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Tropical Cyclone Strike and Wind Probability Applications

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ABSTRACT

Public officials are frequently required to make decisions relative to tropical cyclone preparedness actions. For such decisions to be defensible, they usually adhere to an official government forecast, yet some allowance for forecast error must be made. Complex relationships between errors in tropical cyclone forecast track and in the forecast wind distribution, complicated by lack of user familiarity, makes this a particularly difficult problem. This paper introduces the concept of strike and wind probability as a means of quantifying the tropical cyclone threat, thereby allowing simultaneously for all types of errors. Such probability products will shortly be available for all the tropical cyclone areas of the world. Examples of these products and anticipated future developments are discussed.

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1.0 Introduction

In the 1970's, the authors noted a leveling off, if not a reversal, in the trend of increasing accuracy of tropical cyclone forecasts in the western North Pacific (Jarrell, et al, 1978). A similar plateau was subsequently noted by Neumann and Pelissier (1981) for the western North Atlantic. Since there also appeared to be no imminent developments which would restore a positive trend, ways to make the existing forecasts more useful were examined.

The search led to probability as a means to extract the information content from current forecasts. The idea was that a forecast might be better expressed as the probability that the tropical cyclone will occupy a specific point in time and space, or that it will cause a particular effect. What began as a parochial U.S. Navy regional effort, the typhoon strike probability forecast, has now

evolved into a world-wide program of tropical cyclone related products involving several government agencies, the private sector and recently foreign governments as well.

The original strike probability program for the western North Pacific was based on a study of tropical cyclone forecast errors (Jarrell, et.al., 1978). Studies by Neumann and Pelissier (1981) and Thompson et.al. (1981) formed the statistical basis for the western North Atlantic and eastern North Pacific.

The aim of this paper is to acquaint the reader with the program, its products and plans, and to provide enough technical information to permit the reader to understand the applications.

For general purposes a tropical cyclone "strike" is arbitrarily defined as passing the point of interest so that the storm passes within 75 nm (139 km) to the left or 50 nm (93 km) to the right relative to the forecast track. This allows for tropical cyclone associated winds extending farther on the right side. Figure 1a shows a forecast track for Pacific Typhoon Owen, September 1979. Error ellipses are shown for 50, 75, and 90% probability levels around the 24-hr forecast. Figure 1b illustrates 24-hr strike probabilities computed from the same information for points in the vicinity of the forecast position. Figure 1c depicts the information of Fig. 1b contoured in the vicinity of the forecast position.

The wind probability concept is similar to strike probability except the area of critical winds is treated as

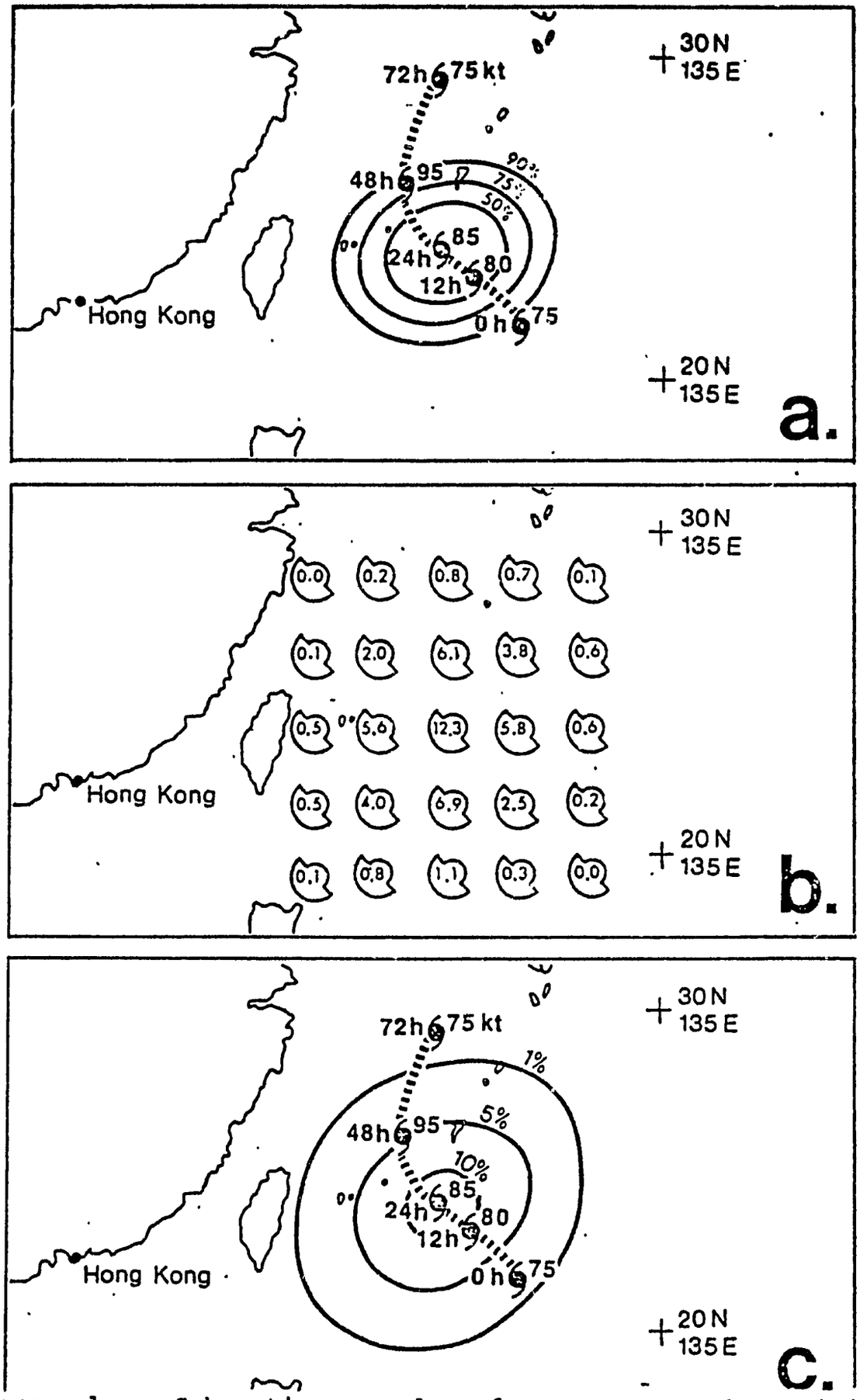


Figure 1. Schematic example of western North Pacific Typhoon Owen, Sept. 25, 1979, 0600 GMT, depicting: a) 50, 75, 90% probability forecast error ellipses about the 24-hr forecast point; b) 24-hr strike probabilities calculated for selected points; and c) contoured 24-hr strike probabilities. The forecast positions and intensities presented are those of the official forecast issued by the Joint Typhoon Warning Center, Guam.

a random variable. From the forecast of wind radii[1], and an historical record of the accuracy of such forecasts, the probability of a forecast radius taking on any value can be estimated. It is assumed that if a point falls within a particular isotach the point will experience winds of at least the isotach value.

