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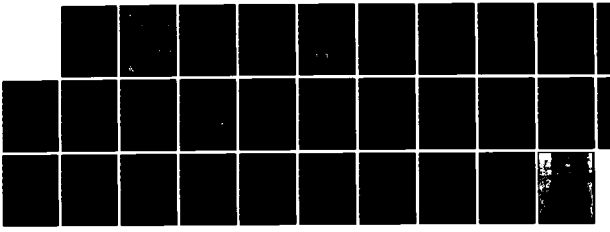

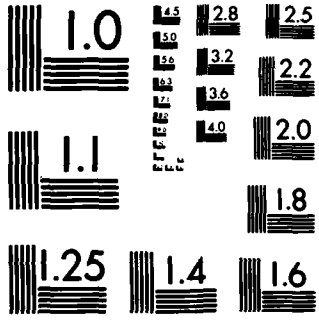

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SETTING HURRICANE CONDITIONS OF READINESS WITH HIGH CONFIDENCE

Prepared By:

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A procedure for setting hurricane readiness conditions with a high degree of reliability is described. The methodology utilizes a large number of computer-simulated forecasts for actual hurricanes since 1899 that passed near Key West, FL or Guantanamo Bay, Cuba. Wind probabilities were computed from these forecasts assuming present-day official forecast error characteristics, and then compared to hindsight estimates of actual winds. These data were used to establish hurricane condition thresholds ((continued on reverse))

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at desired levels of confidence as related to wind probability. Threshold values for 95% confidence are given for hurricane readiness conditions at Key West and Guantanamo Bay.

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1. INTRODUCTION

While there have been notable improvements made during past decades in the field of tropical cyclone forecasting, it is still far from an exact science. Decisions which rely upon these imprecise forecasts are themselves uncertain and therefore carry inherent risks of being incorrect.

A procedure will be described which can help to minimize these risks by providing a much improved estimate of the probable threat to a specified area by an approaching tropical cyclone. Some of the recent research findings used in the development of this procedure includes:

1) Certain forecasts are inherently more difficult to make and will likely result in larger errors, as shown by Jarrell et al. (1978). The degree, or class, of difficulty can be estimated in advance.

2) Crutcher et al (1982) found that the pattern of distribution of Atlantic hurricane forecast errors within classes closely approximates a random bivariate normal distribution (normal in both E-W and N-S directions).

3) Jarrell's (1978) development of Tropical Cyclone Strike Probability provides a tested method to estimate the likelihood of a cyclone's center passing over, or striking, a specific location.

4) In Wind Probability Forecasting, Jarrell (1981) extends the Strike Probability concepts to estimate the

probability of 50 kt (and 30 kt) winds occurring at a specific location.

5) Cyclone/Hurricane Acceptable Risk Model (CHARM) concept: There is some destructive wind level (e.g., 50 kt) for which preparations must be made and some lower wind level (e.g., 30 kt) which prohibits most preparations (Jarrell and Brand, 1983).

Wind probabilites incorporate the three diverse elements of a standard tropical cyclone forecast (track, maximum wind and wind radii) into a single quantity [detailed in section 2.4] which represents the threat posed by a cyclone. This threat is then used as the basis for decisions regarding setting the proper readiness conditions.* The concept of applying such objective threat estimates to tropical cyclones is a unique feature of a procedure introduced herein as SETCON.

1.1 CBR Rationale

A cost-benefit ratio (CBR) is simple, yet can be a powerful tool to use. A CBR of .75 (75/100) means that every $.75 in action costs would be expected to return $1.00 in benefits. Correspondingly, a CBR of 1.25 would generally be economic grounds not to act since it represents a situation in which every $1.25 of costs would return only $1.00 in

*Hurricane conditions I and II are set when hurricane force winds (≥64kt) are expected within 12 and 24 hours respectively. Hurricane conditions III and IV are set when hurricane force winds are considered possible within 48 and 72 hours respectively. Similar tropical storm conditions of readiness relate to wind speeds from 34 to 63 kts.

benefits. With perfect information CBRs can greatly simplify decision making.

With imperfect information, such as weather forecasts, we won't know with certainty what the weather elements will actually be; but technology now exists to estimate event probabilities, for example, an event like a hurricane strike occurring. There is a rule of thumb which relates this probability to the CBR. This rule states: "In the long run, protective measures should be taken only when the expected losses are greater than the preventative costs." In a more technical sense, this occurs when the probability of damage exceeds the ratio of the cost of protection to the cost of damage which would occur without protection. This ratio is, of course, the CBR.

In order to make an accurate and objective decision regarding which actions to take (e.g., which readiness condition to set), a calculation of the CBR for each condition is needed. Unfortunately, it is impossible to determine a CBR in advance of a tropical cyclone since the CBR is partially determined by the actual course of events, i.e., what damages actually occurred. It is also virtually impossible to make a direct and reliable estimate of a CBR related to condition setting because of the diverse economic considerations of complex actions involved in the setting of a condition. For example, how can we adequately estimate the economic value of human lives, the decrease of our national security due to reduced readiness of military bases or long-term effects of salt water intrusion cause by storm surge, etc?

A dilemma occurs because while a CBR value can't be directly measured or even reliably estimated, it is still

useful for an objective analysis. A procedure introduced herein to apply wind probabilities to hurricane conditions or SETCON solves this dilemma by indirectly estimating the CBR values (see section 3.0). The CBR estimate is determined from the user's selection of a confidence level for correctly setting a certain warning condition. For example, the user may desire to be 95% confident of correctly setting condition I. By this we mean that condition I is actually set 95% of the times that it should be set. By analyzing past cyclones we can determine what CBR value would result in that specified confidence level.

2. METHODOLODY

A procedure was used which involved over 10,000 computer-simulated forecasts for actual hurricanes which passed near Key West, Florida or Guantanamo Bay, Cuba. Wind probabilities were computed from these forecasts and then compared to the actual conditions which subsequently developed. This data enabled the selection of hurricane condition threshold values related to wind probability, resulting in the desired confidence levels.

