error distance 24 h					
km	233	150			
(n mi)	(125.7)	(80.8)			
Error distance 48 h					
km	458	285			
(n mi)	(247.0)	(153.8)			
Error distance 72 h					
km	685	419			
(n mi)	(369.4)	(226.0)			
Total variance explained (%)			10.5	8.8	6.6

* NE: Was rejected in linear regression.

coefficient of any available predictor with the magnitude of the errors (at either 24, 48 or 72 h) exceeded 0.185, and the total explained variance of the error distance did not exceed 11%. The variables contributing most to the explained variance were the maximum wind, latitude, longitude, west-east movement and south–north movement. The concept of predicting the error was then oriented toward discriminant analysis where forecasts could be identified, and hopefully forecast, as either "good" or "bad." This will be discussed later.

In order to examine the forecast errors in more detail, the errors were stratified and mean errors were computed for each stratification along the range of each variable. Significant trends were evident. In this analysis, stratifications were selected to keep the number of cases in each group relatively high. As an aid in interpreting the forthcoming figures, relative frequencies, all based on 4809 cases, are shown for the 24 h forecasts. Since they are in percentages of the total, the frequencies roughly apply also for 48 and 72 h forecasts. Actual frequencies are typically a few hundred and are not indicated except where they drop below 100.

In each of the 24, 48 and 72 h forecast situations, the mean forecast errors were minimal at lower latitudes (Fig. 1a), gradually increasing with latitude. This indicates, as expected, that storms are more accurately forecast before they recurve and move into higher latitudes. Mean forecast errors decrease with decreasing east longitude (Fig. 1b). Generally, a forecast for a storm in a more westerly position is one based on a longer than average history, and is in an area of better synoptic data and land radar coverage, given the proximity to the Philippines, Taiwan, Japan and the continental area west of 130°E.

The geographic variations of mean 24 and 48 h forecast errors can be seen in Fig. 2. This figure dramatically shows, for example, the difference between tropical cyclone forecast errors for tropical cyclones affecting the Philippines vs those affecting the Japan Korea area.

Maximum wind (Fig. 3) is another important parameter. The mean errors decrease with increasing maximum wind speeds, indicating that better developed tropical cyclones with longer histories and more accurate center locations are more accurately forecast. This general trend is visible for all three forecast times.

Forecasts are generally better for tropical cyclones moving west (Fig. 4a and become progressively more difficult as westward movement diminishes and becomes eastward as associated with recurvature. As for the south–north component (Fig. 4b), the best fore-

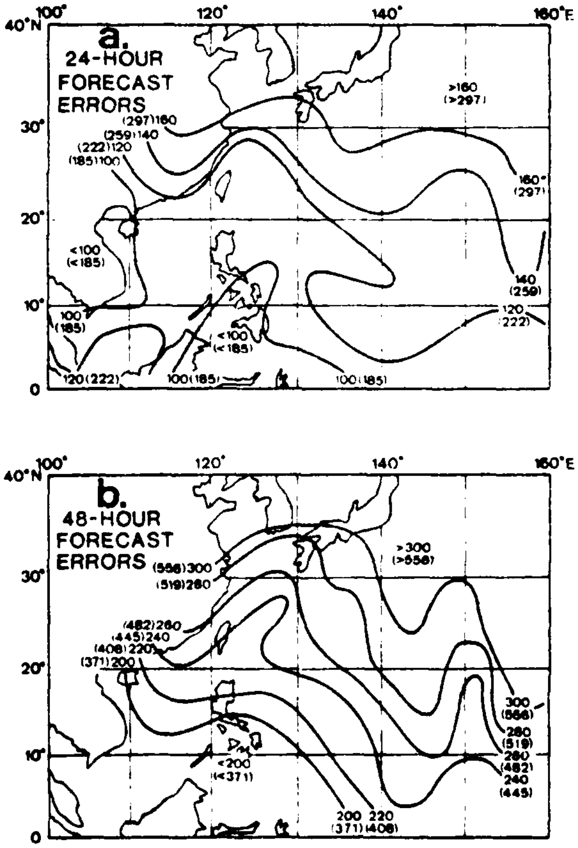

FIG. 2. Geographic distribution of mean 24 h and 48 h forecast errors for western North Pacific tropical cyclones. Errors are based on 1966–75 data and relate to mean forecasts from initial positions. Values are given in km ( ) and n mi.

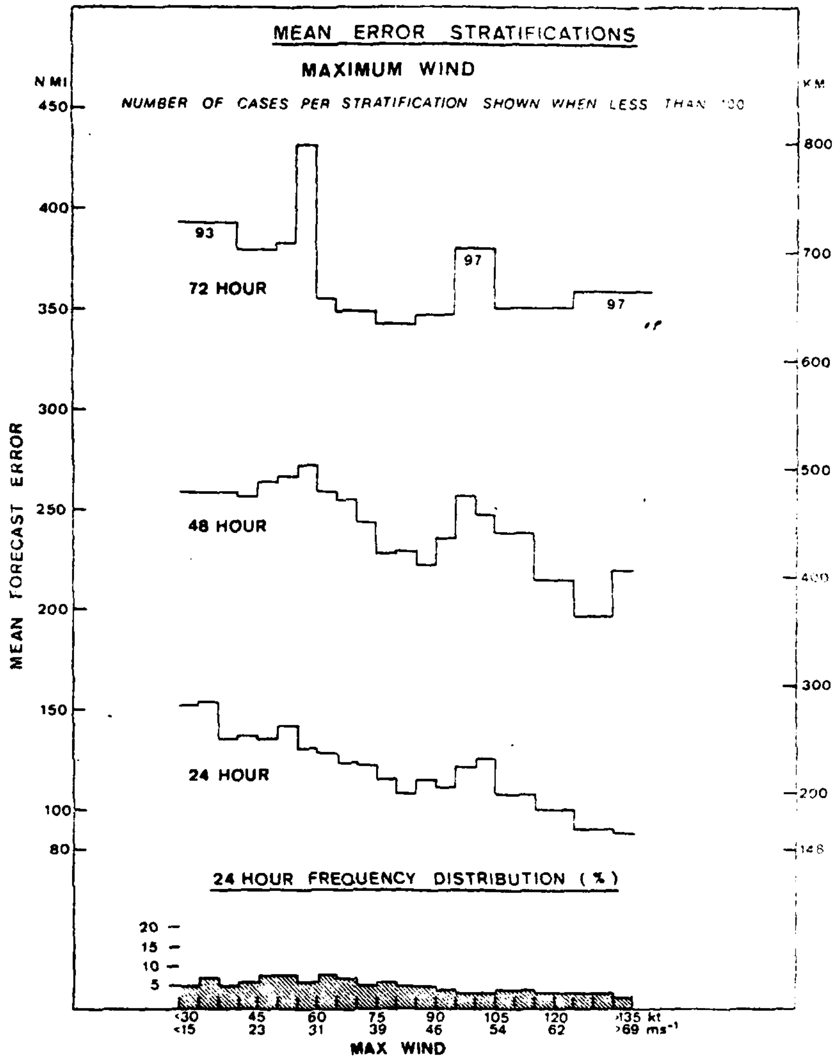

FIG. 3. Mean error stratifications by maximum wind.