A 30-kt wind probability is the sum of the probabilities of each possible 30-kt wind radii occurring, times the probability of a strike within that radius about the point of interest. Assymmetry is provided by offsetting the point of interest.

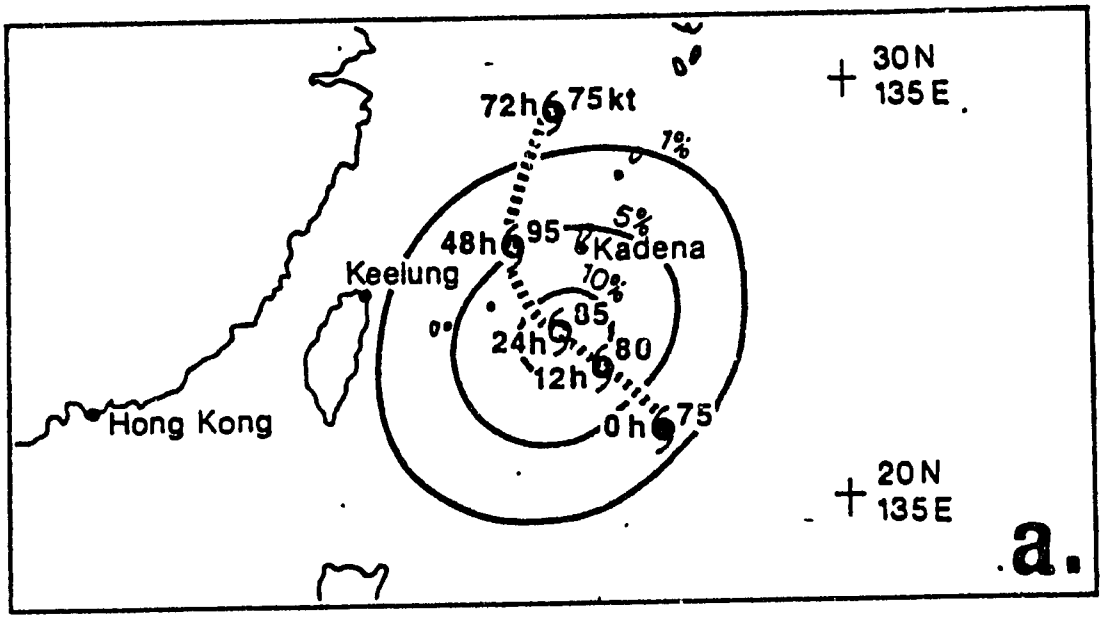
[1]The 30-kt or gale force (34-kt) and 50-kt wind areas are described in forecasts by a radius from the storm center which may vary with bearing from the center. Note: units will be used throughout this paper that relate to the standard output of the tropical cyclone warnings issued and will not necessarily be in SI units.

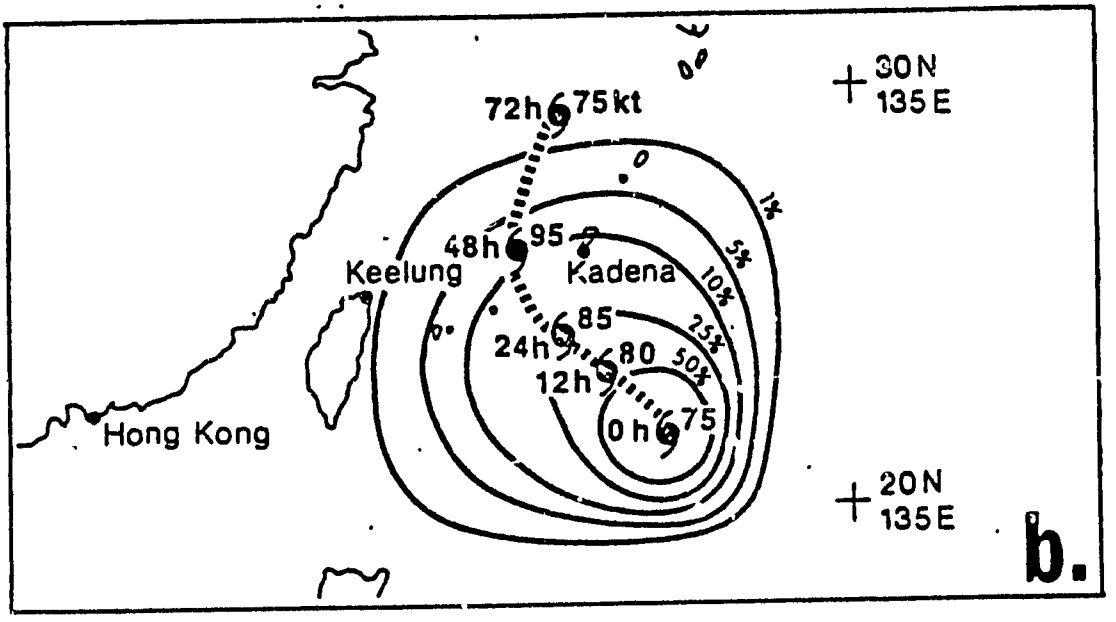
2.0 Applications

a) Strike Probability

The most basic application of knowledge of tropical cyclone forecast error characteristics as an aid to decision makers is strike probability. This is simply the probability that the tropical cyclone will fall somewhere within a particular small geographic area close enough to an important point that it might cause damage. Figure 2 illustrates 24-hr strike probabilities for Typhoon Owen in two different forms. Figure 2a depicts the instantaneous 24-hr strike probabilities mapped over a large geographical region. Instantaneous strike at 24-hr is defined as the cyclone being located within a pre-defined area 24 hours after forecast time (i.e., arbitrarily depicted in Fig. 1 as 75 nm to the left and 50 nm to the right of each geographic location on the map; right and left are relative to the forecast track).