2.1 Need to Create Forecasts

The analysis of past tropical cyclones is a crucial step in the development of the methodology. With the incredibly complex nature of a tropical cyclone, it is necessary to study large numbers of forecasts in order to ensure a high degree of confidence and reliability in the results. Also needed are forecasts that have been made by the current methods in order to be certain that the effects are caused by cyclone variabilities and not by changes in forecast methodology. These are conflicting requirements since a study of forecasts from recent tropical cyclones would involve a relatively small population of forecasts due to the small annual number of cyclones. By looking back to 1870, when the tropical cyclone track archive begins, we do obtain a large number of cyclones. However, even if there existed a long archived record of forecasts, the methods have evolved, which means, that again there is a relatively small population of forecasts which have resulted from similar and current methods. Using older forecast methods would be inappropriate since they do not incorporate today's more advanced forecasting skills.

This problem is surmounted by creating a new set of forecasts to serve as the data base. This solution has two distinct advantages:

1) All forecasts can be made independent of each other, thus multiple independent forecasts can be made from the same starting point.

2) It is relatively easy to create a large number of forecasts since the forecasts are created by a computer simulation process. This large number of forecasts at present forecasting skill levels would otherwise take centuries to accumulate.

2.2 Creation of Forecasts

The concept of creating forecasts, or predictions, after we know the outcome is easily justified by noting research by Crutcher et al (1982). Crutcher et al. found that tropical cyclone forecasts can be classified into one of three categories or clusters with varying degrees of difficulty. Within each cluster, the forecast errors follow a bivariate normal distribution with the means, standard deviations, and correlation coefficient known for each class.

The procedure to create forecasts consists of six steps. First, a uniformly distributed random number is selected to determine which difficulty class the forecast would come from. Second, a pair of normally distributed random numbers (R_x, R_y) is drawn to create the two components

(E_x, E_y) of a forecast error. The process uses the means (M_x, M_y), standard deviations (S_x, S_y), and correlation coefficient (R) for a 72-hour forecast from the selected difficulty class. The computation is as follows:

$$Ex = M_x + S_x R_x$$
$$Ey = M_y + RS_y R_x + S_y R_y (1-R^2)^{1/2}$$

The third step involves generating a CLIPER* (Neumann, 1972) forecast from the same starting point. This forecast is used in steps 4 and 5. In step 4, the simulated 72-hour forecast is checked for reasonableness by ensuring that it falls within a 50% probability ellipse around the CLIPER forecast. If the forecast is found to be unreasonable, it is rejected and the process starts over at step 2. This type of reasonableness test is fairly common in operational centers (see JTWC, 1972). Up to 100 tries are made before it is concluded that no reasonable forecast can be made using CLIPER and the process moves to the next point along the track. Step 5 involves adding the error components to the 72-hour verifying position and using CLIPER to fit the intermediate track between the starting point and this 72-hour forecast position. The final or 6th step involves a forecast for maximum winds, where again normal random numbers are selected to specify the nowcast and 72-hour maximum wind forecast errors, which are added to the initial and 72-hour verifying maximum winds to create forecasts. Intermediate forecasts are linearly interpolated. The track forecast process is illustrated in Figure 1.

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*CLIPER was used because it is fast, objective, competitive in accuracy with the better techniques available today and all its required input information was readily available.

Legend

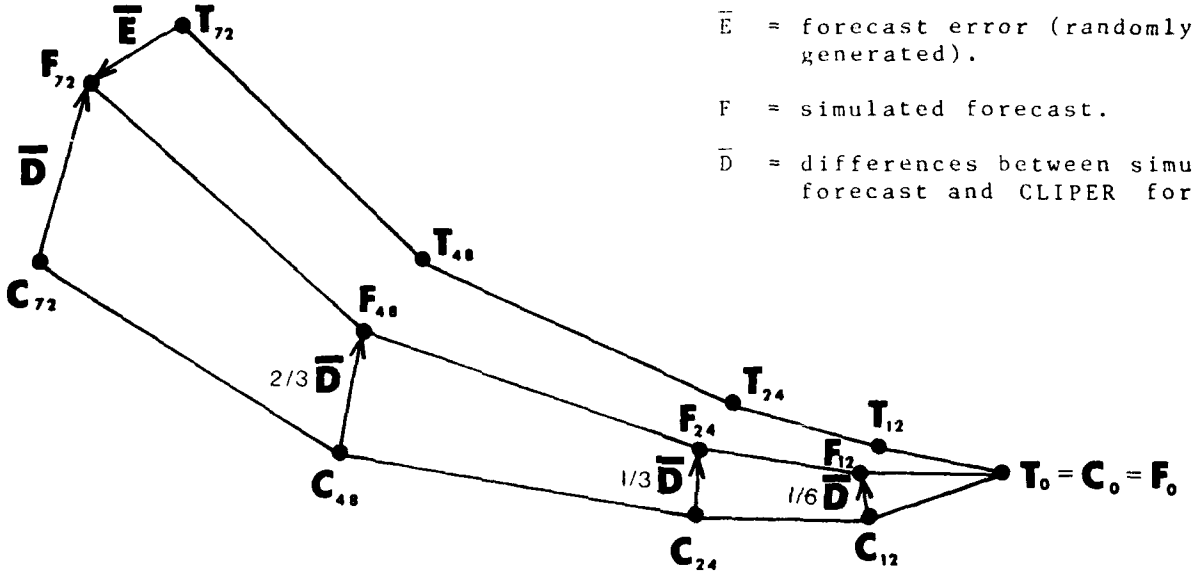
T_i = actual cyclone position at time i (i=0,12,24,48,72).

C = CLIPER forecast.

$\bar{E}$ = forecast error (randomly generated).

F = simulated forecast.

$\bar{D}$ = differences between simulated forecast and CLIPER forecast.



Procedure to Create Forecasts: $F_i = C_i + (i/72)\bar{D}$, given T_i (cyclone track)

1) generate random error $\bar{E}$.

2) set $F_{72}=T_{72}-\bar{E}$ as final (72 hr) position of forecast.