casts are centered at or near zero, again implying better forecasts when the storm is moving west with little or no deflection north or south. Errors increased markedly for storms moving south, as well as for tropical cyclones moving north, as would be associated with recurvature.

Fig. 5a shows the number of tropical cyclones occurring simultaneously is related to an increasing forecast error. This is reinforced by Fig. 5b, which examines distance to the nearest storm as a function of forecast error. With tropical cyclones in close proximity—less than 1112 km (600 n mi)—forecast errors increase dramatically. The time of year also relates to number of tropical cyclones occurring simultaneously and the monthly variation of forecast errors can be seen in Fig. 5(c). The peak months of tropical cyclone activity produces generally larger errors at 24 h. This trend becomes progressively less evident at longer forecast ranges.

The number of 6 h points along the track (Fig. 6a), a measure of the length of storm history, showed a trend congruous with that of maximum wind: as the storm's history and development increased, the forecast errors decreased. This trend also becomes less apparent as forecast range increases from 24 and 72 h.

The last variable, initial position error (Fig. 6b) was evaluated using initial "warning position"[5] data available from 1971–1975. A consistent and prominent trend shows the mean forecast errors increasing as the initial position errors increase. This supports the basic fore-

---

[5] The "warning position" is the position the forecaster feels the tropical cyclone is located at time of issuance of the forecast. The distance between the warning position and the post analysis best track position is the initial position error.

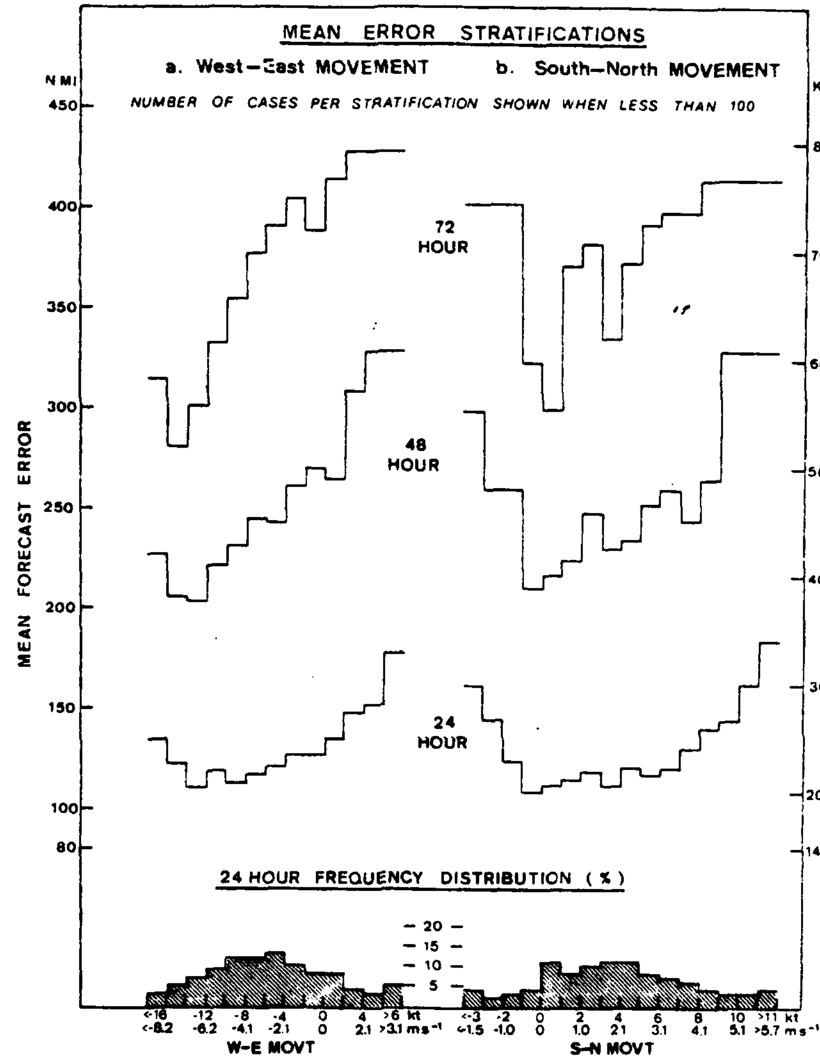

Fig. 4. Mean error stratifications by west–east and south–north components of movement.

casting premise that accurate observations are necessary for accurate forecasts. This finding is in general agreement with the findings in the Atlantic of Neumann and Hope (1972), Neumann (1975), and Sanders and Gordon (1976), who found that for Atlantic hurricanes, the initial position error was important in objective forecasts.

The slope of the relationship of initial position error to forecast error is interesting. A 23.2 km (12.5 n mi) increase in initial position error relates to a 37.1 km (20 n mi) increase in 24 h average forecast error. A strong relationship also exists at 48 h and even at 72 h. This is an important consideration since initial position error can be related to reconnaissance platforms and hence, subject to some control. This will be discussed in more detail later.

To this point, the forecasts (and hence, forecast errors) have been tacitly assumed to be independent of each other. In reality, successive 6 h forecasts for a particular storm are strongly correlated. This can be seen in Table 2, which gives the estimated autocorrelation coefficients between errors from successive forecasts

Table 2. Autocorrelations between forecast errors of successive forecasts.