Figure 2b depicts time integrated strike probabilities also mapped over a region. The probabilities are time integrated using a geometrical approximation technique. A time integrated 24-hr strike means that the cyclone falls within a pre-defined area at some time <u>within</u> the 24-hr period after forecast time. Since the time integrated event includes many instantaneous events, the time integrated probabilities must be at least as large as the instantaneous values and usually will be much larger. Users at fixed locations cities, bases, etc., find the time integrated probabilities most useful while those concerned with moving targets (i.e., ships) prefer the instantaneous mode.





STRIKE PROBABILITY FORECASTS
TYPHOON OWEN 250600 GMT SEPTEMBER 1979

SUBIC BAY	THREAT	NIL					
CLARK AB	THREAT	NIL					
APRA GUAM	THREAT	NIL					
ANDERSEN	THREAT	NIL					
KADENA AB	00ININ	12ININ	240712	361019	480620	600321	720221
YOKOSUKA	THREAT	NIL					
KEELUNG	00ININ	12ININ	24ININ	360204	480309	600211	720112
YOKOTA AB	THREAT	NIL					
HONG KONG	00ININ	12ININ	24ININ	36ININ	48ININ	60ININ	72IN01
CHEJU-DO	00ININ	12ININ	24ININ	36ININ	48ININ	600103	720206
PUSAN ROK	00ININ	12ININ	24ININ	36ININ	48ININ	60ININ	72IN01
MISAWA JA	THREAT	NIL					
OSAN ROK	THREAT	NIL					
WAKE IS	THREAT	NIL					

c.

Figure 2. Schematic example of western North Pacific Typhoon Owen, Sept. 25, 1979, 0600 GMT, depicting: a) 24-hr instantaneous strike probabilities; b) 24-hr time integrated strike probabilities; and c) Department of Defense strike probability message (see text for format information). The forecast information for Typhoon Owen is based on the official forecast issued by the Joint Typhoon Warning Center, Guam.

Figure 2c illustrates a message consisting of information partially extracted from Figs. 2a and b for specific western North Pacific points of military interest. This product gives both instantaneous and time integrated strike probabilities at 12-hr intervals over a 72-hr forecast period. The format is HHPIPS where HH is forecast period, PI is the instantaneous strike probability, PS is the time integrated probability, both rounded to the nearest whole percent. IN is defined as insignificant or less than 1/2 percent.

Products comparable to that of Fig. 2c are presently available for the western North Pacific, eastern North Pacific, and western North Atlantic Oceans as well as the Bay of Bengal and Arabian Sea. They are being developed for all other tropical cyclone frequented ocean areas.

The utility of strike probability is somewhat limited because only the element of location is addressed without regard to severity. For example, strike probabilities can be identical for an intense super typhoon and a weak tropical depression. The concept of wind probability provides a better measure of threat incorporating the storm's present and forecast maximum wind and wind distribution as a basis.

b) Wind Probability

The wind probability concepts combine the threat of winds being strong and the tropical cyclone passing in close proximity. The development of wind probabilities has lagged the development of strike probabilities by a year or

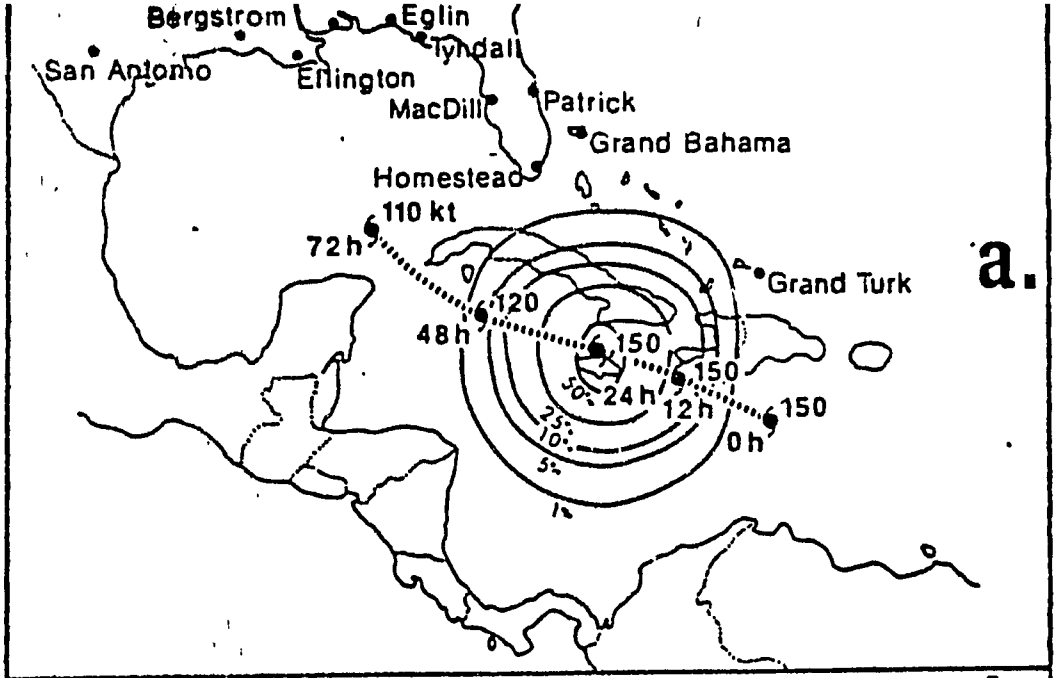
so, but are now available in the same ocean areas as are the strike probabilities. Most wind probabilities have keyed on two wind levels, 30 and 50 kt (approximately 15 and 25 ms^{-1}). These were selected as levels beyond which preparatory actions become difficult and as a lower threshold of significant wind damage, respectively.

Figure 3a depicts 24-hr, 30 kt instantaneous wind probabilities for Atlantic Hurricane Allen (August 5, 1980). Figure 3b is a message giving strike, 30-kt wind and 50-kt wind probabilities based on the National Hurricane Center forecast depicted in Fig. 3a for U.S. Air Force points of interest. The format of this information corresponds to that of Fig. 2c with additional information now showing the probabilities of 30- and 50-kt winds throughout the forecast time periods.

The wind probability programs are generalized in that other wind probability levels of user interest can be computed. For example, in the Bay of Bengal, a program has been developed for the Office of Foreign Disaster Assistance (OFDA), Agency for International Development (AID), Department of State that uses 20, 33 and 50 ms^{-1} as critical wind probability levels.

c) Geographic Depiction

Previously geographical depictions of tropical cyclone strike and wind probabilities have been used to illustrate examples with no indication as to graphical display availability. Such depictions are available within the U.S. Navy communications network via the Naval Environmental



b.