3) generate CLIPER forecast using T_0, T_{-12}, T_{-24}.

4) check reasonableness of $\bar{D}$ against CLIPER forecast.

5) interpolate on $\bar{D}$, e.g. 48/72 = 2/3, to add to C_i to find F_i for i = 48,24,12.

Figure 1. Illustration of procedure used to simulate a tropical cyclone forecast.

The year 1899 was selected as the first year for the analysis because estimates of maximum winds are a part of the track record from that year. The initial study analyzed 197 different tropical cyclones which passed within 360 n mi of Key West during the period 1899-1979. Forecasts were made along the track of these tropical cyclones at times within and including the 72 hours preceeding each cyclone's closest point of approach to Key West. Each forecast error is randomly selected, so by choosing different random errors, we can create new and independent versions of each forecast. This repetitive process allows the creation of a very large number of reasonable forecasts---over 19,000 for Key West alone.

After this large data set of forecasts was created a check was made to ensure that the error distribution was proper. This was done by checking to see if the actual random numbers used were still Guassian (remember they were drawn from a Gaussian distribution, but some were rejected). For both Guantanamo Bay and Key West it turned out that the distributions were too peaked (small standard deviation), the result of using too many numbers near the center of the distribution and rejecting too many outlying numbers. This was caused by the requirement for forecasts to fall within a 50% ellipse around the CLIPER forecast. To correct this, a portion of the original forecasts from the interior of the distribution were randomly discarded leaving about half of the original number. The final set of about 10,000 forecasts for Key West was again analyzed ensuring that random numbers were representative of a population with zero means, unit standard deviations and zero correlation between pairs.

2.3 Verification Data

For a given location, damage caused by a tropical cyclone can be roughly related to maximum winds observed at the point of interest during passage. The archived track and

center wind data permit an estimate of maximum observed wind at a point with the assumption of a wind profile. The wind probability model uses a parametric profile developed by Tsui et al (1982), and estimates the parameters of the profile as a function of latitude, storm motion and center wind speed. Applying that wind profile section of the wind probability model, maximum winds which occurred at the points of interest were estimated.

For clarity and conciseness we have adopted the following notation for tropical cyclone hindcast conditions:

H1 : winds ($\geq$ 64 kt) occurred within 12 hrs (Condition 1)
H2 : winds ($\geq$ 64 kt) occurred within 24 hrs (Condition 2)
H3 : winds ($\geq$ 64 kt) occurred within 48 hrs (Condition 3)
H4 : winds ($\geq$ 64 kt) occurred within 72 hrs (Condition 4)

S1,S2,S3,S4 : Same with winds $\geq$ 50 kt winds
G1,G2,G3,G4 : Same with winds $\geq$ 34 kt winds
D1,D2,D3,D4 : Same with winds < 34 kt

The key to SETCON is the calibration of a model to utilize threat information on approaching cyclones to determine which warning condition should be set. Calibrating the model on a large data base provides solid evidence of the accuracy and reliability of the procedure.

2.4 Wind Probabilities

The consideration of warning conditions during the approach of a tropical cyclone is largely based on the likely maximum wind at a specified location, but standard forecasts only predict wind speeds of the cyclone itself. It is left to the resources of each individual site to develop an estimate of likely wind speeds at that site---a difficult task. However, the use of wind probabilities avoids this difficulty

by quantifying the threat of 30 kt and 50 kt winds occurring at a specified location. The wind probabilities used herein and referred as P_{30} and P_{50} are the time integrated 30 and 50 kt probabilities integrated over the longest available time interval (usually 72 hrs). Wind probability is a previously proven concept (Jarrell, 1981) that is in current worldwide use.

It is important not only to set the correct readiness condition but to set it at the proper time. This timing is critical because most physical preparations cannot be performed in winds greater than 30 kt. Therefore, these preparations must be started sufficiently in advance of 30 kt winds to allow for their completion. P_{50} is the determining factor in whether or not to set a readiness condition, but the timing of the condition is dictated by P_{30}. The Cyclone/Hurricane Acceptable Risk Model (CHARM) (figure 2) is based on these considerations and best estimates of appropriate CBR values for each condition. Each combination of P_{30} and P_{50} determines which warning condition (if any) should be set at that time. According to figure 2, if P_{30} = .80 and P_{50} = .30, then H2 should be set. The positions of the thresholds lines between the conditions are determined by CBRs. Good estimates of CBRs are therefore needed to ensure proper threshold values.

Using the condition setting procedure (SETCON) introduced herein is a quick and simple process. As each wind probability forecast is received for the user's specific location, the user will simply enter a graph similar to figure 2 with the P_{30}, P_{50} pair of values. The result will be the recommended readiness condition.