Time lag (h)	Forecast period 24 h	48 h	72 h
0	1.000	1.000	1.000
6	0.665	0.790	0.838
12	0.432	0.587	0.685
18	0.291	0.432	0.476
24	0.213	0.305	0.371
30	0.173	0.212	0.127
36	0.181	0.171	0.177

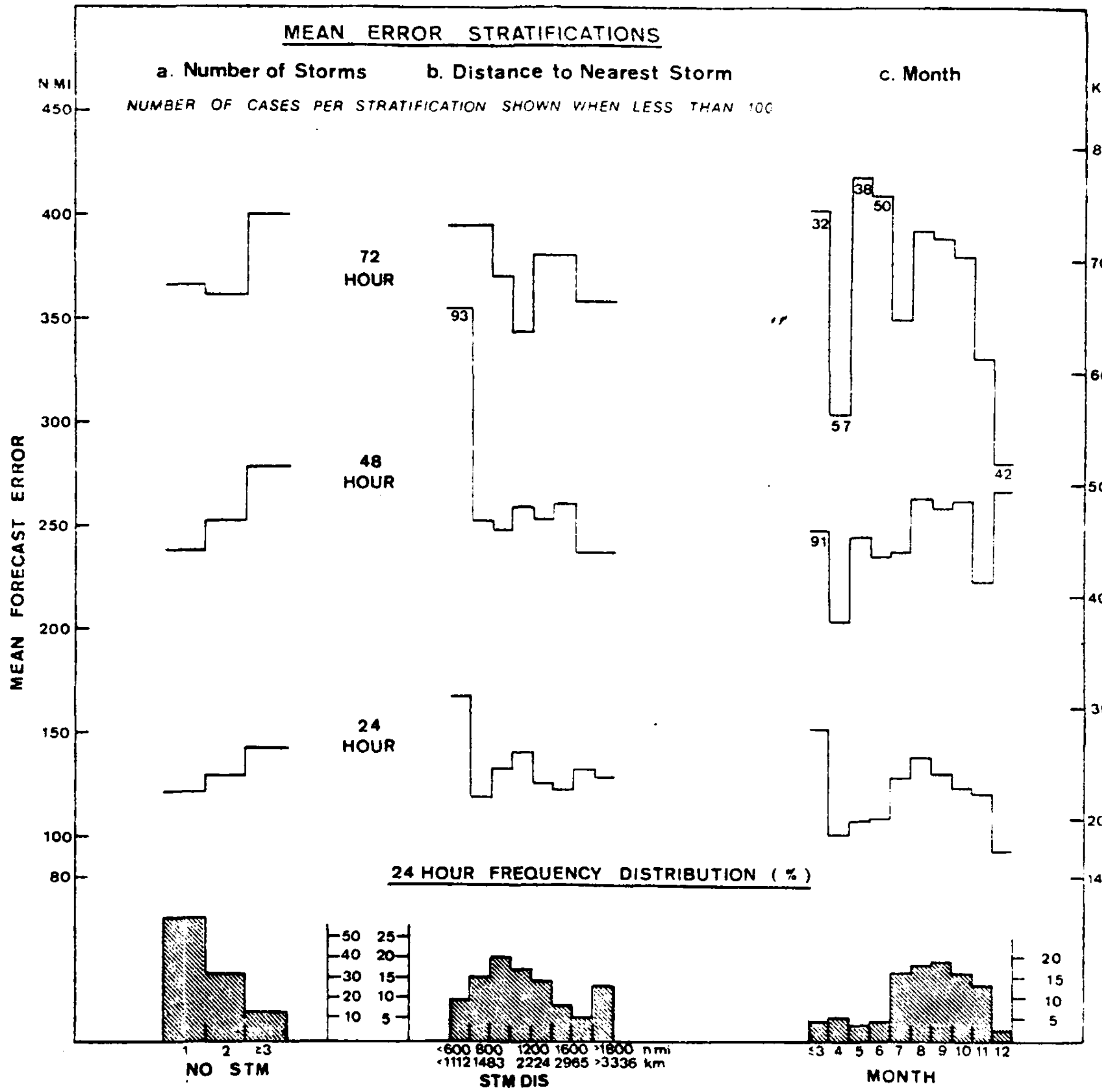

FIG. 5. Mean error stratifications by number of tropical cyclones occurring simultaneously, distance to the nearest storm and month.

with lag times out to 36 h. It can be seen that autocorrelations increase as the forecast interval increases.

The UCLA Biomedical computer program BMDP7M (Dixon, 1975) was used to attempt to discriminate between forecasts likely to produce large errors and those likely to produce small errors. The cases were classed in three groups according to their known 24 h errors. Group 1 consisted of cases where the magnitude of the error was less than the median in both W-E and S-N components. Group 2 had one component above the median and the other below the median while Group 3 had both components above the median. The percentage of cases falling into Groups 1, 2 and 3 was 30, 46 and 24%, respectively.

The discriminators made available for the analysis were those variables previously discussed which were shown to be related to error magnitude and would be known to the forecaster as he made his forecast. These were 1) latitude, 2) longitude, 3) maximum wind, 4) number of storms in progress, 5) and 6) the two components of motion over the previous 12 h, 7) month, and 8) distance to the nearest "other" storm, if one was present; otherwise a large default number was assigned. Of the above parameters the first six were selected by the analysis program as significantly contributing to discrimination.[6]

---

[6] The resulting classification functions are shown in the appendix.