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STRIKE AND WIND PROBABILITY FORECAST
ALLEN     051600 GMT AUGUST 1980
MACDILL     00ININ 12ININ 24ININ 36ININ 48ININ 600102 720105
   50 KNOT  00ININ 12ININ 24ININ 36ININ 48IN01 600205 720208
   30 KNOT  00ININ 12ININ 24ININ 36ININ 480101 600307 720411
TYNDALL     00ININ 12ININ 24ININ 36ININ 48ININ 60ININ 720102
   50 KNOT  00ININ 12ININ 24ININ 36ININ 48ININ 60IN01 720204
   30 KNOT  00ININ 12ININ 24ININ 36ININ 48ININ 600102 720307
EGLIN       00ININ 12ININ 24ININ 36ININ 48ININ 60ININ 720102
   50 KNOT  00ININ 12ININ 24ININ 36ININ 48ININ 60IN01 720104
   30 KNOT  00ININ 12ININ 24ININ 36ININ 48ININ 600101 720206
KEESLER     00ININ 12ININ 24ININ 36ININ 48ININ 60ININ 720101
   50 KNOT  00ININ 12ININ 24ININ 36ININ 48ININ 60ININ 720103
   30 KNOT  00ININ 12ININ 24ININ 36ININ 48ININ 60IN01 720204
ELLINGTON   00ININ 12ININ 24ININ 36ININ 48ININ 60ININ 72ININ
   50 KNOT  00ININ 12ININ 24ININ 36ININ 48ININ 60ININ 72IN01
   30 KNOT  00ININ 12ININ 24ININ 36ININ 48ININ 60ININ 720102
BERGSTROM   00ININ 12ININ 24ININ 36ININ 48ININ 60ININ 72ININ
   50 KNOT  00ININ 12ININ 24ININ 36ININ 48ININ 60ININ 72ININ
   30 KNOT  00ININ 12ININ 24ININ 36ININ 48ININ 60ININ 72IN01
SN ANTONIO  00ININ 12ININ 24ININ 36ININ 48ININ 60ININ 72ININ
   50 KNOT  00ININ 12ININ 24ININ 36ININ 48ININ 60ININ 72ININ
   30 KNOT  00ININ 12ININ 24ININ 36ININ 48ININ 60ININ 72IN01
HOMESTEAD   00ININ 12ININ 24ININ 36ININ 480103 600106 720108
   50 KNOT  00ININ 12ININ 24ININ 36IN01 480205 600310 720212
   30 KNOT  00ININ 12ININ 24ININ 360102 480409 600613 720416
PATRICK     00ININ 12ININ 24ININ 36ININ 48ININ 600102 720104
   50 KNOT  00ININ 12ININ 24ININ 36ININ 48IN01 600204 720208
   30 KNOT  00ININ 12ININ 24ININ 36ININ 480101 600306 720310
ANTIGUA     THREAT NIL
GRAND TURK  00ININ 12ININ 24ININ 36ININ 48ININ 60ININ 72ININ
   50 KNOT  00ININ 12ININ 24ININ 36ININ 48IN01 60IN01 72IN01
   30 KNOT  00ININ 12IN01 24IN01 36IN02 48IN02 60IN03 72IN03
GRNDBAHAMA  00ININ 12ININ 24ININ 36ININ 48IN01 600103 720105
   50 KNOT  00ININ 12ININ 24ININ 36ININ 48IN02 600206 720209
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Figure 3. Schematic example of Atlantic Hurricane Allen, August 5, 1980, 1600 GMT, depicting: a) the 24-hr forecast of 30-kt wind probability; and b) a message estimating strike and wind probabilities for selected Air Force bases (see text for format information). Since tropical cyclone warnings in the western North Atlantic are issued 4 hr after synoptic times, the 0-hr position shown in a) is a backward extrapolated position. The 0-hr strike and wind probabilities as shown in b) also are a 4-hr backward extrapolation from the originating warning time of August 5 1600 GMT. The forecast information for Hurricane Allen is based on the official forecast issued by the National Hurricane Center, Miami.

Display System (NEDS). Figure 4 depicts 48-hr, time integrated 30 kt wind probabilities for four northern hemisphere tropical cyclones. Notice that the information for Typhoon Owen and Hurricane Allen in Fig. 4 is derived from the same source forecasts as those of Figs. 1 and 3, respectively. Total product availability includes a forecast track and intensity plot and maps of probability for 24-, 48-, and 72-hr, strike, as well as 50- and 30-kt wind probabilities in the instantaneous and time integrated modes. These are presently available for call up and display on the NEDS for northern hemisphere ocean basins with availability expected for southern tropical oceans by the end of 1983.

d) Optimum Track Ship Routing

Decisions associated with tropical cyclone avoidance at sea can be critical to any ship near the path of a tropical cyclone. The Optimum Track Ship Routing (OTSR) applications of the tropical cyclone strike/wind probabilities can be used by central site ship routing services or ship's personnel with available minicomputers. The operational applications currently in existence can do the following: (a) "flag" vessels along projected ship routes that encounter probabilities of 30-kt and 50-kt winds associated with tropical cyclones above any user specified critical level; (b) display probabilities for flagged vessels in a tabular form; (c) graphically display tropical cyclone movement, intensity and ship movement with associated probabilities of 30- and 50-kt winds; and (d) compute and display a reroute of the ship in accordance with user specified