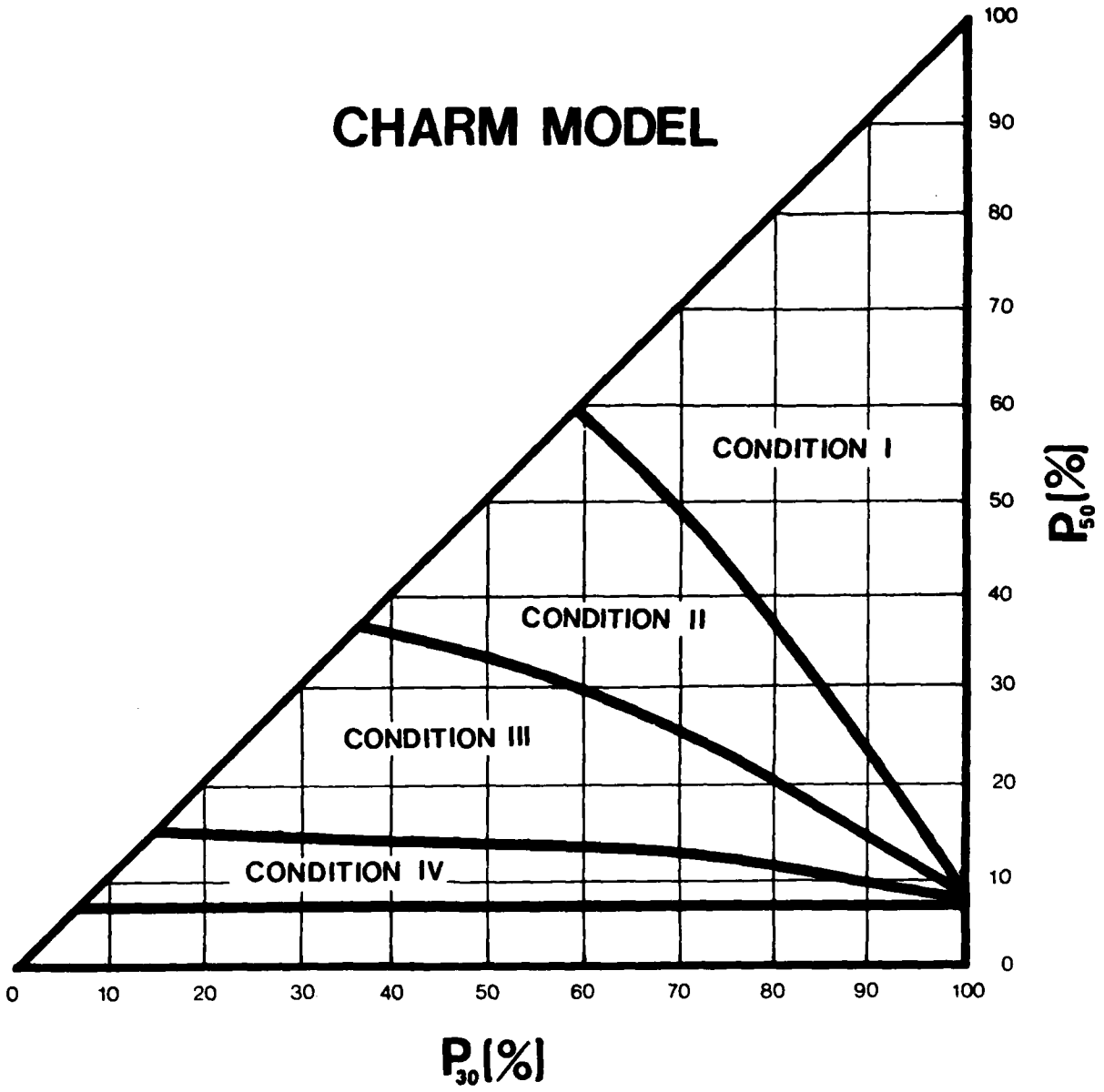


Figure 2. The form of a decision nomograph based on the CHARM model. Actual positions of threshold lines between condition zones are arbitrary.

3. SELECTION OF CBR GUIDELINES

Through a comparison of a large number of wind probability forecasts with the hindsight estimates of actual conditions, threshold or guideline CBRs, can be related to a confidence level. This means that even though it is virtually impossible to directly estimate these guideline values, we may still obtain a set of values of known reliability. In fact, the user's selected degree of reliability, i.e., confidence in percent for each particular condition, determines the guideline CBR values which in turn provide the required confidence levels.

To clarify the meaning of these confidence levels, a 95% (or .95) confidence level for H1 means that condition H1 would be set in at least 95% of the occasions that warranted it, or correspondingly, that H1 would not be set on less than 5% of the instances that it should have been set. A 95% H1 confidence level does <u>not</u> mean that hurricane force winds occur within 12 hours in 95% of the occasions that H1 is set. It must be noted that higher confidence levels necessarily result in higher overwarning rates, a fact which explains why it is unrealistic to expect 100% confidence levels.

Figure 3 shows the selection of a guideline value for hurricane condition II at Key West. Each point (·) represents the P_{30},P_{50} values for one forecast of a cyclone, which in hindsight we know to have caused hurricane force winds at Key West not less than 12 hours nor more than 24 hours subsequent. The curved lines represent CBR values for 24 hours from 0.10 (coincident with P_{50} =10% at the far left) to 1.00 (upper right curved line). A CBR value of