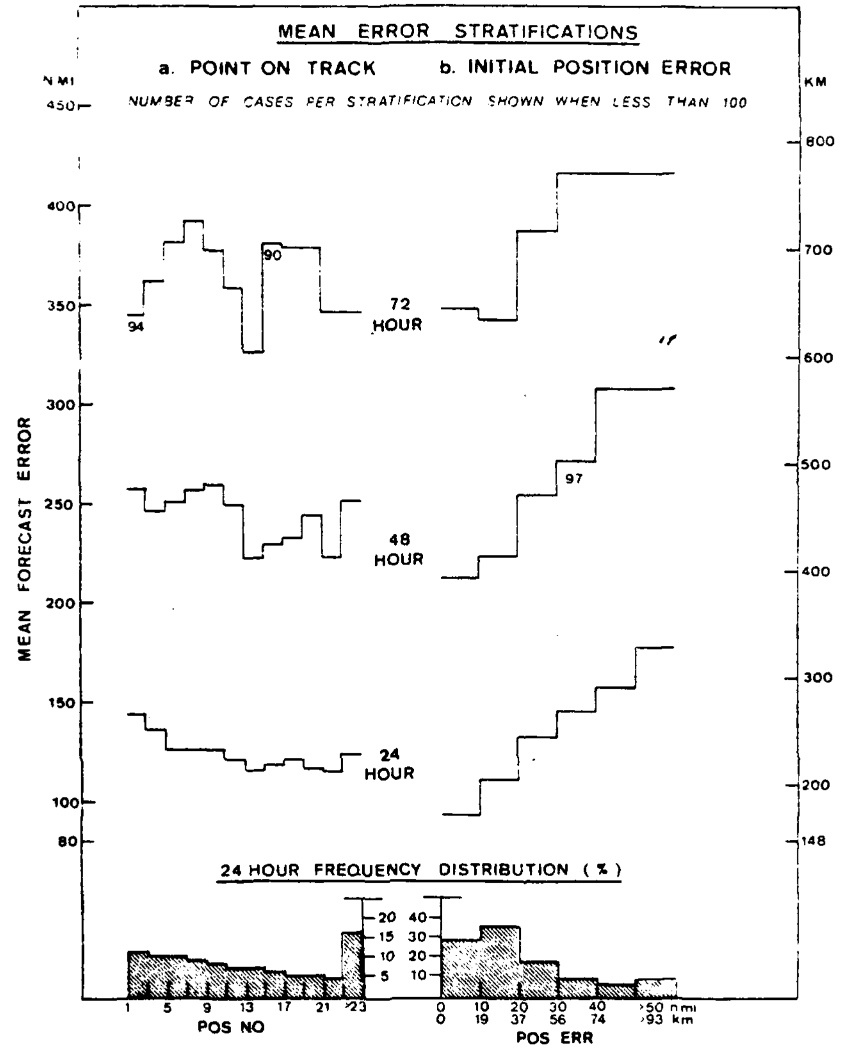

FIG. 6. Mean error stratifications by point on track (position number which is related to life cycle or length of existence of tropical cyclone) and initial position error.

When the classification functions were applied to the dependent data, those identified as Group 1 were typically well developed tropical cyclones (typhoon intensity) in the western part of the region at low latitudes and moving generally west.

Forecasts classed as Group 3 were typically during or after recurvature and included the total spectrum of tropical cyclone intensities. Group 2 included many low latitude weak depressions or tropical cyclones of all intensities at or near typical recurvature latitudes but not as yet exhibiting recurvature. Also included in Group 2 were many otherwise Group 1 cases in multiple storm situations.

The forecast error distributions are illustrated in Fig. 7 by means of 40% probability ellipses based on the assumption of a bivariate normal probability distribution. Ellipses are given for each group for 24, 48 and 72 h forecasts although the discriminant analysis was based on 24 h errors only. The most prominent difference in the three sets of ellipses is their size. The area within each of the Group 1 ellipses is roughly half that of the corresponding Group 3 ellipses and about two-thirds that of the corresponding Group 2 ellipses. The orientation of the major axis is similar for all three groups.

The bias or offset of the ellipse center from the diagram origin is striking for Group 2. The bias to the southwest means forecasts were, in the mean, too far northeast. This could be the result of over anticipation

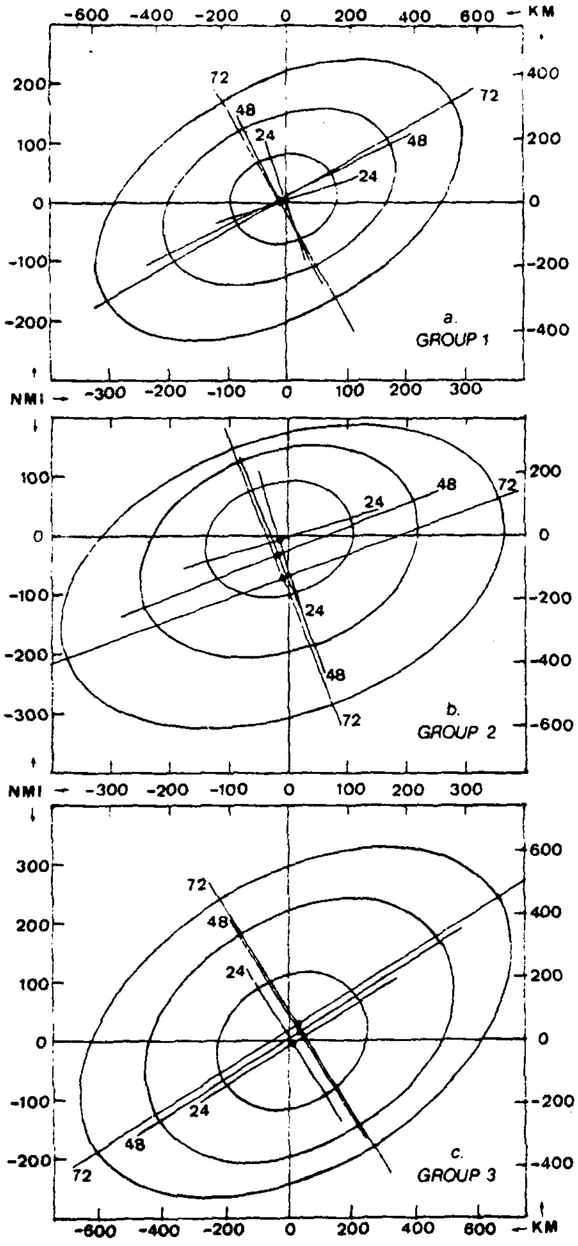

FIG. 7. The 40% probability ellipses for each forecast interval for Group 1, Group 2 and Group 3 forecasts. The origin is the forecast position with each ellipse center the average verifying position relative to forecast position.

of recurvature.[7] Although the bias is much less for Group 3, it is in the opposite direction perhaps due to the underestimation of the acceleration of recurved tropical cyclones. The bias is small but slightly to the west for Group 1. Since these are basically east to west moving tropical cyclones, this means that speed is in the mean slightly underforecast.

The 1976 cases were tested for fit into various probability ellipses constructed on the dependent data. Fig. 8 shows the results of this test. In each of the small graphs the 45° line represents the expected result while the dots connected by line segments represent the observed fit. The maximum deviation is indicated by a vertical arrow. Using the Kolomogorov-Smirnov test (Massey, 1951) based on the effective number of independent cases, none of these differences are significant at the 5% level.[8] The ellipses were generally conservative because 1976 forecasts were better than the 10-year average reflecting in part a general improvement of forecasts over the eleven years involved.

For contrast the Group 3 and Group 1 forecasts were interchanged and the ellipses were again tested. Fig. 9 shows the results of this test. The Group 1 forecast errors are clearly not represented well by the large Group 3 ellipses and conversely the Group 3 forecasts are poorly represented by the Group 1 ellipses.