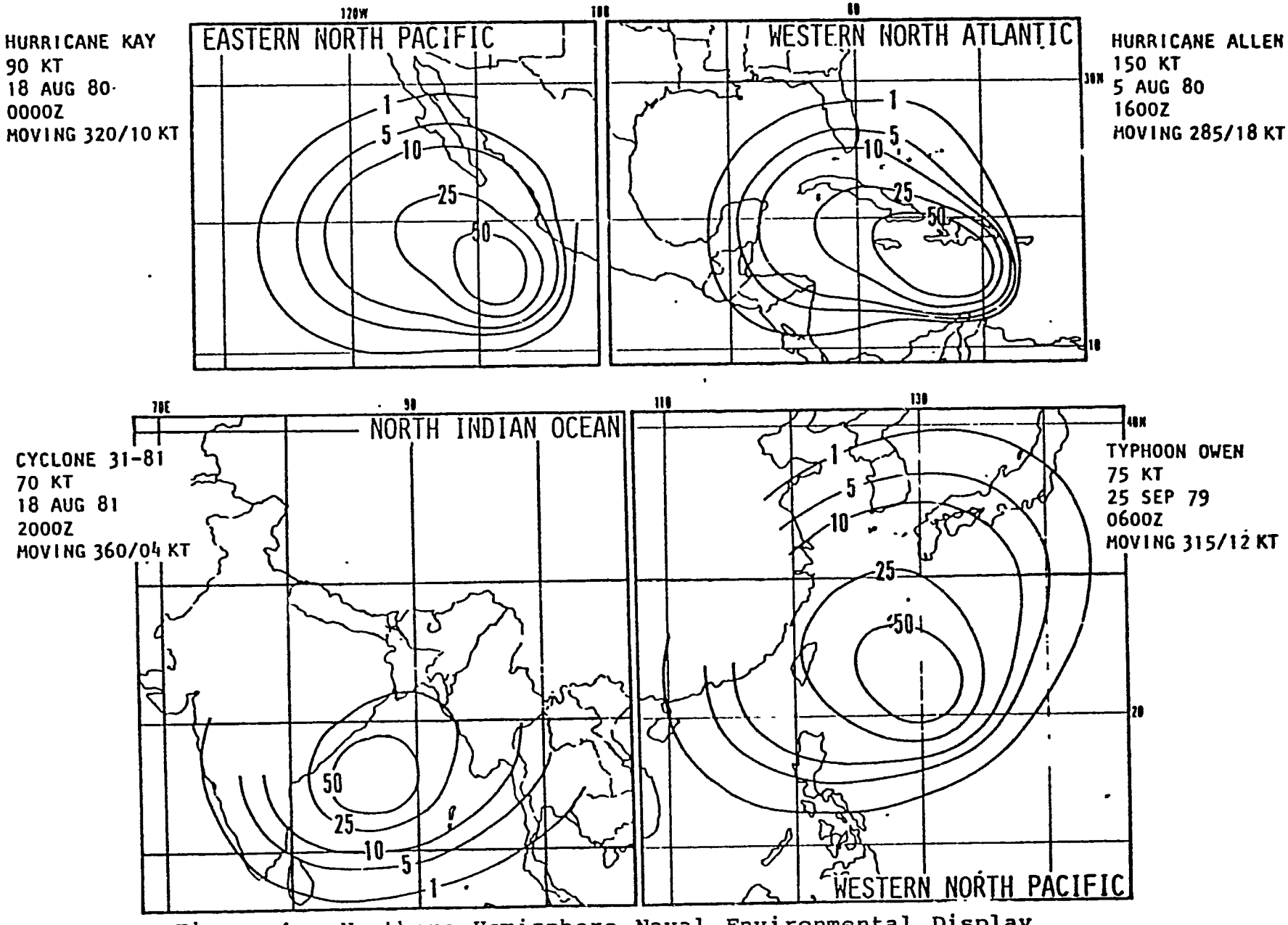

Figure 4. Northern Hemisphere Naval Environmental Display System (NEDS) tropical cyclone threat display for tropical cyclones in four ocean areas. Depicted are 48-hr forecasts of the time integrated 30-kt wind probability (values shown are whole percent for 1-, 5-, 10-, 25- and 50-percent contours).

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avoidance criteria. Figure 5(a) displays a ship route with associated instantaneous probabilities for 30-kt and 50-kt winds at 6-hr intervals for the SS TRANSCOLORADO. The automated reroute is shown as Fig. 5(b), incorporating the avoidance criteria of 95% confidence of avoiding 30-kt winds and 97% confidence of avoiding 50-kt winds.

With the availability of the Hewlett-Packard 9845 desktop computer in the meteorological spaces on all aircraft carriers, the independent capability for heavy weather tropical cyclone avoidance now exists. For example, Fig. 6 displays the HP 9845 output of a tropical cyclone threat analysis and display program (Chin, 1982) for Tropical Storm Dori (warning time 1200 GMT, October 24, 1981) and ship movement for ship "NXYZ". The projected track (solid line) and suggested alternate route (dashed line) are displayed as are the 5% probability isopleths of 30-kt winds. The critical probability values for this example are 5% probability of 30-kt winds and 3% probability of 50-kt winds. Table 2 displays the HP 9845 alphanumeric instantaneous probability values for projected ship track (a) and alternate route (b).

e) Storm Surge Probabilities

One of the most dangerous aspects of a tropical cyclone threat is that of storm surge. Storm surge is thought to account for about 90% of all tropical cyclone related deaths. Storm surge models are very accurate when provided with accurate meteorological input (i.e., forecast track, maximum winds, minimum pressure and radius of