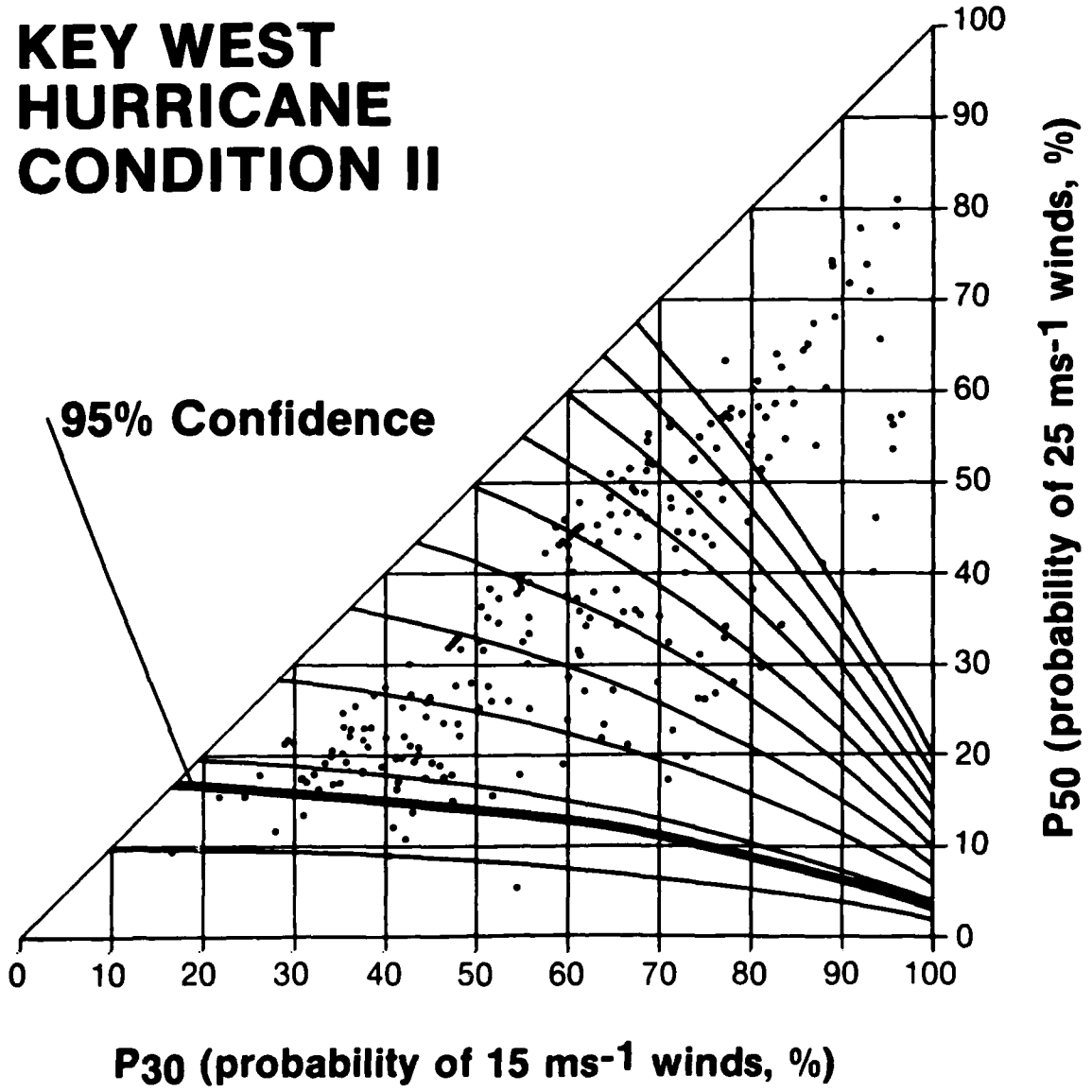


Figure 3. The scatter of P_{30} vs P_{50} plots 12-24 hours prior to hurricane winds at Key West is shown. The curved lines are CBR values for 24 hours before hurricane force winds ranging from 0.10 (coincident with 10% P_{50} line on lower left) to 1.00 (last curved line, upper right).

.17 (heavy curved line) allows a 95% confidence. The points above and to the right of the curve comprise the 95% frequency in which condition II would be correctly set while the 5% failure rate is evident by the small number of points below that same curve. The actual counting is done by computer tabulations.

Table 1. The outcome of using CBR=0.17 as the threshold for setting condition II at Key West is illustrated in a simple two-way contingency table.

	OBSERVED		
	HUR.WINDS	<HUR.WINDS	TOTAL
SET H2	25.1%	40.9%	66.0%
NOT SET H2	0.9%	33.1%	34.0%
TOTAL	26.0%	74.0%	100.0%

Table 1 shows that of those cases where hurricane force winds subsequently occurred, 96% (25.1 of 26) were preceded with wind probabilities exceeding the threshold established by using CBR=.17. Fifty-eight percent (25.1+33.1) of the conditions were correctly set (or not set) when correct is determined on hindsight. Of the 40.9% where condition II would have been set and hurricane force winds did not verify, 6.5% resulted in winds over 50 kt and 8.3% resulted in winds of gale force ($\geq$34 kt). In the following paragraphs the results are examined in some detail.

In our studies for both Key West and Guantanamo Bay, a confidence level of .95 (=95%) for hurricane readiness conditions I, II, III and IV was selected. From this confidence level CBR threshold values for each condition were determined (see Table 2). Briefly, the lower threshold values for Key West are .78, .17, .06, and .04, for conditions I, II, III and IV, respectively.

There are two ways to be wrong in setting conditions. One is to be too late or too early (a timing error) and the other is to be too weak or too strong. In this illustration we only considered setting hurricane conditions, consequently the condition could only be too strong (overwarning), correct, or it was not set (underwarning). These latter cases show up as late since eventually some hurricane condition was set in every case. Also since tropical cyclones were only examined 72 hours before passing the target stations, it was not possible to set condition IV early.

The outcome of setting conditions with a confidence level of 95% are also shown in Table 2. Consider, for example, the figure for Key West Condition I comprising all forecasts for which SETCON suggested a readiness condition I. Hurricane force winds actually occurred at Key West on 58.1% of those occasions, resulting in an overwarning rate, for condition I, of 41.9%. An alternative way to express these two corresponding figures is as a ratio of overwarning rate: correct rate. This results in a ratio of 41.9:58.1 = 0.7:1, or simply .7. This tells us that, for condition I, there are only .7 overwarnings per correct warning. Figures for Condition 2 (for Key West) show a 74% overwarning rate or, alternatively, a ratio of 2.8 overwarnings per correct warning. Thus, a decision maker has to understand that if he adheres to the ground rules stated here, he will be wrong 2.8 out of 3.8 affirmative decisions. This is the cost for being 95% confident of setting the right condition at the appropriate time. Note that wrong is a very strong word and even a 60 kt situation would be considered wrong. Table 3 shows the complete list of these alternative overwarning ratios that result from SETCON. These ratios are somewhat better, i.e., lower, than were anticipated.

Table 2. Comparison of actual outcomes using selected CBR values to set conditions at Key West and Guantanamo. See text for explanation and interpretive examples.