4. Annual variability

Perhaps the most interesting facet of the examination of tropical cyclone forecast errors is the extent of annual variability and possible reasons for the variations. Fig. 10a shows the annual mean errors for the 11 years 1966–76. The picture has been described as a steady improvement to a minimum in errors in 1970, then an unsteady but generally worsening trend in the years since. The least squares trend lines indicate minor improvement over the total period; however, the slopes are too shallow to be conclusive.

A number of factors have been examined to isolate reasons for the large year to year variability. The performance of objective forecast techniques tends to parallel that of the official forecasts. Fig. 10b shows the annual variation of simple linear extrapolation, or persistence of the past 12 h motion vector, as a forecast technique. The persistence error depicts a measure of how well behaved or linear the tracks were. This extrapolation is based on "best track" or post analysis positions. Of course the forecaster faces uncertainty in the location and recent history of the tropical cyclone. Nevertheless, the similarity in the two curves illustrates the vulnerability of the forecasting system to major track or speed changes.

---

[7] As an example for a single year, the 1967 tropical cyclone season had many east-west moving tropical cyclones with below average number of recurving tropical cyclones. The 72 h forecast error bias was 172 km (93 n mi) to the southwest for Group 2 cases.

[8] Because of high autocorrelation, consecutive forecasts on the same tropical cyclone cannot be considered independent. Following Brooks and Carruthers (1953), the equivalent number of independent cases (N_e) was estimated by $N_e = N(1-r)^2/[1-r^2-(1-r^c)/c]$, where N is the total number of cases, r is the autocorrelation coefficient, and c is in the average number of cases per tropical cyclone. For 24, 48 and 72 h, respectively, $N_e = 0.24N$, $0.18N$ and $0.34N$ using (r,c) values of (0.665,17), (0.790,11) and (0.685,5).

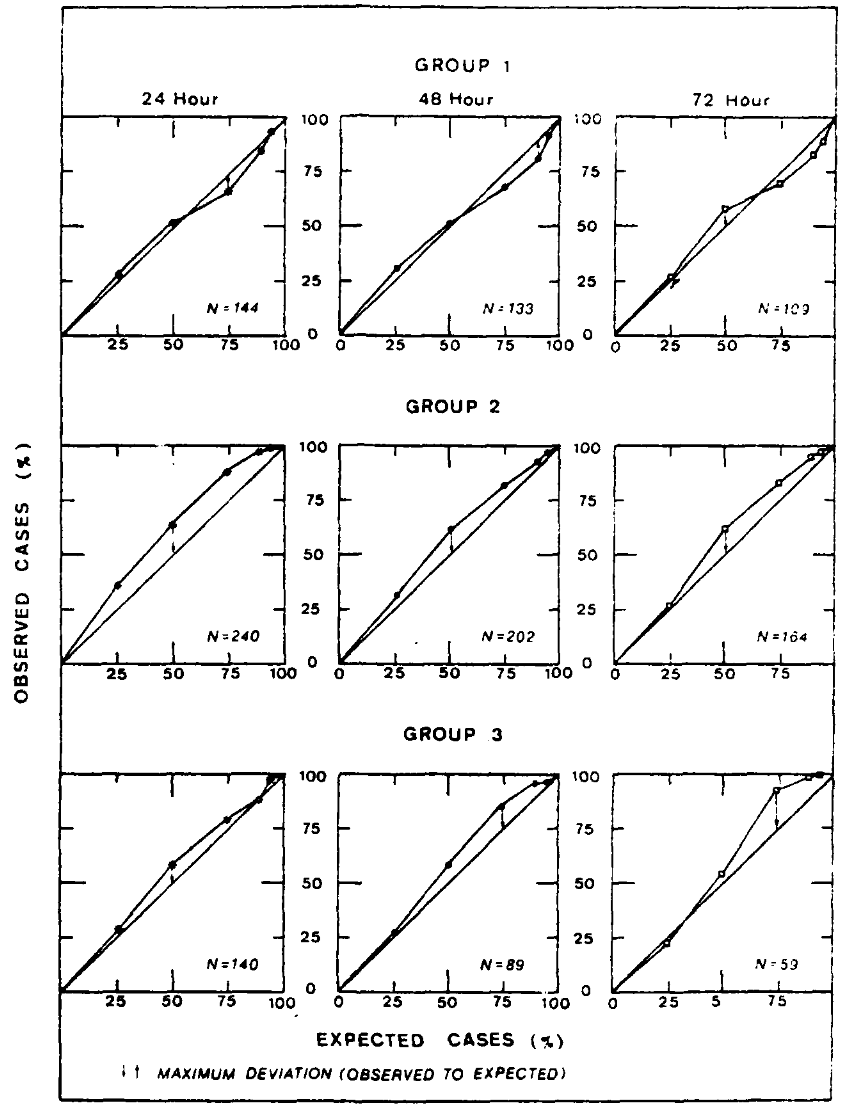

FIG. 8. The 1976 verifying positions that fell into 25, 50, 75, 90 and 95% probability ellipses by Group and Forecast (24, 48 and 72 h). Maximum deviation is indicated by vertical arrow. "Observed" is the ordinate, and "expected" is the abscissa.

Another measure of variability is the type of forecasts which make up a year. That is, the percentage of the year made up of the type expected to give large errors versus those expected to give small errors. In Fig. 10c, the annual mean group numbers (from the previously presented descriminant analysis) are shown. Above average group numbers would be indicative of a difficult year, whereas below average relate to an easy year. The general characteristics of the curves of Fig. 10c follows those of Fig. 10a with correlation coefficients of 0.61, 0.68 and 0.61 at 24, 48 and 72 h, respectively.