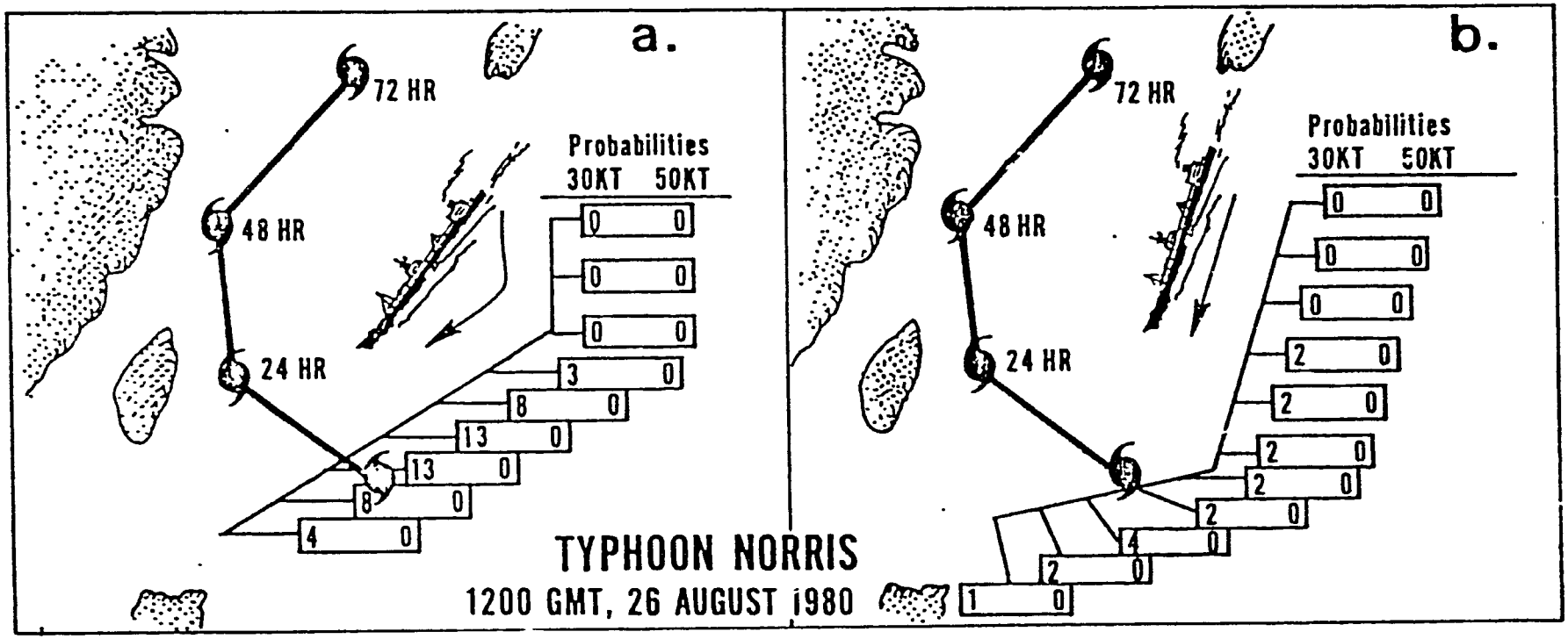
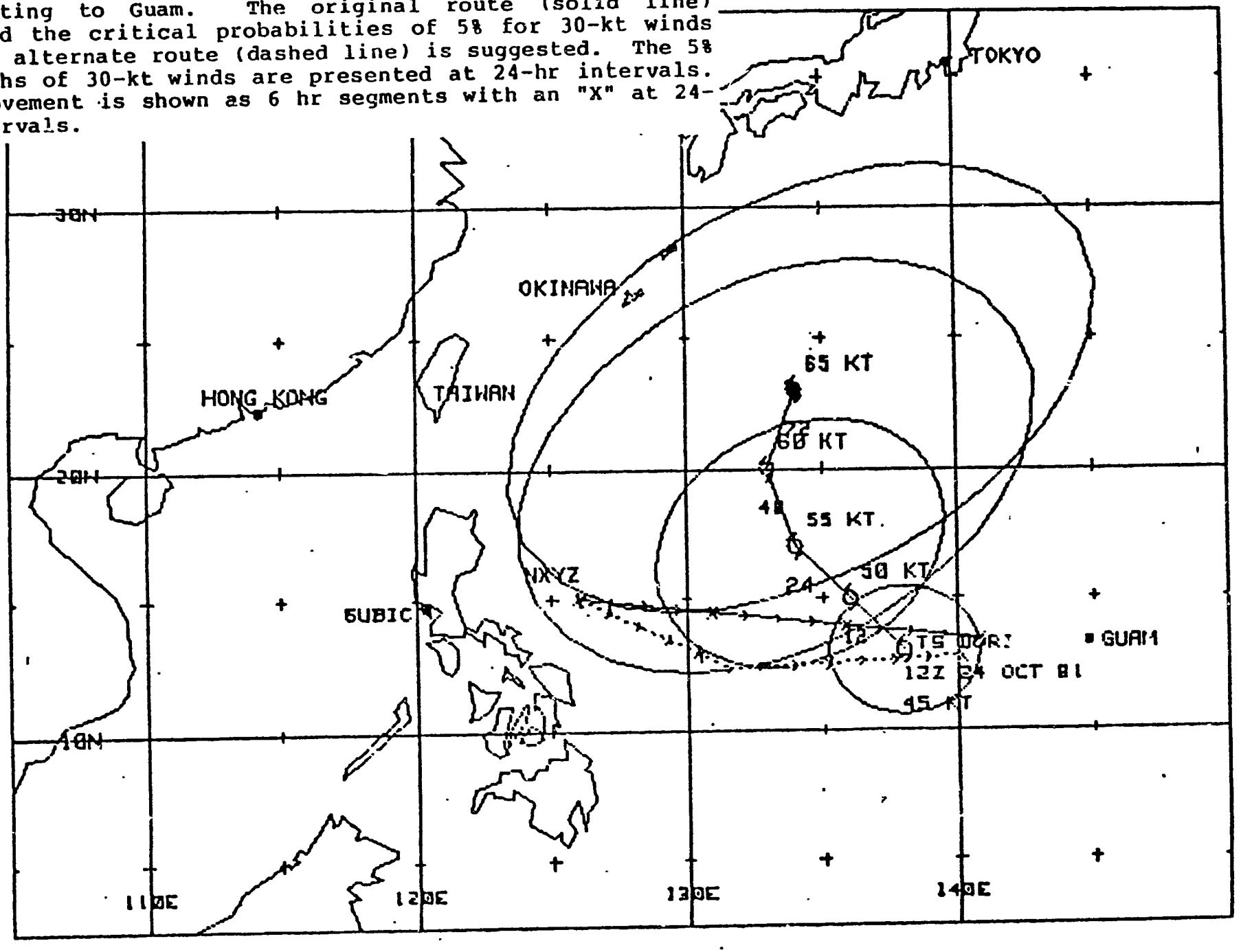


Figure 5. Example of Optimum Track Ship Routing (OTSR) automated reroute capability applications of strike/wind probability. Instantaneous probabilities for 30-kt and 50-kt winds are displayed at 6-hr increments for the SS TRANSCOLORADO before (a), and after (b), automated reroute. Avoidance criteria: 95%, 30-kt winds and 97%, 50-kt winds.

Figure 6. Hewlett-Packard 9845 graphic display showing Tropical Storm Doris' present and forecast positions and intensities and projected ship movement for ship "NXYZ" transitting to Guam. The original route (solid line) exceeded the critical probabilities of 5% for 30-kt winds and and alternate route (dashed line) is suggested. The 5% isopleths of 30-kt winds are presented at 24-hr intervals. Ship movement is shown as 6 hr segments with an "X" at 24-hr intervals.