	KEY WEST				GUANTANAMO			
CONDITION I	CBR = 0.78 CONF = 95%				CBR = 0.50 CONF = 95%			
Actual	Early	On Time	Late	Total	Early	On Time	Late	Total
Hurricane Cond	9.3	48.8	0	58.1	5.2	21.5	0	26.7
Overwarned	5.1	36.8	0	41.9	9.6	63.7	0	73.3
TOTAL	14.4	85.6	0	100.0	14.8	85.2	0	100.0
CONDITION II	CBR = 0.17 CONF = 95%				CBR = 0.18 CONF = 96%			
Actual	Early	On Time	Late	Total	Early	On Time	Late	Total
Hurricane Cond	16.2	8.9	0.9	26.0	5.4	4.0	0.7	10.1
Overwarned	19.8	21.1	33.1	74.0	29.3	28.4	32.2	89.9
TOTAL	36.0	30.0	34.0	100.0	34.7	32.4	32.9	100.0
CONDITION III	CBR = 0.062 CONF = 95%				CBR = 0.068 CONF = 95%			
Actual	Early	On Time	Late	Total	Early	On Time	Late	Total
Hurricane Cond	5.6	5.0	0.2	10.8	2.0	1.4	0.1	3.5
Overwarned	23.1	39.0	27.1	89.2	67.0	18.4	11.1	96.5
TOTAL	28.7	44.0	27.3	100.0	69.0	19.8	11.2	100.0
CONDITION IV	CBR = 0.040 CONF = 96%				CBR = 0.055 CONF = 96%			
Actual	Early	On Time	Late	Total	Early	On Time	Late	Total
Hurricane Cond	X	2.4	1.5	3.9	X	.9	0	0.9
Overwarned	X	32.3	63.8	96.1	X	29.9	69.2	99.1
TOTAL	X	34.7	65.3	100.0	X	30.8	69.2	100.0

Table 3. Ratios of overwarning to correct warning cases when conditions would have been recommended.

	KEY WEST Condition Set					GUANTANAMO BAY Condition Set			
Actual	I	II	III	IV	Actual	I	II	III	IV
Hurricane	0.7	3	8	25	Hurricane	2.7	9	28	110
≥50 kt	0.4	2	6	15	≥50 kt	0.6	3	10	41
≥34 kt	0.1	1	3	8	≥34 kt	0.1	1	5	16

Notice in Table 2 the consistently very low rates for late warnings when hurricane force winds actually occurred: 0%, .9%, .2%, and 1.5% for conditions I, II, III, and IV respectively, at Key West. There is a natural association between "late" cases and "overwarning" cases so that virtually all late cases were also overwarning cases; this means when time was insufficient for preparations, they usually proved unnecessary. This natural association is because both are identified with low probabilities which can result from either distant storms (in time) or weak storms.

There are distinct differences in the results shown in Table 3 for Guantanamo versus Key West. Most notably the overwarning rates are markedly higher for Guantanamo than for Key West. This is caused primarily by land influence at Guantanamo which is almost nonexistent at Key West. A review of actual observed winds at Guantanamo during the period 1945-79 reveals no incidents of hurricane force sustained winds, although well developed hurricanes with over 100 kt central winds passed within 25 n mi on two occasions. In the simulated data, 3% of tropical cyclones passing within 360 miles of Guantanamo were estimated to have caused hurricane force winds compared to 14% causing hurricane force winds at Key West. Hurricane force winds at Key West were estimated to have occurred within the same frequency as winds of 34 kt or greater at Guantanamo. Terrain was not considered in these simulations except as reflected in the archived tropical cyclone maximum wind records. Hurricanes passing near Guantanamo are frequently greatly weakened by not only local mountainous terrain, but by the high mountains of Hispanola upstream from Cuba along the favored track.

Because the occurrence of hurricane force winds is so rare at Guantanamo, the denominator is extremely small

when overwarning rates are calculated. Consequently overwarning rates become very large as seen in Table 3. To be realistic, actual hurricane readiness conditions are probably not appropriate for Guantanamo, rather some lower wind level should be used. Table 3 shows overwarning rates for using the same CBR values as shown in Table 2, but interpreting the outcome relative to 50 and 34 kt winds. Using 50 kt winds at Guantanamo makes the overwarning rates close to those at Key West for hurricane force.

3.1 Using the Guidelines

Figures 4 and 5 show CHARM nomographs for setting conditions at Key West and Guantanamo, respectively. These nomographs are always entered with the 72 hour (or maximum forecast available), time integrated, 30- and 50-kt wind probabilities. It will be helpful to photocopy these nomographs and then plot the wind probabilities thereon every six hours. The zones on the nomographs constitute recommendations as to the proper condition for 95% confidence. This plotting procedure helps to identify trends and to relate changes in the probabilities both to changes in the forecast and to changes in the actual threat as it develops. The very narrow probability zone associated with condition IV implies very little discrimination in the 48-72 hour time frame. In view of this the generally accepted practice of setting condition IV on a seasonal basis for bases deep in the tropics is substantiated.