Fig. 10d shows the percentage of warnings issued by the JTWC based on aircraft reconnaissance and satellite data. There is qualitative correspondence between large percentages of warnings based on reconnaissance in the middle years and generally lower forecast errors. Forecast errors are larger with the lower percentage of warnings based on reconnaissance data in the early and the later years. In the years after 1971 satellite data has to some extent replaced reconnaissance, but as indicated previously initial position error is highly related to forecast error and the initial position error for reconnaissance is less than for satellite data. For 1976 the initial position error was 32.8 km (17.7 n mi) for aircraft reconnaissance versus 56.5 km (30.5 n mi)

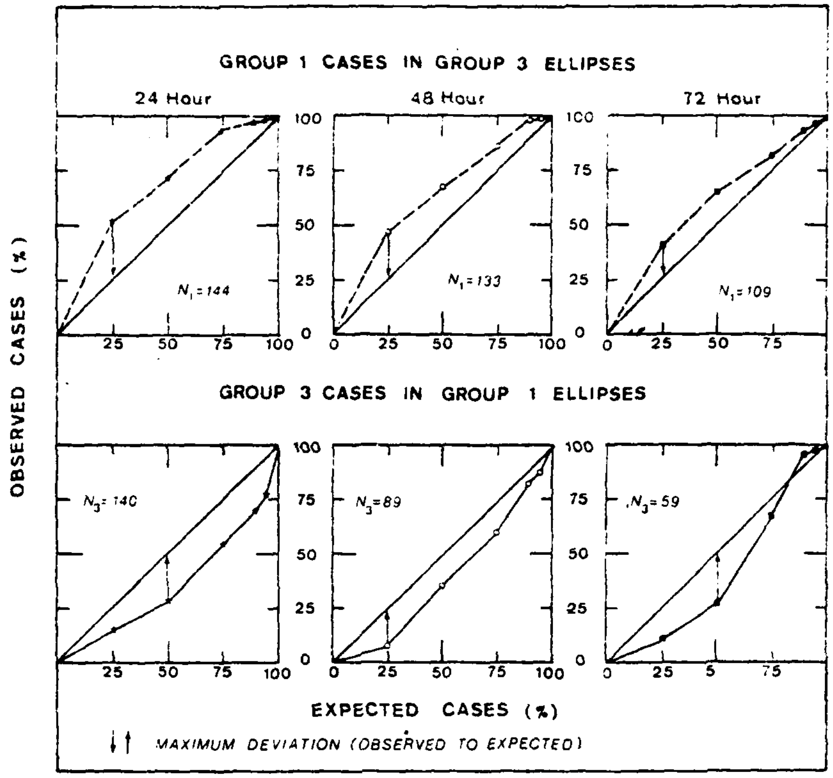

FIG. 9. The 1976 verifying positions that fell into 25, 50, 75, 90 and 95% probability ellipses for Group 1 into Group 3 ellipses and Group 3 into Group 1 ellipses for 24, 48 and 72 h. Maximum deviation is indicated by vertical arrow. "Observed" is the ordinate, and "expected" is the abscissa.

for DMSP.[9] It seems apparent that the reduction of aircraft reconnaissance has had an impact on the forecast errors. In addition, in the years since 1971, aircraft reconnaissance in the western North Pacific has not had the use of the powerful APS-20 radar which provided excellent tropical cyclone "stand-off" fix capability.

Another factor which has changed at the JTWC in recent years is numbers of duty officers or forecasters. The number of forecasters has historically been six: the Director, Operations Officer, and four duty officers. As can be seen by Fig. 10e, the number of duty officers has been increased in recent years. It is certainly not clear that this increase has led to an improvement in forecasting. But the question is: has there been an improvement in forecasting in recent years?

A major objective of this study was to examine this year to year variation in the forecasting system. This is useful not only as a basis for evaluating the effectiveness of the system, but serves a more important purpose. Over the next few years the tropical cyclone warning system in the western North Pacific will rely increasingly on dynamic models as a major input. It is then important that a baseline be established for relatively short term evaluation of the system, hopefully to measure improvements, but also as a guard against system degradation.

To establish such a baseline the year to year performance must be normalized or adjusted. Annual mean error is a poor measure of performance because clearly some years are heavily loaded with difficult forecasts and others weighted toward easier forecasts. As a normalizing tool, a measure of difficulty is necessary. The distribution of forecasts into the three groups presented earlier is one possible measure. The mean group number explains about 40% of the year-to-year variance in mean error. Another important component of error is how persistent the tracks were. The annual persistence error explains from 30 to 50% of the annual variance. Clearly these two measures are not independent. Their correlations decrease in time from about 0.5 at 24 h to 0.25 at 72 h. Another important determinant of forecast error is the error in the initial position. This error is assumed to be independent of group num-

---

[9] It should also be pointed out that the DMSP program has been particularly beneficial or cost saving in the reduction of investigative aircraft missions which are flown when the development or formation of a tropical cyclone is imminent.

ber and persistence error (when persistence is based on the "best track"). Initial position error has been documented on a case by case basis since 1971 and annual means are available since 1970. There are other factors such as the introduction of objective techniques, increased knowledge concerning the behavior and characteristics of tropical cyclones, improvements in the mid-latitude prognostic models, data (synoptic and satellite) availability, and changes in personnel. These are less tangible and will for the moment be ignored.

A system of handicapping the annual errors has been devised to adjust for annual forecast difficulty and the variability in initial position error or more specifically reconnaissance support. The first component of the handicapping system is an estimate of annual error based on a two-predictor least-squares regression equation. The predictand is annual error (AE in km) and the predictors are the annual mean group number (G) and the annual mean persistence error (P in km) as follows:

$$AE_{24} = -76.4 + 0.779P_{24} + 79.1G_{24} \quad (1)$$

$$AE_{48} = -86.5 + 0.748P_{48} + 112.8G_{48} \quad (2)$$

$$AE_{72} = -227.0 + 0.738P_{72} + 207.1G_{72}. \quad (3)$$

These equations explain 43, 62 and 79% of the variance in the annual mean errors at 24, 48 and 72 h, respectively.

The second component of the handicap is based on the percent of forecasts issued where the initial position was based on aircraft reconnaissance. This percentage is known for the 11-year period. This percentage was converted to an equivalent annual mean initial position error by assigning 33.3 km (18 n mi) as the initial position error for reconnaissance based tropical cyclone forecasts (Harrison, 1975 and Pilipowskyj, 1977) and using the known initial position errors (from 1970–76) to deduce the initial position error value based on "other" types of fixes. These "other" types include land and ship radar, satellite data, extrapolation and synoptic data. This average was found to be 64.8 km (35 n mi). The relationship between forecast error (E in km) and initial position error (E_0 in km) as was shown graphically in Fig. 6(b) is

$$E_{24} = 154.3 + 1.6E_0$$
$$= 154.3 + 1.6[33.3R + 64.8(1.0 - R)], \quad (4)$$

$$E_{48} = 363.2 + 2.4E_0$$
$$= 363.2 + 2.4[33.3R + 64.8(1.0 - R)], \quad (5)$$

$$E_{72} = 617.0 + 2.0E_0$$
$$= 617.0 + 2.0[33.3R + 64.8(1.0 - R)], \quad (6)$$

where R is the fraction of warnings during the year that were based on aircraft reconnaissance.