SHIP TRACK

SHIP'S ID: NXYZ
SHIP'S SPEED: 12 KT DIST: 864 NMI
WARNING DTG: 12Z 24 OCT 81 TROPICAL STORM DORI

TIME	LAT	LONG	PROBABILITIES 30 KT WINDS	50 KT WINDS
0	15.0N	126.0E	0.0	0.0
6	14.9N	127.2E	.0	0.0
12	14.7N	128.5E	.0	0.0
18	14.6N	129.7E	2.5	.1
24	14.5N	130.9E	9.6	1.4
30	14.4N	132.2E	12.1	2.2
36	14.2N	133.4E	9.3	1.4
42	14.1N	134.6E	6.4	.8
48	14.0N	135.9E	5.9	.8
54	13.8N	137.1E	3.2	.4
60	13.7N	138.3E	1.8	.2
66	13.6N	139.5E	1.1	.1
72	13.4N	140.9E	.5	.1

ALTERNATE ROUTE
BEGINNING POSITION: 15.0N 126.0E
INTENDED POSITION: 13.0N 145.0E

SHIP'S ID: NXYZ
SHIP'S SPEED: 12 KT DIST: 864 NMI
WARNING DTG: 12Z 24 OCT 81 TROPICAL STORM DORI

TIME	LAT	LONG	PROBABILITIES 30 KT WINDS	50 KT WINDS
0	15.0N	126.0E	0.0	0.0
6	14.5N	127.1E	.0	0.0
12	13.9N	128.2E	.0	0.0
18	13.4N	129.3E	1.4	.0
24	12.9N	130.4E	3.3	.4
30	12.4N	131.5E	3.8	.4
36	12.4N	132.8E	3.6	.4
42	12.5N	134.0E	3.1	.3
48	12.5N	135.2E	3.3	.4
54	12.6N	136.5E	2.1	.2
60	12.6N	137.7E	1.3	.1
66	12.7N	138.9E	.8	.1
72	12.8N	140.1E	.5	.1

Table 2. Hewlett-Packard 9845 alphanumeric display of instantaneous probability values for projected ship track (a) and alternate (b).

maximum winds). The inability to accurately forecast these parameters severely limits the accuracy of storm surge forecasts. For example typical errors in the timing of landfall based on a 24-hr forecast can mean the all important difference in high and low tide. The corresponding lateral forecast error can be the difference in the maximum positive surge to the right of the track to the maximum negative surge to the left.

A program to estimate the probability of a damaging storm surge occurring using an extension of the strike probability concept has been developed. The program was developed for the Office of Foreign Disaster Assistance (OFDA), U.S State Department, for the Bay of Bengal and has been be made available for application by local forecasters there.

Briefly the program uses a catalog of time-height profiles of storm surge which would result at points along the bay if a cyclone with varying characteristics were to make a landfall at selected points. These profiles were determined by simulation with an Alternating Direction Implicit (ADI) model developed by Leendertse (1967) and adapted for six distinctive overlapping Bay of Bengal regions.

The model was run using simulated cyclones having various representative combinations of three parameters: forward speed, heading and maximum winds. In application all possible combinations of the above three parameters in small increments are assumed to have occurred. Their probability of occurrence is calculated by using adaptations of

COLOR	ACTION WORDS	LEAD TIME	CHARM THREAT INDEX
RED	Ride out, take shelter, actions by emergency crews	12hr	$4.00 \leq T$
ORANGE	Doing, closing, evacuating, stopping, securing, manning	24hr	$3.00 \leq T < 4.00$
YELLOW	Arranging, positioning, scheduling, closing non-essentials	48hr	$2.00 \leq T < 3.00$
GREEN	Planning, locating, notifying, checking	72hr	$1.00 \leq T < 2.00$

Table 3. Color coded conditions of Hurricane Readiness are defined in terms of actions words, effective lead time before the onset of hurricane force winds, and a range of CHARM threat indices associated with each.

To illustrate the CHARM threat index, wind probabilities were computed using the National Hurricane Center forecasts issued during the 72-hr period preceding Hurricane David's August 1979 strike at Rosseau on the island of Dominica in the Antilles. CHARM threat indices were then determined by entering the nomograph of Fig. 8 with the appropriate wind probabilities. Table 4 compares the CHARM threat index, derived from 30- and 50-kt wind probabilities with more traditional threat indices (forecast maximum winds at Rosseau and forecast minimum passing distance). In this example the traditional indices wavered back and forth reflecting and amplifying minor changes in the