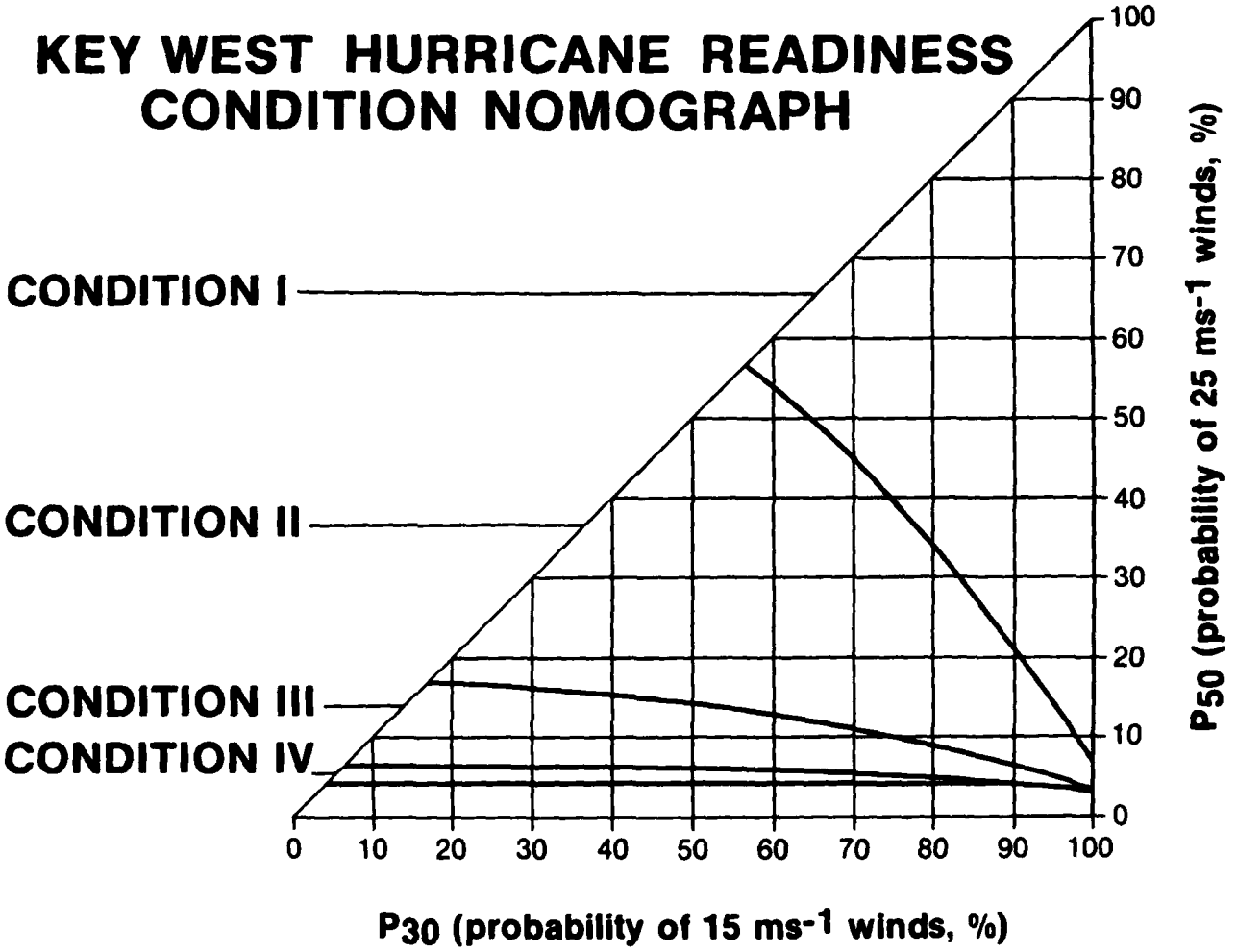


Figure 4. Nomograph for setting conditions at Key West for 95% confidence. Enter with the maximum available (usually 72 hour) time integrated 30 and 50 kt wind probabilities. It is recommended that this nomograph be copied and a separate graph be used to follow the trend of each tropical cyclone.

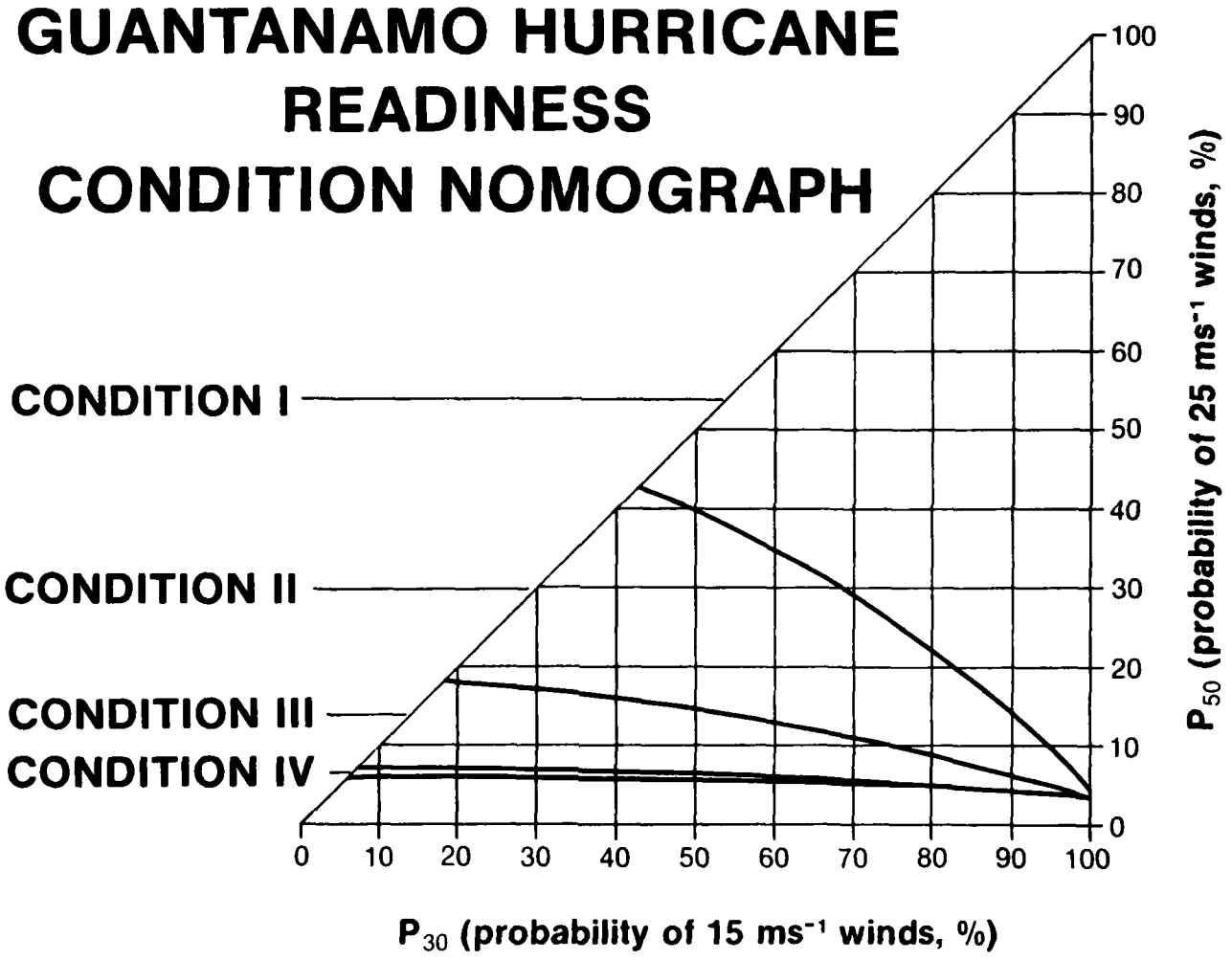


Figure 5. Nomograph for setting conditions at Guantanamo for 95% confidence. Enter with the maximum available (usually 72 hour) time integrated 30 and 50 kt wind probabilities. It is recommended that this nomograph be copied and a separate graph be used to follow the trend of each tropical cyclone.