The two handicaps were each reduced by the minimum of the eleven annual values. The 1973 season for instance, the least difficult year based on Eqs. (1) through (3), was then assigned a zero handicap for difficulty. Similarity in 1968 and 1969, when 95% of the forecasts were based on aircraft reconnaissance, a zero handicap for reconnaissance was assigned. Finally the annual mean errors were reduced by the sum of the two handicap components. Fig. 11 is the "unexplained error." The trend is more consistent than the

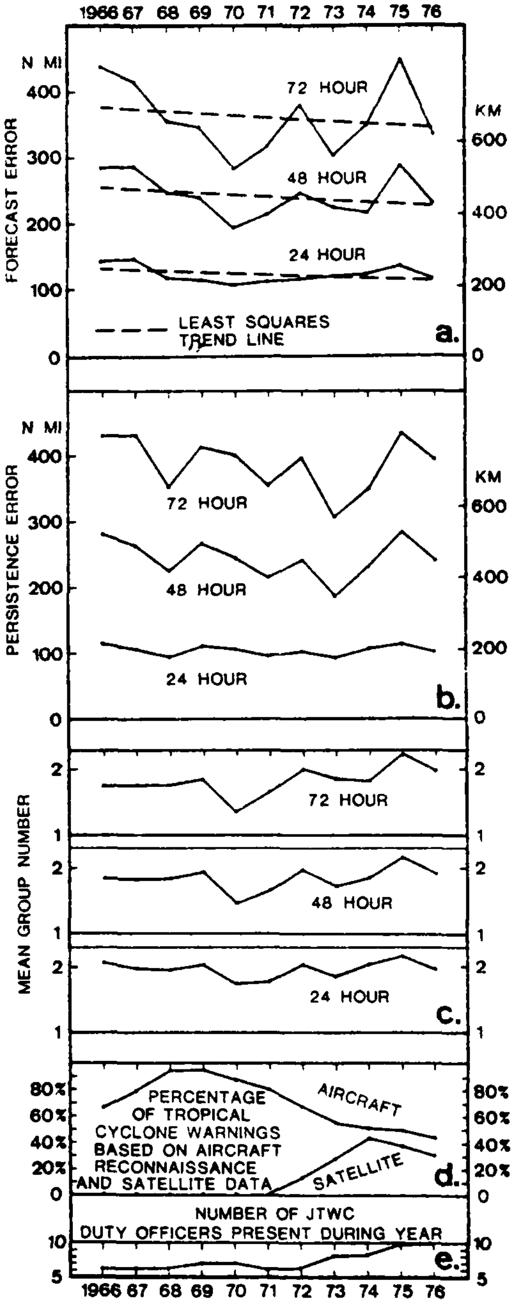

Fig. 10. The annual variation of (a) mean tropical cyclone official forecast error, (b) mean persistence error, (c) mean Group number, (d) percentage of warnings based on reconnaissance and satellite and (e) number of JTWC duty officers.

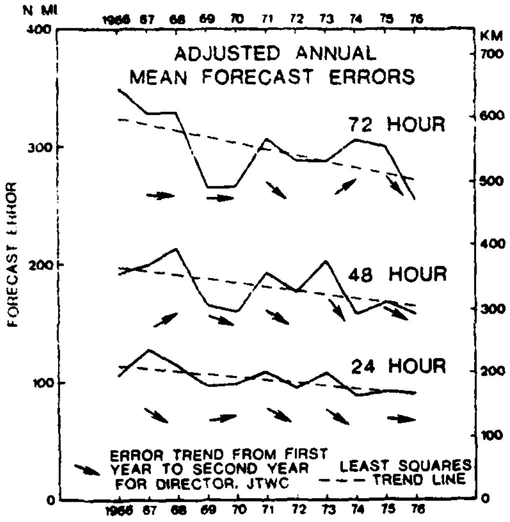

FIG. 11. Annual mean forecast errors adjusted by removal of elements of the annual variation of persistence, forecast difficulty and initial position error.

error trend of Fig. 10a[10] and reflects in part the "pay-off" or result from research efforts, i.e., improved forecasting aids and numerical output, and a better understanding of the tropical cyclone and its surrounding environment. Also in the trend line is the result of more realistic manning of the JTWC in terms of the number of forecasters as well as any change in the quality or skill level or even motivation of the personnel.

It is difficult to assess the net change in the observational network over this eleven year period. There have been some losses, most notably a large reduction in ship reports, particularly in the South China Sea with the Post-Vietnam reduction of Navy and Department of Defense contract vessels. There have also been some reductions in upper wind reporting. These have, in part, been offset by greatly improved satellite support particularly with the DMSP in 1971 and later years although there have been periods when this support left much to be desired. As evident from Fig. 10d, reconnaissance support has eroded significantly from two squadrons (Navy and Air Force) to a present day single, smaller, Air Force squadron.

There has long been concern over the rapid turnover of personnel at the JTWC. The tour length is two years. A new Director, who is a dominating force in the forecast system, was on hand for the 1967 season and for each odd year thereafter. The apparent sawtooth pattern in Fig. 11 supports this concern. For the five two-year tours, the 24 h errors were, on the average, 10% greater in the odd or first year as compared to the even years. The 48 and 72 h forecasts showed similar but less distinct numerical changes.

5. Summary and recommendations

In light of the objectives outlined earlier, for the most part, the goals of the study have been attained. It has been demonstrated that a small number of readily available parameters can, with reasonable effectiveness, classify a tropical cyclone forecast as likely resulting in either markedly above or below average errors. Group 1 forecasts have a high probability of below average errors with a low probability of above average errors. Group 2 forecasts have approximately equal probabilities of being above or below average. Group 3 forecasts have a low probability of below average errors with a higher probability of above average errors. It was found that the error probability ellipses for all three groups are oriented approximately the same (major axis—northeast to southwest), but the area of the Group 1 ellipses was roughly half of the area of the Group 3 ellipses. In addition the year-to-year variation in forecast errors over the past 11 years in the western North Pacific appears to show continued improvement, once the errors are adjusted for the annual biases present, which contribute either negatively or positively to the forecast errors.