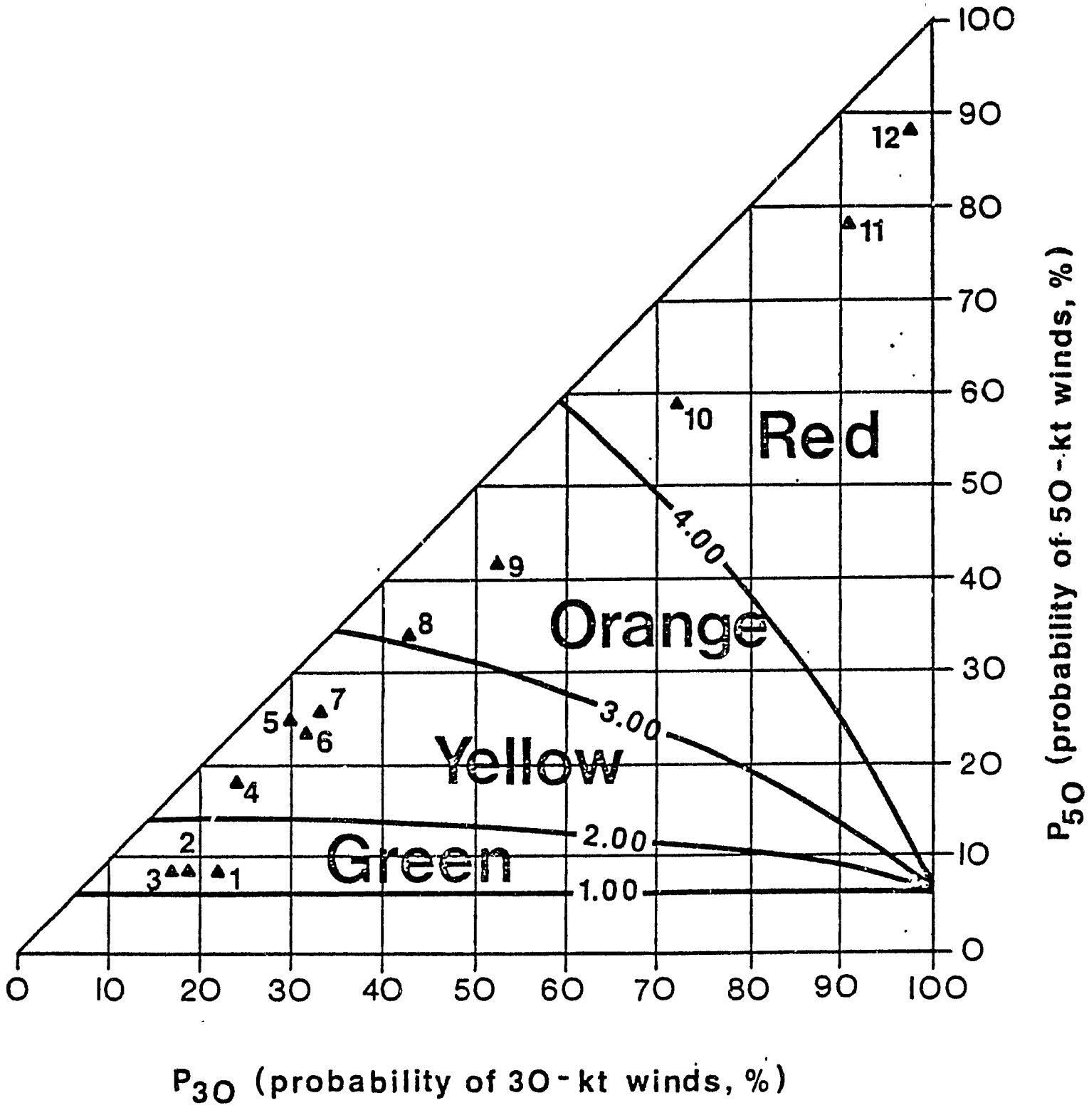


Figure 8. CHARM nomograph for establishing color coded conditions based on 30- and 50-kt wind probabilities. This sample nomograph was constructed using arbitray cost benefit ratios for precautionary actions. Numbered triangles are consecutive forecast wind probabilities given in Table 4.

forecast, while the CHARM index correctly showed a steady trend of increasing threat over the three day period.

CHARM, adapted to local disaster plans, is being considered as a decision aid by at least two foreign governments, and may become a part of the condition setting process at two major western North Pacific military bases.

ACTUAL TIME TO STRIKE	FORECAST MAX WIND (M/S)	FORECAST CPA (KM)	FORECAST P50 PCT	FORECAST P30 PCT	FORECAST CHARM THREAT
72H	15	140	12	12	1.62 GREEN
66H	25	85	12	19	1.61 GREEN
60H	50	0	12	17	1.61 GREEN
54H	50	0	18	24	2.15 YELLOW
48H	20	220	23	32	2.42 YELLOW
42H	10	250	24	30	2.46 YELLOW
36H	10	240	26	34	2.58 YELLOW
30H	15	165	33	43	3.01 ORANGE
24H	25	185	42	52	3.35 ORANGE
18H	60	93	59	73	4.27 RED
12H	60	75	78	91	4.72 RED
6H	60	35	88	98	4.87 RED

Table 4. Comparison of indices of threat to the city of Rosseau as Hurricane David approached in August 1979. All five indices are based on identical forecast information. Maximum wind is inferred from the forecast passing distance with respect to forecast wind radii. Closest Point of Approach (CPA) is forecast closest distance of hurricane track to Rosseau. CHARM is a relative threat level derived from the CHARM model.

3.0 Future Applications

The future use of tropical cyclone probability models will expand in three different directions:

(a) Existing operational products will be introduced to ocean areas where they are presently not available;

(b) Existing products will be improved; and

(c) Additional products will be developed and existing products will be more user oriented; that is, they will be tailored to specific user groups.

During the next year the strike and wind probability models will be completed for the southern Indian and Pacific oceans. That milestone will complete the initial phase of product development . The importance of storm surge makes it highly likely that a suite of storm surge probability models comparable to the present Bay of Bengal model will be developed.

Anticipated improvement to existing models include some improved statistical performance. This will evolve as the length of the archive of forecasts grows. In the Indian Ocean, for example, forecasts have been archived only for about five years, or about 30% of that readily available in the northern hemisphere Atlantic and Pacific oceans. Better statistical modeling of forecast errors such as that described by Crutcher et al. (1982) could also selectively improve model performance.

Products tailored to specific problems include local adjustment to wind probabilities for terrain. Such a

terrain adjustment mechanism has recently been developed for the western North Pacific model specifically for the Naval Bases at Subic Bay, Philippines and Yokosuka, Japan. Independent testing of these adjustments in late 1982 was very encouraging and they are now operational on an evaluation basis. If the terrain adjusted wind probabilities are as well received, they will stimulate similar development for other bases.

A model primarily to support ship routing which will predict sea/swell height probability is being tested. In addition, it is not unrealistic to anticipate the development of rainfall probability models which could drive flood models. With wind, flood and storm surge probability models, it is possible to drive local casualty or damage models.

Other specific user oriented applications include a model being developed which will optimize decisions on single act preparedness problems such as evacuating deep ocean mining or drilling platforms. Models similar to CHARM are on the drawing boards for guidance in setting Department of Defense hurricane or typhoon conditions or hurricane watches and warnings for civilian use. In mid-1983 the Navy is scheduled to begin the routine production hurricane threat estimate for over 125 foreign cities world wide. This will be transmitted as an addressed message to the State Department Operations Center and to embassies, consuls, and missions in threatened areas.

4.0 Summary

The concept of decision making aids such as tropical cyclone strike and wind probabilities has emerged from the historical evolution of how tropical cyclone forecast information is treated. Years ago the tropical cyclone forecast was the only aid in decision making. In time statistics accumulated and average forecast error statistics were used in combination with the tropical cyclone forecast to arrive at decisions. Present day technology allows us to incorporate decision making aids such as those discussed in this paper to arrive at more cost effective decisions. This evolution is schematically depicted in Fig. 9. The authors feel that the decision making aids discussed in this paper are just the tip of the iceberg of the potential that exists.

The tropical cyclone strike and wind probability programs have grown from a simple idea in 1978 to a program with worldwide interest and broad potential application. Program growth is toward global coverage, toward a wider range of basic probability products and toward enhanced applicability by tailoring to specific user problems.

The products are evolving from strike and wind probabilities into storm surge, sea height and rainfall probabilities. The application models relate to optimizing decisions such as setting readiness conditions, evacuating oil rigs and routing ships.

The important problems with these models relate to the possibility that the underlying statistics may change in time and to the inapplicability of certain probabilities, most notably wind, in complex terrain situations.

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