4. FURTHER REFINEMENTS

For stations with minimal terrain protection such as Key West, the procedures outlined herein should work very well. For stations like Guantanamo where there is substantial terrain influence, this work represents a good interim step, particularly when the results are interpreted relative to a lower wind threshold as suggested in section 3.1.

Site specific terrain adjusted wind probabilities have been computed for a number of western Pacific naval bases and those types of probabilities should be developed (where not now available) and applied in simulations to points like Guantanamo to readjust the readiness condition thresholds.

For ships at sea a "danger-area" type presentation can be created from an extension of this work. Such a presentation is shown in figure 6 for hurricane Frederic (1979). Here the 95% thresholds for Key West were used and CBR values were estimated for every 12 hours out to 72 hours. These contours can then be labeled as minimum lead time, or "worst case" lead times for points within the contours. The area within the 24 hour contour would constitute a "danger- area". The Key West thresholds would probably not be appropriate for other points distant from Key West; hence it would be necessary to repeat this study for representative overwater points on a coarse grid.

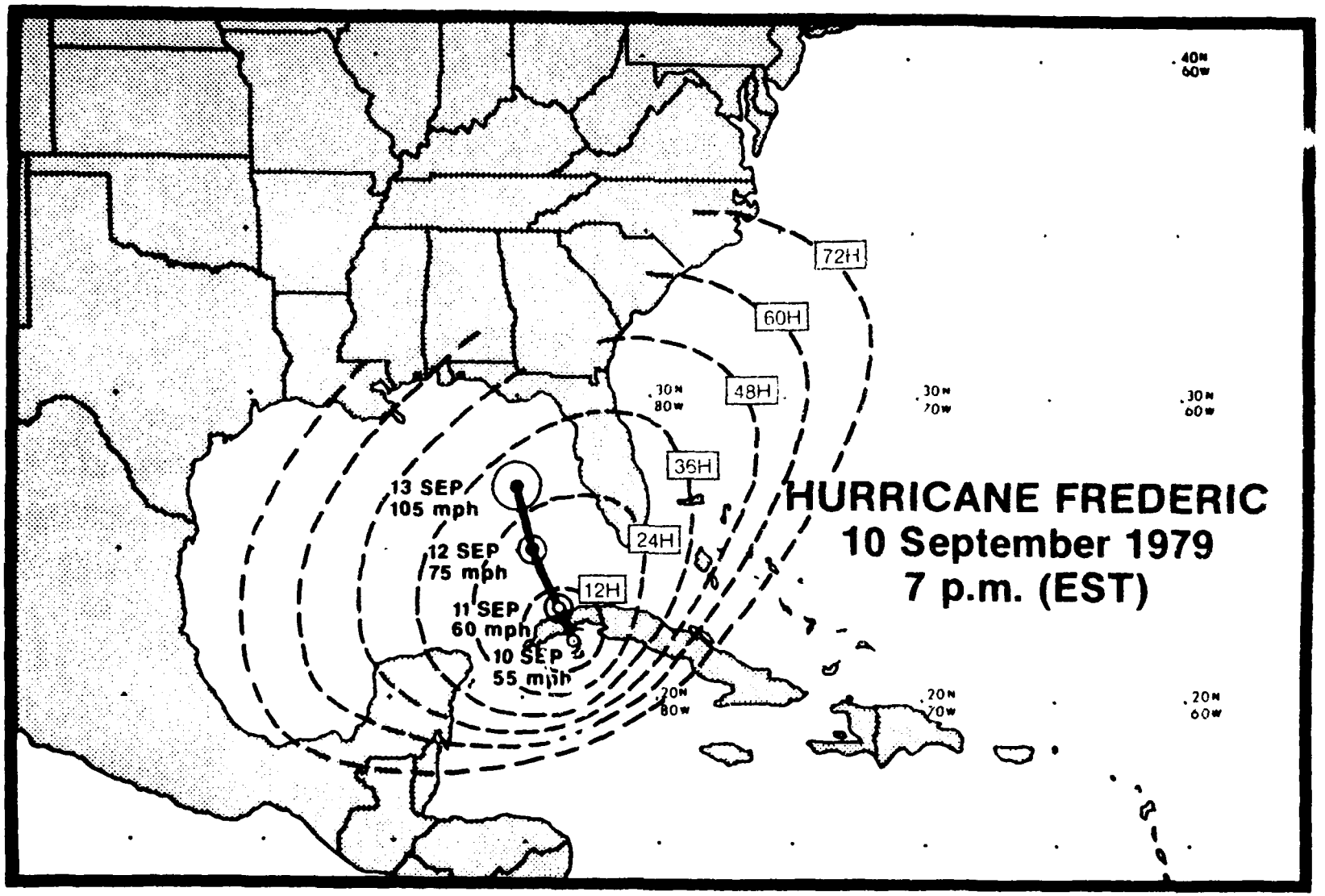


Figure 6. Depiction of minimum lead time (95% confidence) before arrival of hurricane force winds. Solid line is NHC 72 hr forecast and circle around forecast is forecast radius of 50 kt winds.

5. SUMMARY

Great advances have been made in producing tropical cyclone strike and wind probabilities, but not in using them. The simple methodology presented here has the potential to address many complex issues. The concepts are applicable to the wide range of preparedness problems from military decision-making to the state and local level, and to the private sector as well. They can be extended to storm surge or flooding problems by simply relating the hindsight conditions to these or a combination of disaster agents. For example, a storm surge model may be used to define the hindsight "truth" as we did herein with winds. Similarly, a combination of historical documentation and modeled estimates of flooding could be used for hindsight.

The results of the above simulation demonstrates that we can have high confidence in readiness conditions being set up to three days in advance. This data set also permits an easily understood analysis of the cost of that confidence in terms of overwarning or "crying wolf".

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