The examination of additional parameters could improve the identification of potentially poor forecasts. Initial position error, which was shown to be directly related to forecast errors, was not introduced as a discriminator because it is not generally known to the forecaster at the time of the forecast. In addition, the synoptic patterns associated with the tropical cyclone have not been considered. Parameters which are associated with such features as the Tropical Upper Tropospheric Trough (TUTT), subtropical ridges and transient troughs in the westerlies might prove to be important discriminators especially since they many times relate to the basic problem of tropical cyclone recurvature.

Two primary sources of error are implicit from the statistical analysis: 1) those related to the recurvature phenomena—whether to forecast recurvature or not and in the speed of motion after recurvature—and 2) those errors associated with initial positioning. Research aimed at these sources offers considerable potential for improvement in tropical cyclone forecasting. The greatest hope for the solution of the recurvature problem may lie with dynamic models, but synoptic and statistical studies should not be ignored.

The positioning problem suggests improvement in the observational system. While more and better equipped aircraft is a possible, and perhaps expedient solution, developments in the satellite area may be the ultimate solution. This may involve finding a different and more conservative way to define the location of a tropical cyclone other than the so-called eye or estimated center.

A further application of the statistical base presently established would be to derive "threat" or "strike"

---

[10] The adjusted error-year correlation is approximately 0.6 as compared to the actual error-year correlation of 0.3 for Fig. 10(a).

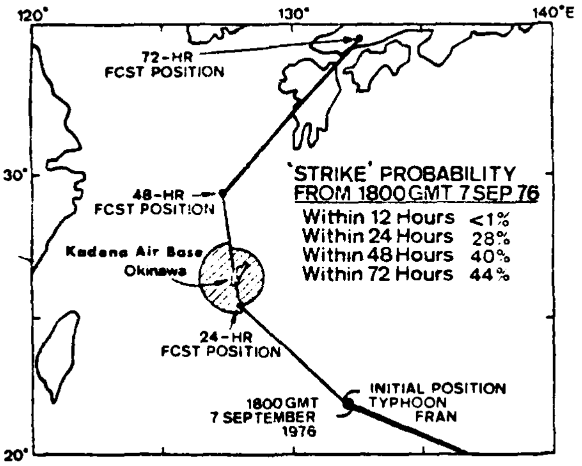

FIG. 12. The "strike" probability of Typhoon Fran (1800 GMT 6 September 1976) passing through the shaded area relative to Kadena Air Base, Okinawa. The probabilities are based on the forecast track and the error distributions for this type of tropical cyclone. It should be noted that Typhoon Fran did in fact miss the shaded area as the storm passed to the east of Okinawa.

probabilities for specific locations in the western North Pacific. For example, Fig. 12 gives the probability integrated over an area 139 km (75 n mi) to the left and 93 km (50 n mi) to the right of Kadena Air Base, Okinawa relative to the forecast track of Typhoon Fran. The integration is also performed over time from that initial time of 1800 GMT, 7 September 1976 to a time 12, 24, 48 and 72 h later.

Acknowledgments. The authors would like to thank the following past Directors of the JTWC, Guam for their input: Lt. Col. W. D. Roper, USAF (Ret); Lt. Col. J. J. R. Kinney, USAF (Ret); Lt. Col. N. Nishimoto, USAF; Col. G. D. Atkinson, USAF and Lt. Col. S. Pilipowskyj, USAF. The technical assistance provided by Prof. W. van der Bijl, Dr. A. I. Weinstein and the suggested area of study by Capitan A. T. Buckmaster, USN, is much appreciated.

APPENDIX

Classification Functions

The discriminant analysis resulted in three functions which are linear combinations of six variables:

	Coefficients		
Variable	**Function 1**	**Function 2**	**Function 3**
Latitude (deg)	−0.06439	0.08352	0.04238
Longitude (deg)	−0.03231	0.00274	−0.03928
Maximum wind (m s^{-1})	0.04371	0.02694	−0.00239
S–N movement (m s^{-1})	−0.15719	0.20958	−0.06587
W–E movement (m s^{-1})	−0.04932	−0.18310	0.01311
Number of storms in progress	−0.26096	0.01186	1.05585
Constant	4.66511	−3.81310	3.14344

The values of the functions at the group mean for each variable are as follows:

	Function 1	Function 2	Function 3
Group 1	0.36059	0.05017	−0.01138
Group 2	−0.04093	−0.07138	0.01688
Group 3	−0.36186	0.07454	−0.01822

In order to determine which group a forecast would fall into, each of the functions f_i for $i=1, 2, 3$ are evaluated using the known actual values for the six variables. A squared distance is then determined from the group mean value ($u_{i,k}$) for the 3 functions (i) and the three groups ($k=1, 2, 3$) with the equation

$$D_k{}^2=\sum_{i=1}^{3} (f_i-u_{i,k})^2.$$

The forecast is assigned to the group (k) corresponding to the minimum $D_k{}^2$ value.

REFERENCES

Brooks, C. E. P., and N. Carruthers, 1953: *Handbook of Statistical Methods in Meteorology.* Her Majesty's Stationary Office, London.

Dixon, W. J., 1975: BMDP biomedical computer programs. University of California Press, Berkeley, 792 pp.

Harrison, E. J., 1975: Forecast verification as a function of reconnaissance platform. U.S. Fleet Weather Central, Guam Tech. Note JTWC 75-2, 7 pp. [Available from USFWC/JTWC, COMNAV MARIANAS Box 17, FPO San Francisco 96630.]

Massey, F. J., 1951: The Kolmogorov-Smirnov test of goodness of fit. *J. Statist. Assoc.*, **46**, 68–78.

Neumann, C. J., and J. R. Hope, 1972: Performance analysis of the HURRAN tropical cyclone forecast system. *Mon. Wea. Rev.*, **100**, 245–55.

Neumann, C. J., 1975: A statistical study of tropical cyclone positioning errors with economic applications. NOAA Tech. Memo. NWS SR-82, 21 pp. [NTIS No. COM-75-11362].

Piliposwkyj, S., 1977: JTWC—Current status and future prospects. *Proceedings of the 1977 Tropical Cyclone Conference*, Environmental Group Pacific Command, 7–22 [Available from EGPC, HQ, Commander-in-Chief—Pacific, FPO San Francisco 96610.]

Sanders, F., and N. J. Gordon, 1976: A study of forecast errors in an operational model for predicting paths of tropical storms. Air Force Geophysic Lab., Sci. Rep. AFGL-TR-77-0079, 56 pp. [NTIS No. AD-A040-935].